COST Action E13

Wood Adhesion and Glued Products

Working Group 2: Glued Wood Products

State of the Art – Report

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Carl-Johan Johansson
Chairman of COST E13 WG 2 – Glued products
December 2001

Preface

By definition COST aims at developing cooperation in science ad technology in Europe. The technical Committee for Forests and Forestry Products recognized the great value that adhesives and bonding technology can apport and have apported to wood and to forest products. It is for this reason that COST E13 on wood adhesives and wood gluing has been created. The aims of this group are multifold, being:

1. To create a platform for building scientific cooperation and partnership across Europe and to facilitate the development of consortia for EU funded research projects (R&D framework programmes).
2. To assess the strength and weaknesses on given areas or disciplines concerning the field of wood adhesives and wood bonding for the various countries, and even more important for the European Community as a whole in relation to the global context.
3. To address such strengths and weaknesses with apt transnational projects and even facilitate national approach of such problems.
4. To make the scientific and industrial community in the wood adhesives and wood gluing cluster more visible and with greater lobbying influence in Europe and abroad.

We have now completed the State of the Art report. I would like to emphasize the necessary and innovative aspects of this work. It is “Europe” with a single voice speaking for the first time through the pages of this report, through you which have contributed to write the different chapters, or that you have just contributed by voice or by organizing.

This is an important exercise as it is only through the dedication of all of you that from such a document, the real, perceived, and urgent areas of need determinant for the future survival of this speciality and of its related industries have started already to emerge. We have a couple of years to go to define and refine these areas even better, in short to distil the numerous points we have already defined in a series of important focuses in the adhesives, bonding and bonded products areas. Take this seriously as you have taken extremely seriously the compilation of this State of the Art report, as your own survival in this field might depend from it, even if you might not be able to perceive this today. “Sitting on the fence”, and just playing at the stateman is a losing proposition in these exercises aimed at a world already in fast forward gear: not to participate actively means not to have your ideas taken into consideration, whatever these ideas and wishes might be: financing from the EU, a bigger market share on the global scene, an innovative product or process, impact on the world scientific stage, or even just survival by defending your own patch from unfriendly, competitive raids. The message is clear: participate actively as the future is only in your own hands. It is through this State of the Art report that each of you will also identify similarity of interests and purpose, will then identify future partners, lobbying friends and common interests without losing but rather gaining in competitive advantage at the cutting edge of the speciality. Do not waste or belittle this opportunity: none of us know, but it might be the only one is ever offered to us.

A.Pizzi

Chairman

COST E13

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Executive Summary

This report presents the state-of-art of research and development in the area of glued products. The presentation is done on different system levels, from the adhesive bond lines, via glued materials and glued joints to products and components. In addition to this, emission and LCA aspects are covered.

Except for giving the state-of-art the aim has been to identify the need for research in the different areas.

After a short introduction the mechanical behaviour of adhesive bond lines is explained by a presentation of tests and test results in chapter 2. Short term as well as long-term behaviour is covered.

Chapter 3 deals with adhesive bonded materials. Wood based materials, such as particleboard, MDF, OSB, plywood and solid wood panels are included, as well as glued laminated timber and structural composite lumber.

Chapter 4 begins with a detailed description of the stress distribution of adhesive joints and of how the joint strength can be modelled. In addition to this different types of joints are presented, such as glued-in rods, finger joints, glued/screwed joints and wood/non-wood joints.

Chapter 5 covers a number of adhesive bonded products and components, for example composite beams, laminated floors and joinery.

Chapter 6 gives an overview of emittable substances from adhesives in the production of glued products and in the finished product. Test methods as well as the regulations concerning emissions are presented.

Chapter 7, finally, deals with Life-Cycle Assessment (LCA), reuse and recycle of glued products.

In a few cases there are sections in the report, which were planned, but no author was found or the material has not been presented in time. In those cases the heading is left in the report and hopefully the section can be completed if a new version of the report is published.

1. Introduction

Björn Källander

The development of adhesives and glued products has always been closely linked to the development of the surrounding society.

The oldest known example of man made adhesives is a product based on local raw materials developed in order to produce a variety of products, reflecting both religious beliefs and the practical needs of everyday life. Neolithic cavemen used collagen adhesives made from animal skins as early as 6100 BC. The adhesive was used for a variety of tasks such as decoration of sculptured skulls, protective lining on rope baskets, waterproof containers and as an adhesive holding together tools and utensils [Weizmann Institute of Science, 1997].

The Neolithic cavemen did not produce pottery and had to develop other means of storing and transporting water. They lived in an environment with scarcity of trees which otherwise is a common source of raw materials for resins and developed an adhesive based on animal hides.

1.1 General

The caveman adhesive in the example above was developed to fulfil specific technical demands with the material available, as has been the case for adhesives developed up until the last few decades.

A modern adhesive or glued product has to function in a more complex society and has to meet more complex demands. An example of this is when environmental aspects have become more focused and the focus of adhesives technology development also to a large extent been turned towards environmental issues.

A general impression regarding structural products is that the trend is towards construction systems rather than single components. Methods to design a building, manufacture and deliver the material, erect and join the components are increasingly being developed.

Regarding non - structural products the environmental issues are increasingly important. Health hazards during production and emissions from delivered products must be and are being eliminated. Non-structural adhesives are also often used in combinations of wood and other materials.

New adhesives have been added to the established Phenol Formaldehyde (PF), Phenol Resorcinol Formaldehyde (PRF), casein and Urea Formaldehyde (UF) adhesives. Poly Urethane (PUR), Emulsion Polymer Isocyanite (EPI) and epoxy resins are used for structural as well as non-structural applications. New adhesives have opened up for new production processes such as gluing of unseasoned wood, green gluing.

The use of adhesives in the wood industry has been widened from the original joining of wood. Adhesives are used to glue in steel rods for reinforcement o the wood as well as steel plates to connect structural components. Glass fibre reinforced plastics can reinforce laminated beams. Wood damaged by decay is strengthened by means of impregnation with adhesives.

In spite of the increasing knowledge of the chemistry, mechanics and rheology of adhesives and adhesive joints, we still lack established standard procedures to determine the long-term stability and suitability for constructional purposes of new kinds of adhesives and production processes. The ongoing development of standard procedures to test and approve new adhesives and glued products is of vital importance to the wood based industry.

The glued materials in the wood based industry were early in the 20th century mainly massive wood and veneer. Later sawdust and chips were used for production of panels. Today adhesives are used to glue wood to a variety of materials ranging such as steel and aluminium, concrete, glass and polymers. This has created new possibilities at the same time as it has put new demands on the adhesives and the gluing processes.

New wood based products and composites with wood have been introduced. Laminated Veneer Lumber (LVL) and Parallel Strand Lumber (PSL) have emerged as alternatives to glulam for large structural components. Various kinds of I- beams have been introduced. Wafer Board (WB) is an alternative to plywood. MDF is used as an alternative both for chipboard and massive wood in the carpentry industry. Among these materials can be mentioned products made from recycled plastic and wood, such as outdoor panels and plastic lumber.

Wood is considered an environmentally healthy material, and the environmental aspects can give the wood based industry an advantage in comparison to other industries. However, if adhesives are used in an inappropriate way this advantage can be lost and instead turned to a major disadvantage. Emissions during production and after installing the product as well as life cycle analysis are of great interest to the customers.

The development of new adhesives, adhesion technologies and glued products has opened new possibilities for the wood based industry. The development in USA where engineered wood is used in a large part of the building industry is an example that clearly shows the possibilities of glued wood products.

At the same time it is of vital importance that the wood based industry accelerates the development process and introduction of new, better and cheaper products in order to keep its competitiveness in comparison to other industries. The wood based industry must ensure a continuous and accelerated development of processes and products if it should be able to keep the pace of other industries.

The introduction of new adhesives and glued products is time consuming and costly. The development of wood adhesives and glued products would be encouraged by a simple and uniform system of approval throughout Europe.

It is noticeable that some of the more successful new-glued wood products that have been introduced in the last years to a great extent are based on existing adhesives and components, rather than a development of new adhesives. Examples are Laminated Veneer Lumber (LVL) and steam pressed MDF. This could be interpreted such as the potential of the newly developed adhesive systems, such as PUR or EPI, not yet have been fully utilised.

1.2 Non Structural Applications

Resins based on "natural" raw materials such as animal resins of the same principal type as the one used by the Neolithic cavemen and casein adhesives were used up to the Second World War, after which they were started to be replaced by synthetic resin. Today the most common adhesives for non-structural applications are Urea Formaldehyde (UF) and Poly Vinyl Acetate (PVA) adhesives.

Most PVA and UF adhesives have limited durability against water, which makes them unsuitable for products exposed to moisture. The desire to improve the durability of the adhesives has lead to the development of modified PVA as well as UF adhesives. Two component PVA adhesives as well as Melamine Urea Formaldehyde (MUF) adhesives can fulfil the requirements of class D4 according to the standard EN 204 - 205, giving a good water and moisture resistance.

Today the strength and durability as well as the adaptation to the demands of the production process of UF resins is to a degree limited by environmental restrictions, where the amounts of formaldehyde in the resins is reduced as much as technically feasible.

1.2.1 Indoor Applications

The by far largest volumes of adhesives used for non-structural applications are UF adhesives used for fibreboard production. The formaldehyde content of the resin and the emissions to indoor air has been a major problem for the fibreboard industry and is still a problem regarding products made from fibreboard.

Wood flooring, either if it is parquet or laminate floors, have high demands on the dimensional stability of the finished product. As the thickness of the products has decreased, the demands on the glue lines have increased accordingly.

The use of adhesives in the furniture industry is only to a degree wood adhesives, since a great variety of different materials are glued together. All possible combinations of wood and other materials can be used and will not be discussed further in this chapter.

However, there is one pure wood gluing operation in the furniture that is equally challenging technically and important to the function of the piece of furniture: connections between different furniture parts. The combination of high stresses, different shrinkage and swelling properties of the wood in different directions and difficulties to ensure a proper gluing process often makes the joints the weakest point of a piece of furniture.

1.2.2 Outdoors Applications

The durability of wood products exposed to outdoor conditions, such as in wood for windows and doors was questioned after a long series of reported damages in Scandinavia. This lead to a set of strict rules and regulations on how to produce wood windows and doors.

By measures like choosing wood raw materials and adhesives correctly, using designs aimed at protecting the wood construction and by implementing systematic quality control systems the window and door industry has managed to reduce or eliminate the problems, but the market impact of the earlier damages are still great.

Today are only adhesives that fulfil the requirements of EN 204 - 205 class D4 accepted for windows and doors are in Scandinavia, and glue lines are not placed closer than 15 mm to weather exposed surfaces in order to ensure a durable glue line.

The damage to the wood window industry by the earlier quality problems shows how important quality management is not only to structural wood components, but also to the non-structural applications.

1.2.3 Semi Structural Applications

The term non-structural refers to the glue line being a crucial part of the stability of the building. There are a number of applications where the glue line not is considered structural even though it is part of a load-carrying component.

Such examples are laminated or finger jointed wall studs where the component is loaded in compression parallel to the glue line and massive wall panels and massive wooden floors where the main load on the component does not directly effects the glue line.

This kind of products is produced in relatively large and growing volumes, for instance in production of wall studs for the Japanese market.

1.2.4 Environmental Aspects

The environmental aspects are of great importance to wood adhesives used for non-structural applications. This is regarding indoor emissions at the customer as well as emissions during the production process.

Since non-structural adhesives often are used inside buildings and also often have large areas exposed to the indoor air, emissions from the products have to be controlled. The formaldehyde problem has been and is a negative factor for products made of fibreboard and other products with relatively large amounts of UF adhesives. This has lead to a decrease in the amounts of formaldehyde in the resins.

New adhesives like EPI and PU use isocyanate for the curing process. The emission of isocyanates during production is a serious problem and could lead to severe restrictions in the future.

Epoxy adhesives can cause health problems in direct skin contact due to incompletely hardened resin.

1.3 Structural Applications

The use of glued wood products for structural applications have had a great increase in the last two decades, mainly due to newly developed engineered wood products and systems.

1.3.1 Wood Based Panels

The large-scale industrial production of glued wood products started with the plywood industry in the late 19th century [Raknes, 1986]. The production of wood based panels is still an important part of the world's total volume of wood production. A number of new types of wood based panels have been introduced since plywood. Products like hardboard, particleboard and Medium Density Fibreboard (MDF), Wafer Board (WB) and Oriented Strand Board (OSB). Products like Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) are produced as panels and delivered both as beams and structural panels. There are also combined products like OSB with MDF surfaces "Triboard". Today the growing segments are mainly MDF and OSB.

Wood based panels are used in a range of applications from non structural to fully load carrying purposes, and panels are often used as a combined elements that for instance both form a climate barrier and function as wind stiffening. Traditionally chipboard has been used for constructional purposes in for instance internal flooring in Europe while plywood, WB or OSB has been used in America for the same purposes.

1.3.2 Beams

An efficient method to create large building spans with wood was introduced with glulam in the early years of the 20th century. Today the glulam industry face competition not only from steel and concrete beams but also new wood based beams like Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL).

Although laminated wood beams often are associated with impressive buildings the greatest volumes of laminated beams are produced in fairly small dimensions used as roof trusses, floor joists or wall studs.

In addition to the beams mentioned above there are other types of engineered wood such as composite beams of various types. Examples of which are I- beams made with massive wood or laminated wood in the flanges and web made of hardboard or other panels as well as various metal webs. Building systems based on composite beams are today used in the absolute majority of one family houses built in USA.

1.3.3 Structural Elements

Glued structural components or elements where wood is combined with other materials such as aluminium or steel have proven to be very competitive. These elements are often delivered to the building site at a high degree of readiness.

One example of such a combination is roof elements with plywood panels on the compression side and steel or aluminium profiles on the tension side. The roof element can be delivered to the building site ready with insulation and both the interior and exterior surfaces finished.

Elements like the one described above are highly competitive, but can also be difficult to introduce to the market due to their special features. Standard testing and approval procedures can be difficult to apply due to new combinations of materials or designs.

1.3.4 Connections Between Structural And Between Non Structural Components

The most important application of adhesives in the wood industry is to achieve bigger components. To join planks endwise to longer lamellas. To glue lamellas together to form massive beams.

The most common of all such joints is the finger joint. The strength, durability and cost of the finger joints are of great importance to the wood industry whether they are situated in glulam beams or in finger jointed constructional wood.

Connections between large structural elements can be seen as equally important to the wood industry. Today it is difficult or impossible to glue large structural components on a building site, and thus the size of structural elements that can be delivered is limited by the maximum possible transportation size, or approximately 30 m length. The steel industry faces no such limit as steel readily can be welded on site, and hence wood has a major competition problem regarding very large structures.

Examples of methods that have been developed today are finger jointing of full size beams, glued in rods, glued in metal plates and various mechanical fasteners. However, both the methods and the regulations regarding these methods need to be improved.

In addition to the structural applications of connectors are the non-structural connections such as connections in furniture. Although often of great importance economically and sometimes with extremely high technical demands these connectors seem to have received less attention by the scientific world.

1.3.5 Indoor and Outdoor Exposure

The durability of glue lines and glued wood products is well illustrated by glulam bridges, where the combination of outdoor exposure, heavy loads and chemical pollutions such as salt creates a most severe environment.

Out door exposure of glue lines as well as wood constructions have proven that PRF is fully durable in all environments were it is possible to use wood. This has set the level for the demands on durability of adhesives for outdoor exposure.

New adhesives like PUR and EPI have also shown positive results both in accelerated ageing and outdoor exposure tests, although not as good as PRF. The tests have once been developed for PRF resins and we do not know how suitable they are for new adhesive types. Since we lack the long time experience of these new adhesives it has been difficult to introduce these new adhesives to the market.

Although the original adhesive used for glulam production, casein, not is water resistant and not is considered suitable for outdoor applications, the experiences from old structures have shown that the glue lines have an acceptable durability as long as the wood is protected from direct exposure to water.

1.4 Problems to Introduce New Products

Up until the Second World War, wood and wood adhesives was used for high tech applications, and great efforts were made to develop both the adhesives and the glued constructions in for instance the aircraft industry. After the Second World War the efforts spent on development of wood adhesives decreased. At that time casein resin, urea formaldehyde resin and phenol-resorcinol formaldehyde resin were already developed, and through the following years experiences regarding their performance both in laboratory tests and during long term exposure under working conditions were gathered. Safe and efficient procedures to test and approve the adhesives as well as glued products were developed for each of the adhesive types above.

Today a number of new adhesives for constructional purposes have been developed, adhesives that could have advantages to the established resin types. However, the introduction of these new adhesive to the market has proven to be difficult. The reasons for this are to an extent the earlier development of adhesives. We lack the long time experience of these adhesives that we have from the established resin types, such as PRF. At the same time these new adhesives do not readily fit into the testing and approval systems developed for the more established resins. When there are approval procedures these often vary from country to country. This has made it difficult to get a new adhesive approved for load bearing purposes.

The difficulties to reach the market with new adhesives as well as glued products efficiently hinder the development of wood based products. This will in a longer perspective have a devastating effect on the competitiveness of the wood industry. We urgently need to develop an efficient system to approve new adhesives and new-glued products.

Literature:

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Weizmann Institute of Science, 1997. Homepage.

2. Tests and Test Results on Mechanical Properties of Adhesive Bond Lines

Per Johan Gustafsson

2.1 Introduction and Bond Structural Hierarchy

Bond lines are tested by several purposes: determination of durability, manufacturing quality control and determination of strength properties. Here tests that relate to strength properties shall be discussed. By strength properties are here meant the mechanical properties or parameters needed for strength design or analysis of glued joints.

The choice of strength properties to be tested is governed by the method used for assessment of joint strength. Thus, in some cases the wood fracture area ratio is of the prime importance, in other cases the ultimate load or load versus deformation.

An alternative to the testing of bond lines is testing of the adhesive. Knowing the properties of the adhesive it is by principle possible to predict the properties of the bond line, provided that the properties of the adhesive-adherend interface are know. This is illustrated in figure 2.2.1. By several reasons such predictions are in general difficult to accomplish, one difficulty being to determine the interface properties.

Figure 2.2.1 also shows how strength analysis can be carried at various structural levels. By principle, if the mechanical properties in terms of the stress versus deformation are known at one structural level, then the strength properties at all levels above can be predicted theoretically by means of the equations of equilibrium and compatibility. Making the material testing at a low structural level, great generality is achieved, but then the difficulties and uncertainties involved in the prediction of properties at higher levels increase. A reasonable level for the testing may therefor be the bond line level. This means that the testing have to be done for each bond line combination of adhesive and adherend material, but not for each geometry or loading of the joint. For verification of methods of prediction, testing has to be made also at the higher structural levels.

In this chapter, bond line tests and test results are discussed. Bond line models and methods for joint strength calculation are discussed in chapter 4.1.

2.2 Strength and Stress Versus Deformation

2.2.1 Standard Test Methods

The frequently used American, German and British standard bond line test methods, figure 2.2.2, relate to loading of the bond line in shear and to strength, not to stiffness or deformation. The shear loading is along the grain of the wood and certain species of wood are to be used. The American and German tests are evaluated as for pure and uniform shear stress along the bond line, although the stress along the bond line is known to be more or less non-uniform and affected by normal stress.

No standard test appears to be available for fracture toughness or other measure of resistance to failure by crack propagation. This is notable since failure of glued wooden joints in many cases, perhaps in most cases, can be due to crack propagation starting in a small region where the stresses locally are very high.

The geometry of the specimen adopted in the ASTM D 905-86 standard is shown in the upper part of figure 2.2.2. The wood used is maple and load is applied with a constant rate of motion of the movable head, 0,37 mm/min. The overlap length is 44,5 mm. The mean shear stress at failure and the percentage of wood failure is reported. Stress analysis, see chapter 4.1, shows that the shear stress is far from uniform at failure and also that normal stresses develops in the bond line, although not very great. This means that the recorded mean shear strength value should not be considered as the shear strength of the bond line.

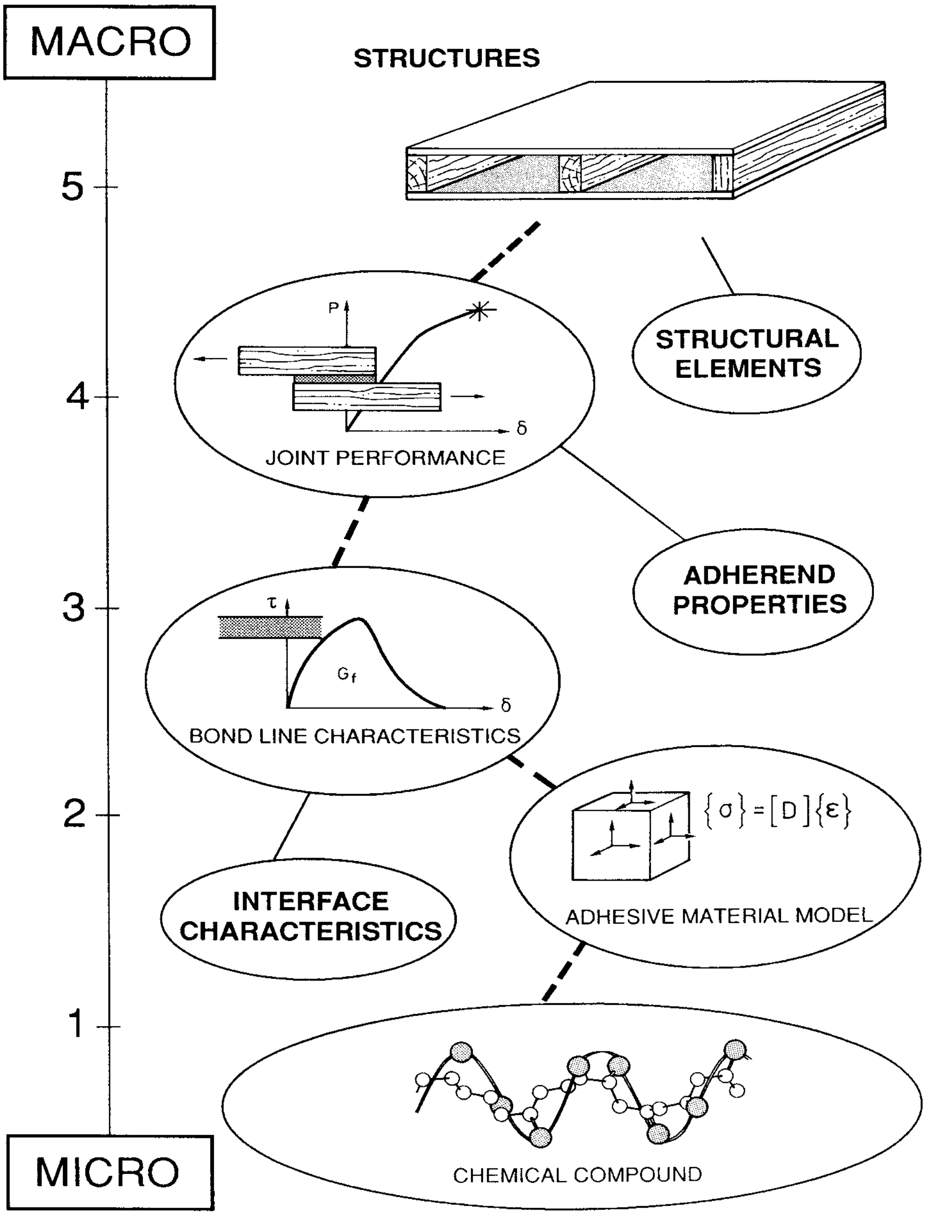


Figure 2.2.1: System levels for characterisation of mechanical properties in adhesive bonding design. (From Wernersson, 1994).

The middle of figure 2.2.2 shows the German standard DIN 53254 for thin and thick bonds. This standard corresponds closely to the standard proposed by CEN as a European standard. The overlap length is short, only 10 mm. The specimens are cut from large laminated veneer sheets, commonly made of beech. In this way edge gluing effects are avoided, but instead difficulties may arise when milling the notches. Stress analysis of the CEN-specimen shows that the shear stress distribution at failure is fairly uniform, see chapter 4.1 figure 4.1.5. The state of stress is, however, not pure shear since tensile normal stresses are found at the ends of the bond line. Like ASTM, DIN defines the strength as the mean shear stress at failure.

The lover part of figure 2.2.2 shows the British standard BS-1204 for thin and thick bonds. The overlap length is 25 mm and the adherend material is beach. The test result shall be given as the failure load, not the mean stress at failure, to avoid having the specimen strength confused with the materials strength of the bond line. The adherend parts consist of one layer for the thin bond specimen and three layers for the thick bond specimen.

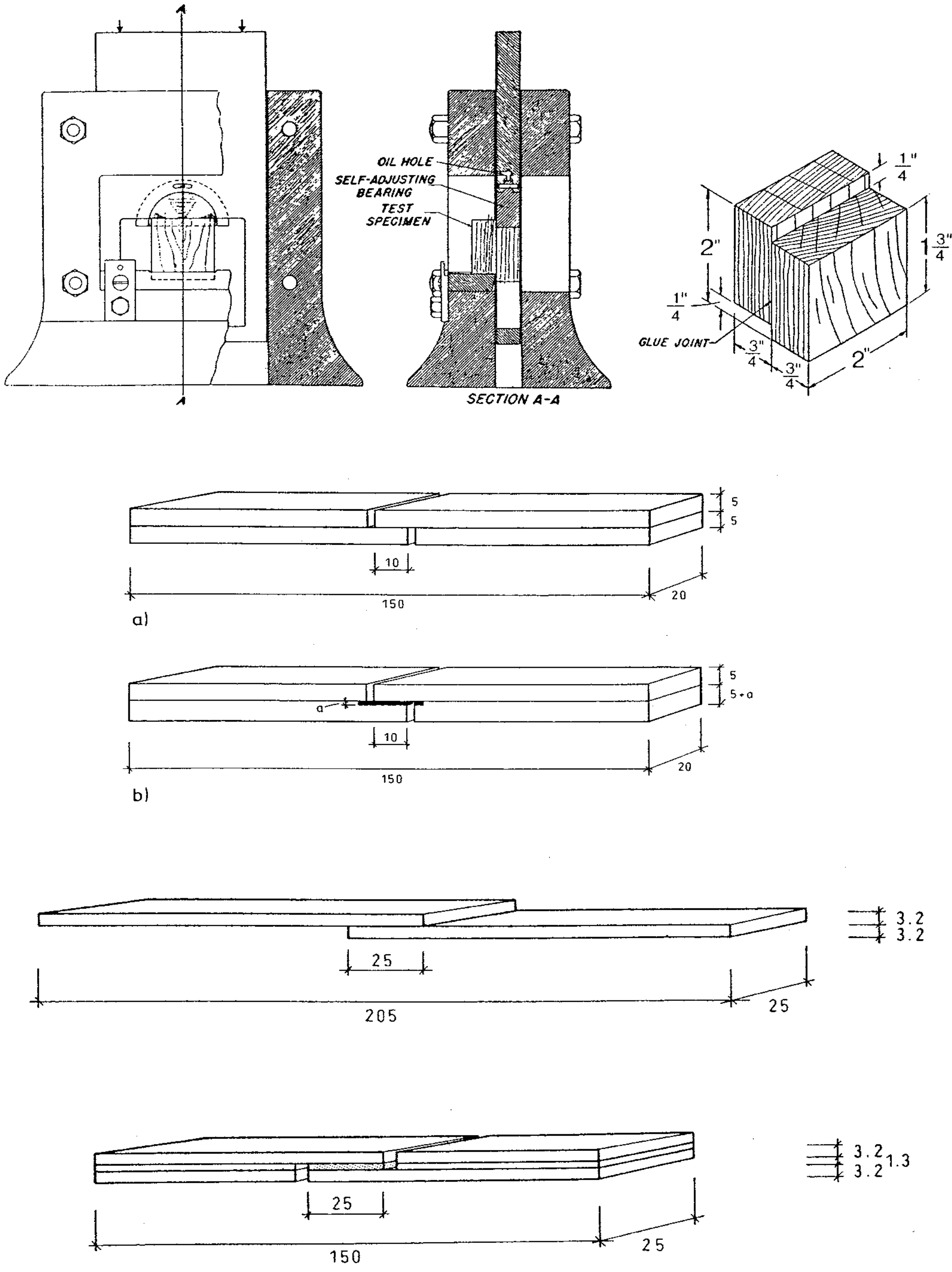


Figure 2.2.2: Upper: ASTM D905 - Middle: DIN 53254 for thin and thick bonds - Lower: BS 1204 for thin and thick bonds

2.2.2 Stress versus Deformation at Pure Shear and at Pure Tension

Bond line stress versus deformation properties in terms of shear stress-slip performance and tensile stress-widening performance of bond lines in between wooden adherends is reported in (Wernersson, 1990). The set-up and the specimen are shown for shear testing is shown in figure 2.2.3. The glued area was made small in order to achieve a reasonably uniform shear stress distribution and the anti-symmetrical loading of the geometrically symmetrical specimen was expected to result in pure shear without any normal stress. The set-up and the loading device was made very stiff since also the fracture softening branch of the stress deformation curve, with decreasing stress at increasing deformation, was to be recorded. If the stiffness is insufficient sudden instability failure will develop at peak load.

Test results obtained for common wood adhesives, figure 2.2.3, show that the bond line shear deformation is very small in the elastic region. This elastic deformation is probably of very small matter for the stress distribution along a bond line. The deformations after the elastic region are on the other hand large, corresponding to several hundred percent shear strain before complete separation of the two adherends. This deformation affects the stress distribution and produces fracture toughness and fracture energy. The fracture energy is, in the case of joint failure due to crack propagation, decisive for the bearing capacity of the joint.

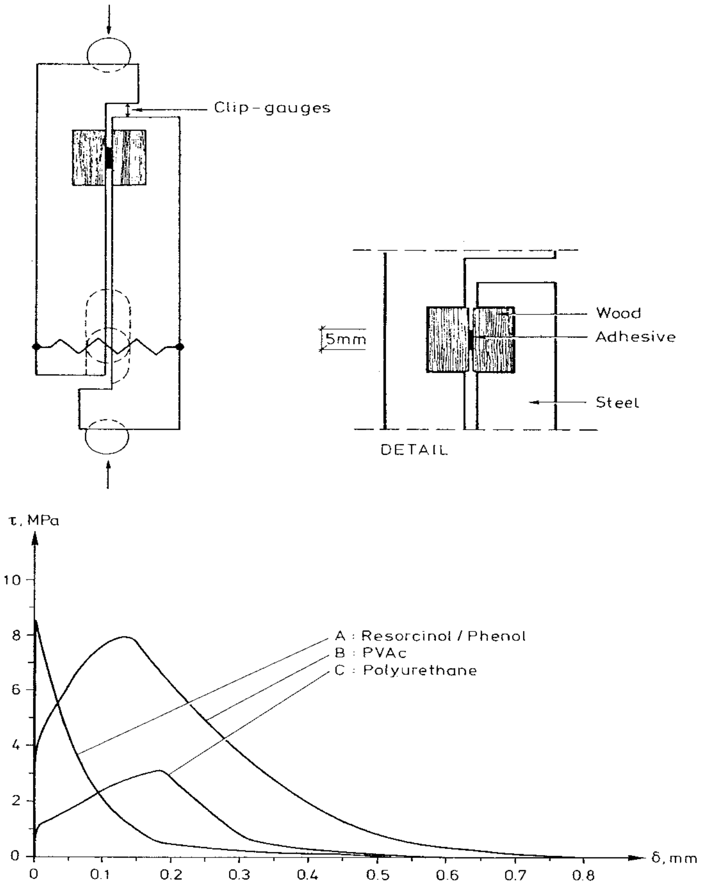


Figure 2.2.3: Test set-up, specimen and examples of test results valid for bond line shear stress versus bond line shear deformation.

In figure 2.2.4 is a corresponding specimen, a set-up and test results shown for pure tension perpendicular to the bond line. The normal deformation is the widening of the bond line, the deformations in the wood outside the bond line being subtracted. The test results for polyurethane shown in figure 2.2.3 and 2.2.4 were obtained for a one-component glue, apparently giving a poor bond line quality in this case.

The stress-deformation curves obtained can be used in non-linear joint strength analysis, e.g. by finite element calculations, and give from the peak stress information about the shear or tensile strength of the bond and from the area under the curves information about the bond line fracture energy. These two parameters are of fundamental importance in rational joint strength analysis.

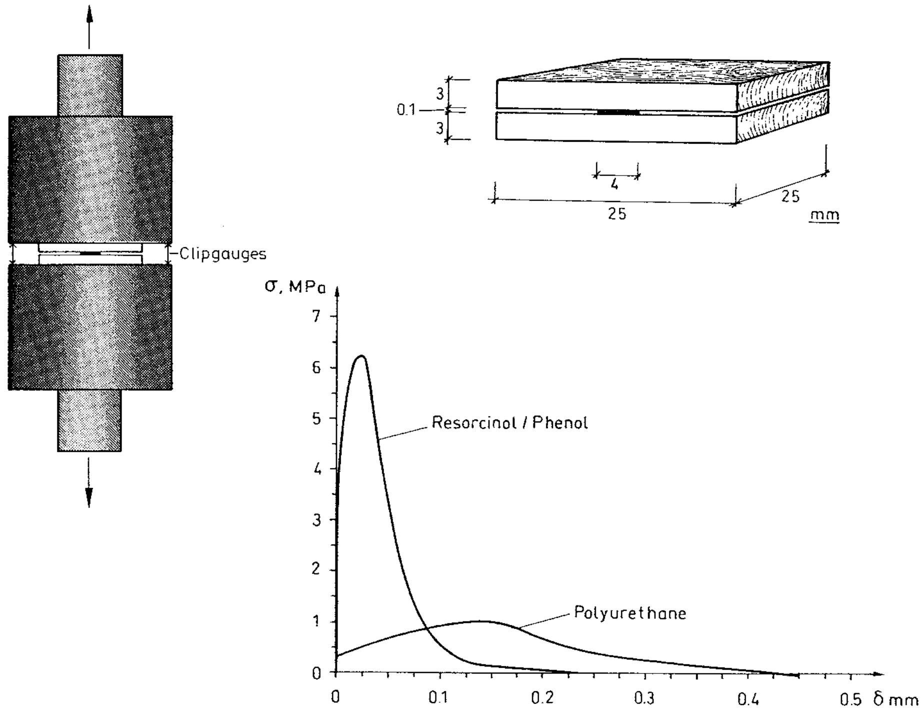
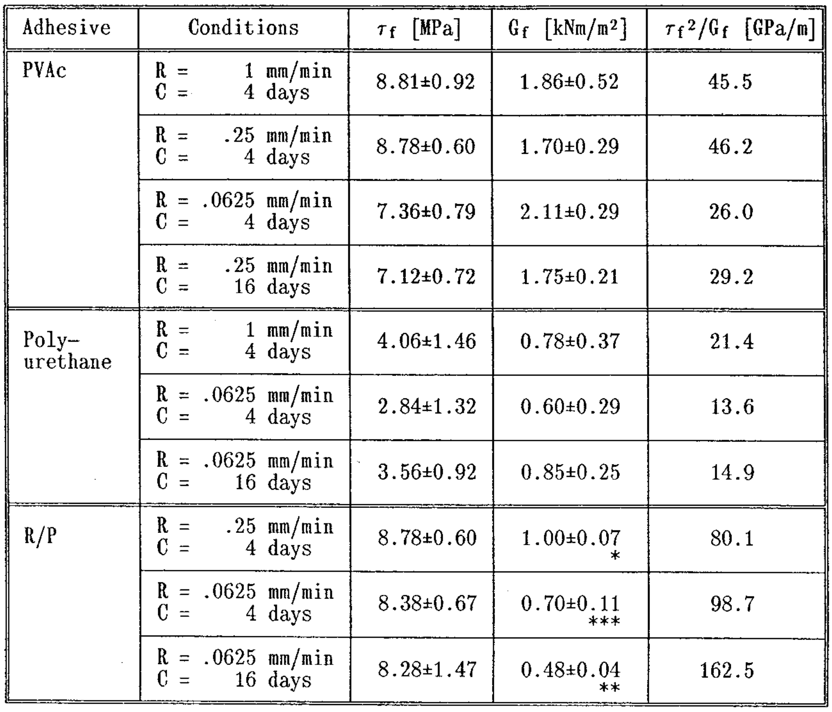
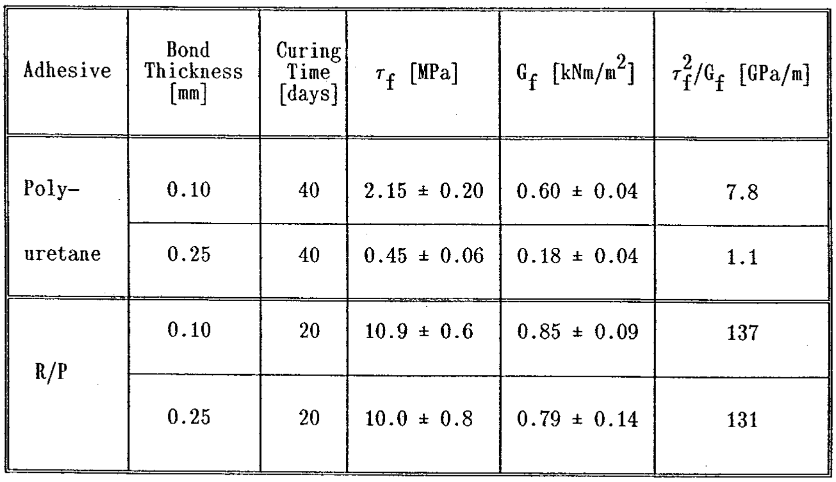


Figure 2.2.4: Test set-up, specimen and examples of test results valid for bond line tensile stress vs. bond line widening deformation.

Table 2.2.1 shows the results of an experimental investigation on three adhesives where the shear strength and fracture energy were determined for various rate of loading, curing time and bond line thickness.



Adhesive	Conditions	τ_f [MPa]	G_f [kNm/m^2]	τ_f^2/G_f [GPa/m]
PVAc	R = 1 mm/min C = 4 days	8.81±0.92	1.86±0.52	45.5
	R = .25 mm/min C = 4 days	8.78±0.60	1.70±0.29	46.2
	R = .0625 mm/min C = 4 days	7.36±0.79	2.11±0.29	26.0
	R = .25 mm/min C = 16 days	7.12±0.72	1.75±0.21	29.2
Poly-urethane	R = 1 mm/min C = 4 days	4.06±1.46	0.78±0.37	21.4
	R = .0625 mm/min C = 4 days	2.84±1.32	0.60±0.29	13.6
	R = .0625 mm/min C = 16 days	3.56±0.92	0.85±0.25	14.9
R/P	R = .25 mm/min C = 4 days	8.78±0.60	1.00±0.07 *	80.1
	R = .0625 mm/min C = 4 days	8.38±0.67	0.70±0.11 ***	98.7
	R = .0625 mm/min C = 16 days	8.28±1.47	0.48±0.04 **	162.5



Adhesive	Bond Thickness [mm]	Curing Time [days]	τ_f [MPa]	G_f [kNm/m^2]	τ_f^2/G_f [GPa/m]
Poly-uretane	0.10	40	2.15 ± 0.20	0.60 ± 0.04	7.8
	0.25	40	0.45 ± 0.06	0.18 ± 0.04	1.1
R/P	0.10	20	10.9 ± 0.6	0.85 ± 0.09	137
	0.25	20	10.0 ± 0.8	0.79 ± 0.14	131

Table 2.2.1: Shear strength, fracture energy and a brittleness ratio at various conditions.

2.2.3 Stress versus Deformation at Mixed Shear and Tension

Using small specimens, see left hand side of figure 2.2.5, glued to steel plates of a loading machine with two independent actuators it is possible to test the bond line stress-deformation performance for mixed shear and tension deformation paths (Wernersson, 1994). Examples of results obtained for a softwood resorcinol/phenol bond line are shown in figure 2.2.6. The angle shown in this figure indicates the inclination of the deformation path. The path is radial and angle 900 indicates pure shear slip deformation. Compressive normal stress was found for deformation paths equal to or close to pure shear slip.

In figure 2.2.7 is peak shear stress plotted versus peak tensile stress for the resorcinol/phenol bond line and for a PVAc bond line. In most cases the shear stress and the normal stress was peaking almost at the same time. Circles indicate mean values and crosses individual test results. In figure 2.2.8 is total fracture energy, i.e. the sum of the shear and tensile fracture energies, plotted versus the deformation path inclination. The complete lines show the test results and the doted lines illustrate a model.

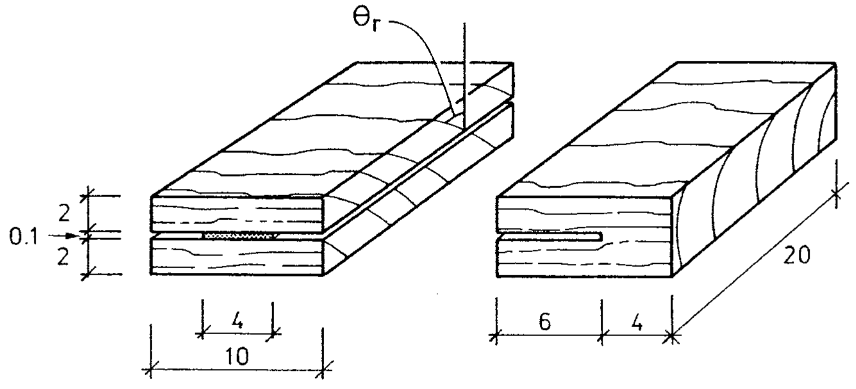


Figure 2.2.5: Specimen used in testing of properties at mixed shear-tension loading.

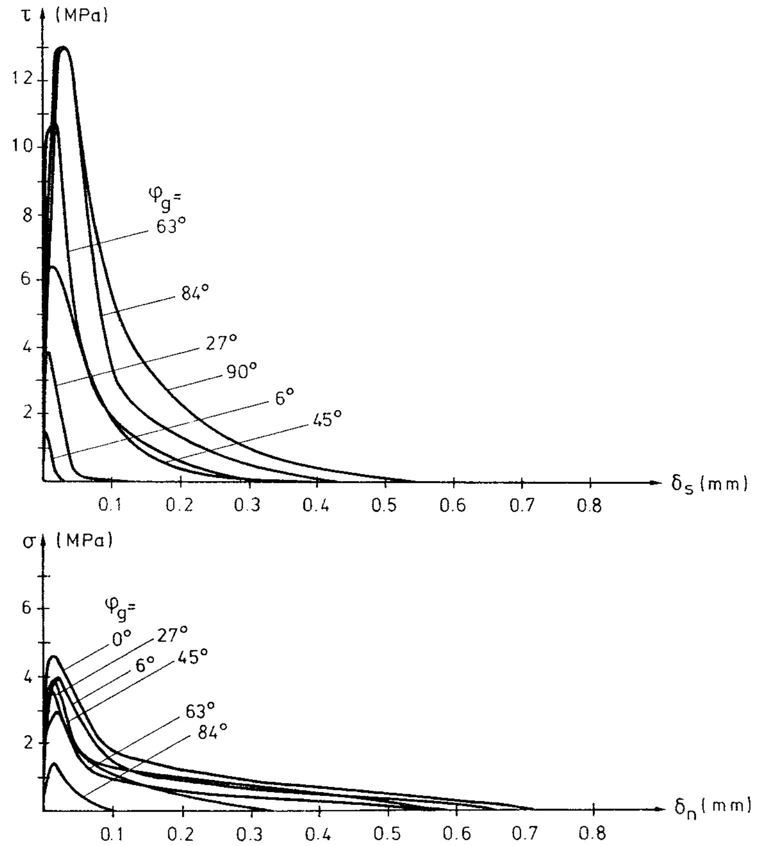


Figure 2.2.6: Shear stress- shear deformation and normal stress - normal deformation for a softwood resorcinol/phenol bond line at various deformation path inclination.

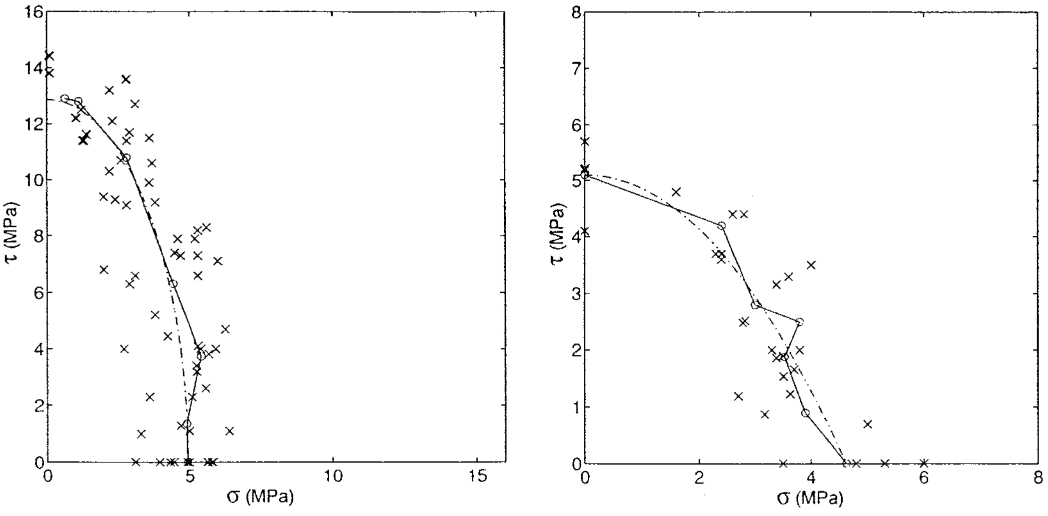


Figure 2.2.7: Peak shear stress versus peak normal stress for a resorcinol/phenol bond line (left) and a PVAc bond line (right).

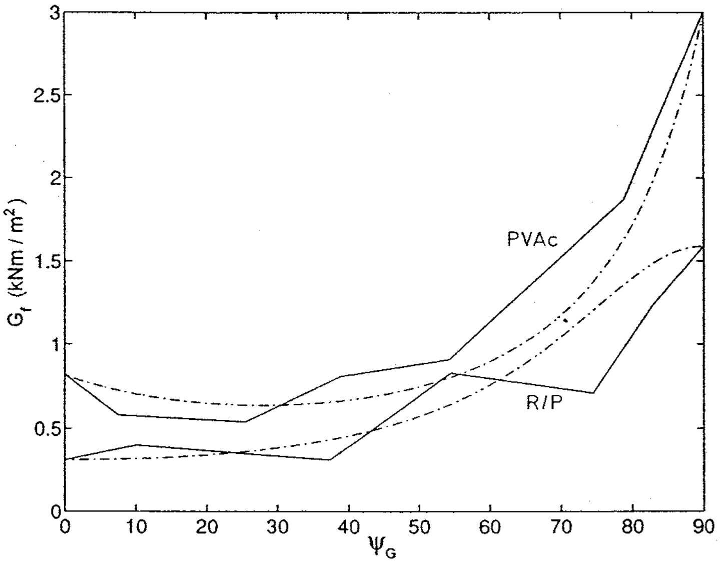


Figure 2.2.8: Fracture energy of a PVAc bond line and a R/P bond line versus deformation path inclination.

2.2.4 Stress versus Deformation in a Finger Joint Bond Line and in a Glued In Rod Bond Line

Using the bi-axial testing equipment used for the testing referred to in section 2.2.3 tests results for the mechanical properties of a bond line in a finger joint has been determined (Serrano, 1997). The specimens tested were cut from 10 mm thick, planed finger-jointed boards as shown in figure 2.2.9. The specimens are very small in order to get a stable test performance and a reasonably uniform stress distribution along the bond line. The inclination between grain direction of the wood and the bond line is approximately 6°. The size of the bond area tested is 3 times 10 mm. The specimens were glued to steel plates and tested for three deformation paths: $\delta_h/\delta_v = \infty$ (tension along finger joint), $\delta_h/\delta_v = 2$ (mixed) and $\delta_h/\delta_v = 0$ (tension perpendicular to finger joint). Three glues were tested: a RP, a PUR and a PVAc. The wood was spruce with density 526 kg/m^3 at the current moisture content, 12,6%. For each loading path and glue 3 nominally equal tests were made, making a total of 27 tests.

In figure 2.2.10 are the results obtained for the RP finger joint bond lines shown. The orientation of the coordinate system used for definition of the stress and deformation components are according to the orientation of the bond line, as indicated in figure 2.2.9. The deformation shown in the diagrams for tension along the joint and for the mixed loading is δ_s. The deformation for tension perpendicular to grain is δ_n. The deformation shown represent are from recording of the relative displacement in between the steel plates. This means that the elastic pre-peak stress deformations shown in the diagrams are dominated by elastic deformations of the in wood, outside the bond line. It is apparent that the post peak shear stress decreased rapidly at increasing δ_s. The performance was, however, stable without any instantaneous decrease in stress.

For loading along the finger joint compressive normal stress develops as the shear stress decreases and the bond is damaged. For loading perpendicular to the joint is shear stress developing as the normal stress decreases. Figure 2.2.10 also shows a failure envelop for shear stress versus normal stress. For loading along grain and for the mixed loading are the peak shear and normal stresses plotted, while for loading perpendicular to grain is only the peak normal stress plotted since the peak shear stress develops at a much later stage.

In figure 2.2.11 are the same set results obtained for the PUR bond lines shown. The results obtained for PVAc are fairly similar to those obtained for PUR, see (Serrano, 1997).

As a part of a European ongoing project about the strength properties of joints made of rods glued into glulam, the stress-deformation properties of rod to glulam bond lines has been tested (Serrano, 2000), (Johansson et al, 1995). The test set-up and test results in terms of average curves are shown in figure 2.2.12. The length of the tested bond area was 8 mm and the size of steel rods was M16. The diameter of the hole was 17 mm. Also rods made of glass-fibre reinforced polyester (FRP) rods were tested. The three glues tested were a new type of fibre-reinforced phenol-resorcinol (PRF), a two-component polyurethan (PUR) and an epoxy (EPX).

Most of the tests were made with the rod and the tensile pull-out load orientated along the grain of the wood. This is indicated by 0°. Other fibre-to-rod angles were also tested for the epoxy, as shown in figure 2.2.12. The bond line shear deformation shown was determined from the recorded total deformation by subtracting the elastic deformations. These elastic shear deformations of the bond line are assumed to be negligible as compared to the deformations of the wood.

The PRF glue had zero adhesion to the steel rod, so that the force transfer from adhesive to the rod was as from a rod (which had a M16 screw threading) to a nut. Fracture of the PRF bond line took partly place as damage of the “threading” of the “adhesive nut”, partly as failure in the wood along the bond line. Failure of the PUR took essentially place within the adhesive. Failure of the epoxy bond lines took essentially place in the wood, very close to the wood-adhesive interface.

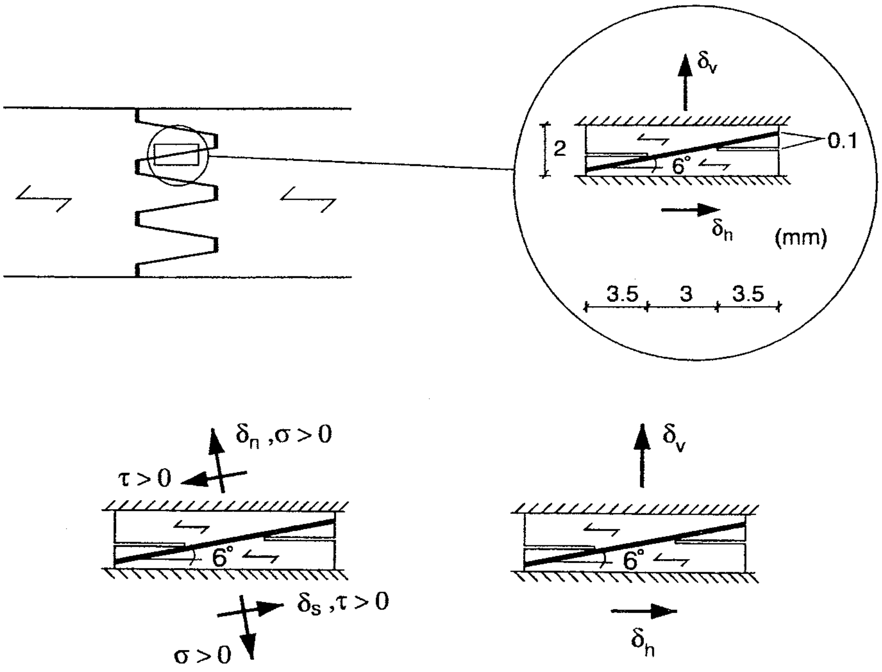


Figure 2.2.9: Finger joint bond line specimen and notation for stresses and deformations.

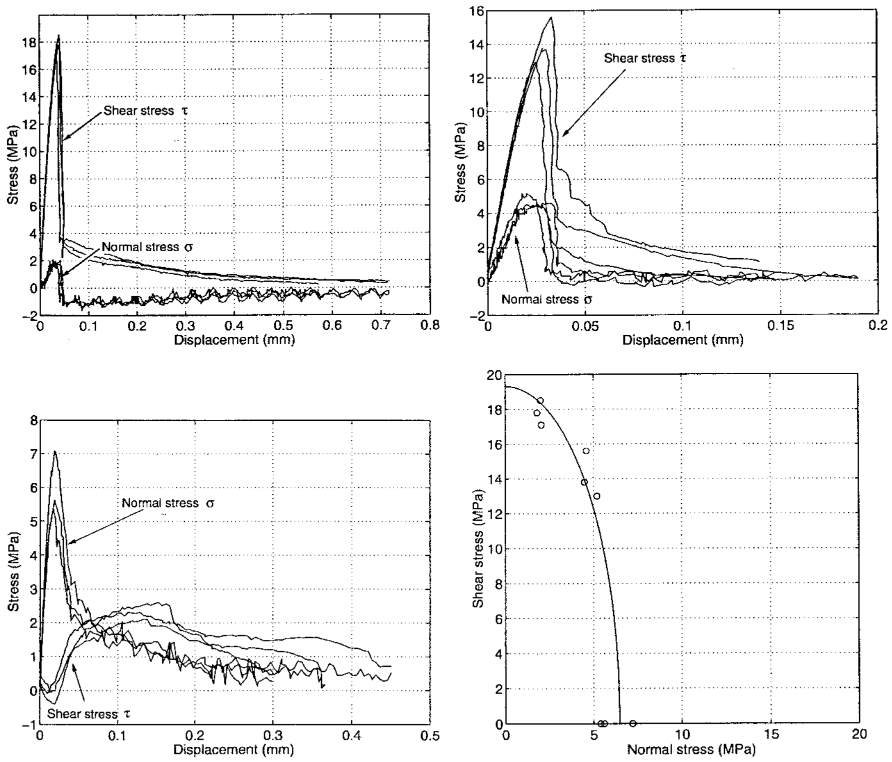


Figure 2.2.10: Results for a RP finger joint bond line, (Serrano, 1997).
Upper left: stress versus δ_s at loading along grain (along finger joint)
Upper right: stress versus δ_s at loading $\delta_h/\delta_v = 2$
Lower left: stress versus δ_n at loading perp to grain (perp to finger joint)
Lower right: failure envelope

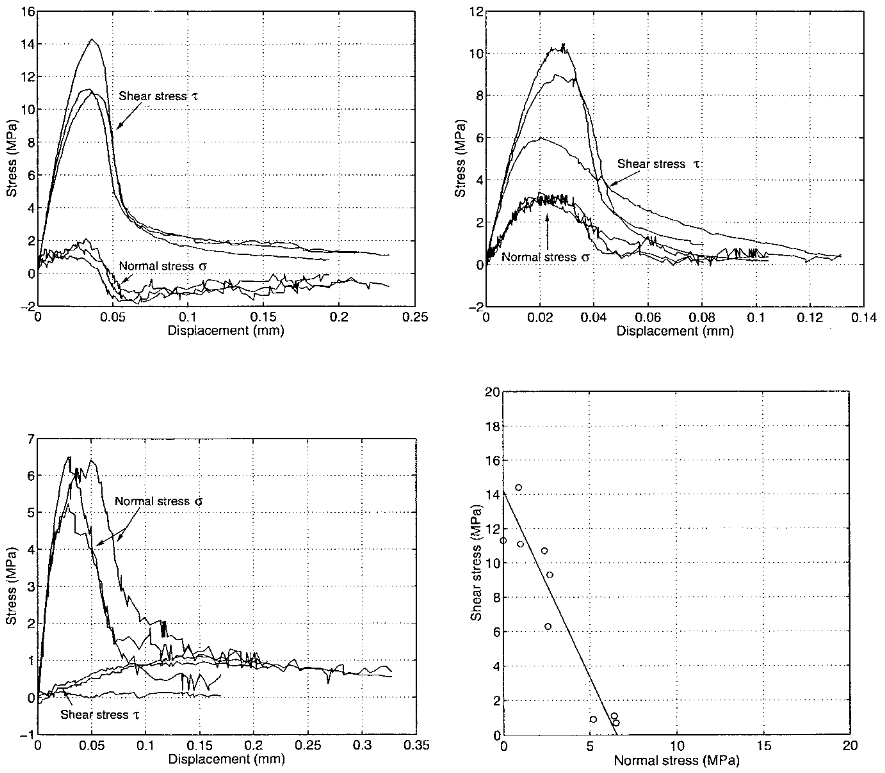


Figure 2.2.11: Results as in figure 2.2.10 for a PUR finger joint bond line.

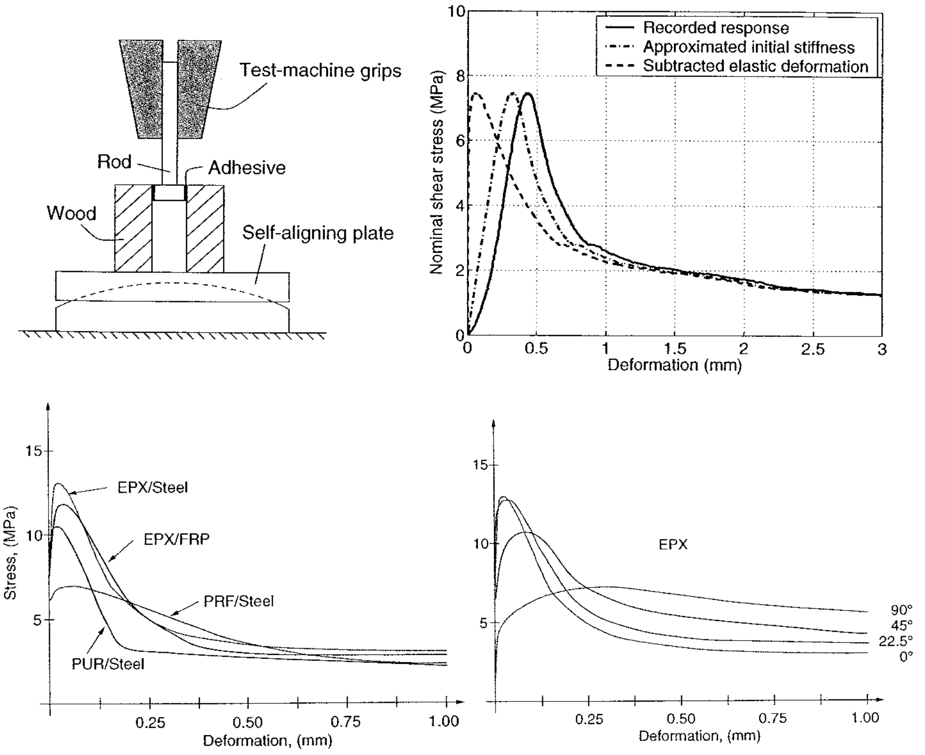


Figure 2.2.12: Shear stress versus shear deformation for bond lines along a steel or glass fibre rod glued into glulam. - Upper left: Test set-up - Upper right: Evaluation of bond line deformation from recorded relative displacement. - Lower left: Results for orientation of the rod along grain. - Lower right: Results for rods glued by epoxy in various incl. to grain.

2.3 Influence of State of Stress on Strength

A general state of stress is defined by 6 independent stress components. In the above section 2.1 examples of test results regarding the influence of simultaneous normal and shear stress acting across the bond line are indicated. It is not known whether any test method or test result for more general states of stress within a wood adhesive bond line has been reported. The bulk material yield performance of many polymers, including epoxy resins, is known to be dependent of the both the deviatoric and hydrostatic stress components (Adams and Wake, 1984) and in chapter 4 a corresponding general state of stress yield criterion from literature is given.

2.4 Influence of Climatic Conditions on Strength

Influence of temperature and wood moisture content on shear strength is reported in (River, 1984) for four so-called non-rigid adhesives: a polyurethane, a crosslinked isocyanate emulsion polymer, an epoxy-polyamide and an epoxy-triamine. The tests were made with the bond line loaded in shear according to ASTM D3983: Measuring strength and shear modulus of non-rigid adhesives by the thick adherend tensile lap specimen. The specimens were before testing conditioned for about 2 weeks in order to reach the moisture condition intended. During the testing, the specimens were inside an environmental chamber in the test machine. The test results, see table 2.4.2, indicates that temperature and moisture may have a very strong influence on the strength. The values in table 2.4.2 are average values from three tests. Several of the soaked specimens failed before testing. They are included in the averages as zero strength specimens. None of the soaked isocyanate specimens failed before being tested.

Table 2.4.2: Average shear strength in MPa. From (River, 1984).

Adhesive	Temperature	8% MC	19%MC	Soaked
Polyurethane	23 °C	5,7	4,3	0,7
	49 °C	4,5	4,9	0,6
	71 °C	4,9	1,9	0,0
Isocyanate	23 °C	9,3	10,7	4,1
	49 °C	8,6	8,4	3,2
	71 °C	6,2	4,8	2,4
Epoxy-polyamid	23 °C	14,0	12,0	0,0
	49 °C	9,7	2,5	0,0
	71 °C	2,1	1,8	0,0
Epoxy-triamine	23 °C	14,0	11,0	1,9
	49 °C	16,0	8,0	2,8
	71 °C	9,2	4,9	0,0

2.5 Influence of Load Duration on Strength and Deformation

2.5.1 Examples of Duration of Load Test Methods

Proposals for European standard methods for testing creep and duration of load strength properties of wood adhesives are referred to in (Källander, 2000). Discussions within the working group CEN/TC193/SC1/WG4 focus on methods according to ASTM D4680-92 and D3535-92. The specimen used in D4680 is according to figure 2.2.2, but the absolute size is smaller, the size of bonded area being 1” by ¾” (25,4 by 19,1 mm²). Constant load was in tests presented by (Källander, 2000) applied by means of a spring device as shown in figure 2.5.13. Load is applied on the loading shaft by means of a testing machine of any common type. When the desired load level is reached, the shaft is fixed with the locking nut. Sufficiently constant load is achieved by using a spring of small stiffness and negligible creep. ASTM D3535 is a test method for laminating adhesives used under wet conditions. Other methods for testing the performance at long duration of load are illustrated in figures 2.5.14 and 2.5.15. The method in figure 2.5.14 is according to a British standard, BS 3544. The specimen is a double lap joint loaded in bending and specimens are loaded in a chain of attachment parts made of steel. The steel part will carry the load if the specimen fails or creeps too much. The bond line shear stress is not uniform due to the bending action. The method illustrated in figure 2.5.15 is from (River and Gillespie, 1981). The figure shows the position of shims for controlling glue-line thickness and the location of saw kerfs to form five shear test areas of different length. The shear slip deformation was measured by microscope observations of a reference line scribed on each test joint perpendicular to the glue-line and across the adherends.

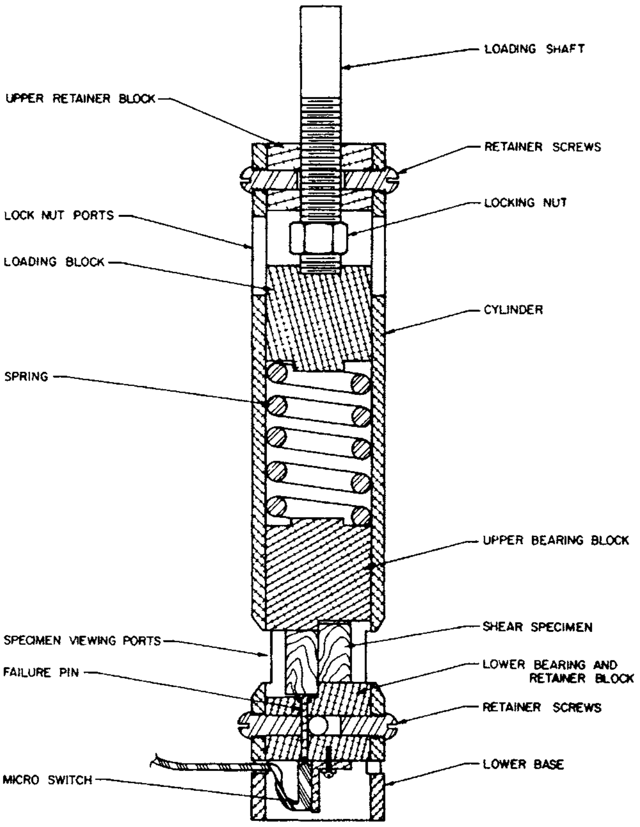


Figure 2.5.13: Long duration of load testing device with loading by a spring.

2.5.2 Examples of Duration of Load Test Results

Using the equipment shown in figure 2.5.13, (Källander, 2000) tested the time to failure for three glues, for several levels of constant load and at the severe climatic condition of 500C/75%RH. The glues tested were a phenol-resorcinol, PRF, and two one-component polyurethanes, PU1 and PU2. The wood glued was beech with a density of about 660 kg/m^3. The short term strengths found were 14,2, 11,7 and 12,0 MPa for the PRF, PU1 and PU2, respectively. The fracture surfaces indicated 61% wood failure for the PRF and 0% wood failure for the polyurethane glues. For each load level 10 specimens were tested and in figure 2.5.16 are the median times to failure indicated. The testes were finished after 1600 hours, at which time only 2 of 10 PRF specimens loaded to 77% load level had failed. Observations of possible creep were made by means of a magnifying glass, giving an accuracy of 0,05-0,1 mm. No creep was, however, observed.

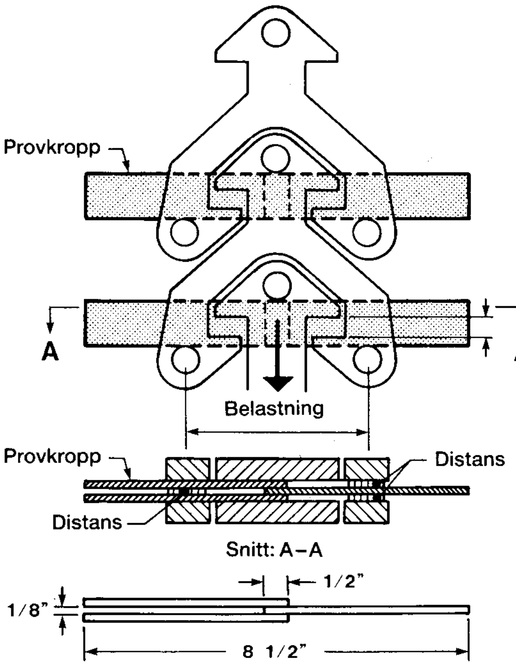


Figure 2.5.14: British standard, BS 3544.

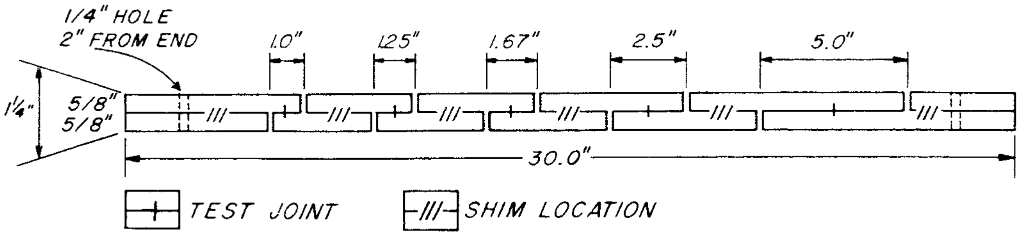


Figure 2.5.15: Test specimen with lap joints of various length and stress level.

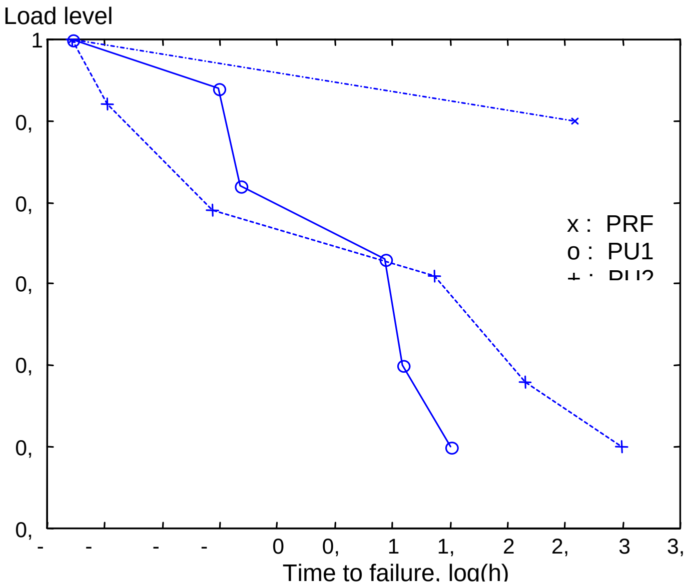


Figure 2.5.16: Time to failure for three adhesives tested at 50°C/75%RH.

The second example of test results refers to the shear creep properties of bond lines with six different commercial construction adhesives, tested by (River and Gillespie, 1981). The test arrangement is shown in figure 2.5.15. The adhesives tested were placed under dead load at three temperatures, 27°C, 49°C and 71°C, for 70 days. Five stress levels were tested and the shear slip was measured by means of a microscope after 10, 100, 1.000, 10.000 and 100.000 minutes (70 days).

In the tests three types of adhesive strain response to an applied load with time were identified. The three generalized types are illustrated in figure 2.5.17. At time t = 0 a constant load is applied and at time t = t1 the load is removed. Response type I was found at 27°C for two adhesives described as tough and hard, one with an elastomer base. For the same adhesives the performance was of type III at the higher temperatures, leading to tertiary creep and failure. Performance type II was recorded for one adhesive described as flexible and rubber-like and for two adhesives with an elastomer base. In table 2.5.3 the shear slip is indicated for to of the adhesives, loaded with constant loads for 70 days two temperatures 27°C and 49°C two. The shear slips are shown for two stress levels, 0,22 and 0,44 MPa, 70 days after loading. The short term, 10 minutes after loading, and the recovery 2 years after unloading are indicated relative values. Table 2.5.3 and figure 2.5.16 shows that it can be difficult to predict the long time loading creep and strength from the short term tests results. From table 2.5.3 it is moreover evident that the strain at a given time is not proportional to the stress, indicating that models within the framework linear visco-elasticity may not apply to bond lines, not even at low stress levels. The thickness of the bond lines tested was by use of the shims made equal to 0,40 mm. Accordingly, the 0,46 mm shear slip after 70 days at stress 0,44 MPa corresponds to a very large shear strain, 0,46/0,40 = 115%, and a very low “total shear stiffness” 0,44 MPa/1,15 = 0,38 MPa. Such low stiffness suggests, both for adhesive A and adhesive B, a uniform shear stress distribution after long duration of constant load.

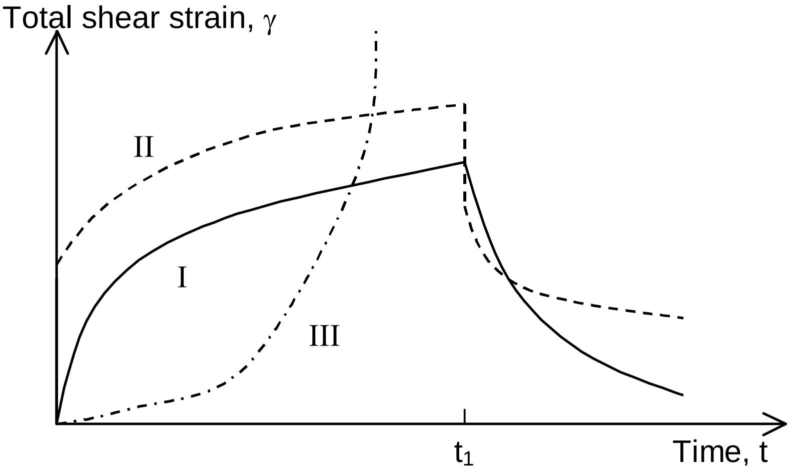


Figure 2.5.17: Generalized types of adhesive strain response to an applied load with time.

Table 2.5.3: Shear slip, δ, for two adhesives, A and B, at t = 70 days, 10 min and 2 years. Unloading to zero load at t = t_1 = 70 days.

	δ(t = 70days)		δ(t = 10min)/δ(t = 70days)		1-δ(t = 2years)/δ(t = 70days)	
	0,44 MPa	0,22 MPa	0,44 MPa	0,22 MPa	0,44 MPa	0,22 MPa
A, 27°C	0,46 mm	0,13 mm	60%	60%	96%	100%
A, 49°C	0,53 mm	0,15 mm	45%	50%	72%	85%
B, 27°C	0,28 mm	0,02 mm	<1%	<1%	31%	97%
B, 49°C	failure	failure	<1%	<1%	-	-

A third example of test results illustrating the duration of load performance of adhesives is taken from an ongoing project on the pull-out strength of threaded rods glued into holes in glulam made of spruce. The diameter of the holes was 17 mm and the outer diameter of the threaded rods was d = 16 mm, the shaping of the rods being “M16”. The glued length was L = 160 mm. Three adhesives were tested: a resorcinol/phenol (PRF), a polyurethane (PUR), and an epoxy. The climatic condition was an open shelter climate of southern Sweden. Table 4 shows the main test results: the short-term ramp load strength and the time to failure for two load levels of constant load. The ramp load strengths are indicated as the average of mean shear stress at failure, i.e. means of Pfailure/(πdL). Time to failure in the ramp load tests was about 3 minutes and the load levels for the constant loads were 70% and 80% of the ramp load strengths. Times to failure indicated for constant loading is the time to failure for the third specimen in each set of tests, each set comprising five nominally equal specimens. Tests were made both for orientation of the rod parallel to grain of for the rod perpendicular to grain. The shear stress distribution along the 160 mm long bond is most probably not uniform. The values obtained for strength and time to failure are therefore not true material properties, but instead properties of the entire joint.

Table 2.5.4: Short term shear strength and time to failure for glued in rods.

Glue	Orientation of rod vs. grain	Ramp load, shear strength, MPa	70% load level, Time to failure, h	80% load level, Time to failure, h
PRF	Parallel	6,9	157	7
PUR	Parallel	8,5	55	2
Epoxy	Parallel	7,1	2136	43
PRF	Perpendicular	6,3	457	65
PUR	Perpendicular	8,0	435	2

2.6 Other Factors that Influence of Bond Strength

Bond strength and also the stress versus deformation performance is affected by a number of factors. In the above some of these have to some extent been discussed:

- State of stress
- Climatic conditions (temperature, moisture, sunshine, climatic variations, ozone, possible pollutions, etc)
- Duration of the load

Factors that that of course may influence the strength and deformation performance include:

- Adhesive
- Adherend material and its surface conditions
- Preparations, method and conditions of gluing and hardening
- Bond line thickness

These factors might be said define a bond rather than being thought of as influencing factors.

Other factors that may influence the mechanical performance of a bond line include

- Cyclic loading, both few cycles giving plastic deformation and/or damage in each cycle and high frequency loading with thousands of cycles giving risk for fatigue failure. A report (in Danish) on the fatigue strength of finger joints is (Mullit, Nielsen, 1993).
- Impact loading.
- Ageing.
- Stress concentration. If using a linear elastic stress calculation model, there is a need for separate treatment of stress concentrations, making a stress concentration a factor that formally influences the strength of the bond. In the most common case, that of a sharp crack formally giving infinite stress, linear elastic fracture mechanics is used. This means that the strength parameter maximum stress is replaced by critical stress intensity or by critical energy release rate. A recent study on experimental bond strength characterization of wood adhesive bonds within the framework of linear elastic fracture mechanics is (Gagliano, Frazier, 2000).

2.7 Research Needs on Mechanical Properties of Adhesive Bond Lines

Contemporary design practice for wood adhesive joints is to a high degree based on empirical experiences including experimentally found figures for the strength of joints of specified shaping, materials and type loading and rules of thumb such as the strive for wood failure rather than adhesive failure. In contemporary wood adhesive joint research there is however a trend and strive towards development of more general and rational methods for strength analysis and design. The rational methods follow foundations of sciences such as strength of materials and continuum and fracture mechanics. Although full scale testing will be needed also in the future, i.a. for experimental verification of theoretical results, it can be proposed that future basic research should be aiming at developments within the framework of rational theories. Input to rational joint strength analysis has three parts: material properties, joint geometry and loading. Here the material properties of the bond line are in focus: level 3 in figure 2.2.1.

The bond line material property needed before a rational joint strength analysis is primarily a constitutive relation giving the rate of local stress for a given conditions in terms of deformation rate, the present stress and deformation, and the stress and deformation history. As an example, for a 1D state of stress and monotonic ramp loading the constitutive relation can be represented by a stress versus deformation curve such as shown in figure 2.2.3 or 2.2.4. This constitutive relation may include the influence of climatic conditions and ageing.

Even for a 1D state of stress, for instance pure shear, it is not very simple to accurately determine the stress vs. deformation properties, partly because of the needed to know the local stress and deformation, e.g. by testing very small specimens with a fairly uniform stress distribution. On the other hand, use of small specimens can imply various difficulties during the specimen preparation. This points at a research need:

- Development of a reliable and convenient standard method by which local bond line stress versus local bond line deformation can be tested (for pure and mixed states of stress and deformation, and at various loading rate and climatic conditions).

General challenges in this development of a test method, or test methods, are to find a test set-up that produces uniform stress and enable recording of the local shear and normal deformations across the bond line.

For some types of bond lines the deformations are very small as compared to those of the surrounding adhered material. Such bonds may be particularly difficult to test, but on the other hand for such bonds it may be sufficient to determine two parameters that are characteristic for the stress vs. deformation performance: the peak stress and the work to complete fracture (or the fracture energy or the critical energy release rate).

Having a good test method there are a number of conditions and parameters of that are of interest to test for existing and new adhesive/adherend combinations, i.a.:

- Bond lines with softwood rather than hardwood adherend material
- Various orientation of the wood
- Bond lines made up of wood/adhesive/other material (steel, glass fibre composites, etc)
- Cyclic loading
- Fatigue loading
- Impact loading (very high deformation rate)
- Creep and creep fracture
- Ageing before or during loading
- Various constant and varying temperature and moisture conditions

Bond line test results according to the above list opens up good possibilities for development of bond line constitutive equations, in turn making rational joint strength analysis and design feasible. It is probable that different classes of bond lines can be identified, corresponding to different constitutive equations, the different bond lines within a group being different only in terms of the numerical values of the parameters of the equation.

According to the above there is a need for test methods that can produce experimental results on bond line properties, needed as input to rational strength analysis of joints. Another area of research would be investigations for understanding the reasons for the properties of the bond line. This would suggest studies at a lower structural level than the bond line level, figure 2.2.1.

Literature:

Adams R, Wake W., 1984. “Structural Adhesive Joints in Engineering.” Elsevier Applied Science Publishers.

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3. Materials

3.1 Wood-Based Panels

3.1.1 Particleboards

George Ntalos and Athanasios Grigoriou

3.1.1.1. Description Applications

Particleboard was defined by FAO (Food and Agricultural Organization of United Nation) as:

> "A sheet material manufactured from small pieces of wood or other lignocellulosic materials (e.g. chips, flakes, splinters, strands, shivers, etc.) agglomerated by use of an organic binder together with one of the following agents: heat, pressure, moisture, a catalyst, etc."

Another definition was given by EN 309 (1992):

> "Particleboard: Panel material manufactured under pressure and heat from particles of wood (wood flakes, chips, shavings, saw-dust, wafers, strands and similar) and/or other lignocellulosic material in particle form (flax shivers, hemp shivers, bagasse fragments and similar) with the addition of an adhesive".

The main motivation of particleboard development was the idea to utilize the residues produced by other wood industries for the manufacture of new products.

Parallel steps of development were made for synthetic glues as well, and from 1960, when the first particleboard industry started working has made a tremendous lead and managed to grow worldwide from 30.000 m^3 in 1950 to 55.000.000 m^3 in 1989 and 72.752.200 m^3 in 1998. We can see the same development in Europe.

The main raw material for particleboards is wood but also other lignocellulosic materials, such as woody residues of cotton, baggasse, flax, bamboo straw sunflower and other agroresidues can be used.

Particleboards are widely used in the construction of many products such as: floor underlayment, kitchen cabinets, shelving, wall panelling, door cores, furniture, signs and insulation.

3.1.1.2. Process

There are several types of particleboards. According to their structure and method of manufacturing the EN 309 (1992) defines the following types of particleboard

1. According to the manufacturing process
2. According to the state of surface
3. According to the shape
4. According to the size and shape of particles
5. According to the boards structure
6. According to the use (interior, exterior)

a) Preparation of raw material

For the manufacturing of good quality particles the moisture content of the raw material should be fairly high between 30% and 60%. Particleboard plants uses combinations of hogs, chippers, hammer mills and ring flakers in order to reduce mechanically the available raw material of wood (logs, wood wastes) into small particles. Homogeneous material of particles with high degree of slenderness (long, thin particles), no oversized, no splinters and no dust is essential for obtaining particleboards with good strength and smooth surfaces. After chipping oversized and undersized particles are separated from the desired particles by using air streams or screen classifiers.

b) Drying

After the chipping the particles still have high moisture content. The desired moisture content of the finished board will be around 8% and therefore some drying of the particles will be necessary. Experience has defined the correct moisture content to which the particles must be dried and this is depending on the type of the resin and his viscosity but it may be under 4%. The main methods used to dry particles are rotary disk and suspension drying. Operating temperatures depends on the moisture content of the incoming wood particles.

After drying, all particles pass through sieves to remove some portion of these fragments, which are not included in the desired limits of the particle size. So we must remove the dust like fragments that increase resin inquirements and then the oversize fragments are rechipped. Dust is usually burned for energy production.

c) Addition of resins and wax

The dried particles are ready to be mixed with resin binder and other additives. Frequently used resins for particleboard include urea-formaldehyde and to a much lesser extent, phenol formaldehyde, melamine-formaldehyde, and isocyanate. The type and amount of resin used depend on the type and application of particleboard. Based on the weight of dry resin solids and oven-dry weight of the particles, the resin content can range between 4 and 10%. The resin content of the outer face layers is usually slightly higher than that of the core layer. Besides resin, paraffin or wax emulsion is added, in percentage from 0,3% to 1% based on the oven-dry weight of the particles, to improve short-term moisture resistance.

d) Board forming

After gluing the resin-coated particles are ready to acquire their final board shape. The weight and volume of the particles are metered out in order to achieve the desired board thickness and density. The mat of particles is formed by the back- and - forth movement of the tray or hopper feeder. The production of three-layer boards requires three or more forming stations. In continuous mat-forming system, the particles are distributed in one or several layers on travelling cauls or on a moving belt. The two outer face layers usually consist of particles that differ in geometry from those in the core. The mat is usually cold pressed to reduce mat thickness prior to hot pressing.

e) Pressing

After pre-pressing, the mats are hot-pressed into panels. Presses can be divided into platen and continuous types. Both of these types of presses can be as wide as 3,7 m. Multi-opening presses can be as long as 10 m and single - opening presses, up to 30,5 m long. Hot press temperature for UF resins usually range from 150°C to 190°C. Pressure depends on a number of factors, but it is usually in the range of 1,50 to 3,50 MPa. The time that boards remain under pressure depends on the board thickness, on glue type and on moisture content of mat and it should be long enough for the heat to penetrate even in the centre of the board.

f) Finishing

After pressing the board is trimmed to obtain the desired length and width and to square the edges. Trimmers usually consist of saws with tungsten carbide tips. After trimming, the boards are sanded or planed prior to packaging and shipping. Particleboards may also be veneered or overlaid with other materials to provide a decorative surface, or they may be finished with lacquer or paint.

3.1.1.3. Testing and Requirements - Properties

There are quality specifications for general requirements for all board types that are defined in EN 312-1 as we can see in table 3.1.1.1.

Table 3.1.1.1: General requirements for all board types

Tolerance in thickness after sanding	
Within the board	± 0,3 mm
Between boards	± 0,4 mm
Tolerances in thickness before sanding	
Within the board	-0,3 mm +1,7 mm
Between boards	-0,4 mm +1,6 mm
Tolerances in length and width	± 5mm

Edge straightness tolerance	1,5 mm/m
Squareness tolerance	2 mm/m
Moisture content	5 to 13%
Tolerance on the mean density within a board	± 10%
Formaldehyde potential (Perforator value in measured with spectrophotometer)	
Class 1	≤ 8 mg /100 g
Class 2	≤ 30 mg/100g

The requirements for general-purpose boards according to EN 312-2 are presented in tables 3.1.1.2 and 3.1.1.3.

Table 3.1.1.2: Requirements for general-purpose boards

		Thickness range (mm)						
Property	Unit	>3 to 6	>6 to 13	>13 to 20	>20 to 25	>25 to 32	>32 to 40	>40
BS	N.mm^{-2}	14	12,5	11,5	10	8,5	7	5,5
IB	N.mm^{-2}	0,31	0,28	0,24	0,20	0,17	0,14	0,14

BS = bending strength ; IB = internal bond

Table 3.1.1.3: Requirements for thermal conductivity for general-purpose boards.

Thermal expansion factor on the plane of the particleboard	8 10^{-6} to 12 10^{-6} K^{-1}
Thermal conductivity	0,10 to 0,15 Wm^{-1} K^{-1}

The requirements for mechanical properties for boards for use in interior fitments (including furniture) in dry conditions according to EN 312-3 are given in table 3.1.1.4.

Table 3.1.1.4: Requirements for mechanical properties for boards for use in interior fitments (including furniture) in dry conditions.

		Thickness range (mm)							
Property	Unit	>3 to 4	>4 to 6	>6 to 13	>13 to 20	>20 to 25	>25 to 32	>32 to 40	>40
BS	N.mm^{-2}	13	15	14	13	11,5	10	8,5	7
MOE	N.mm^{-2}	2.100	2.300	2.100	1.900	1.750	1.600	1.400	1.250
IB	N.mm^{-2}	0,45	0,45	0,40	0,35	0,30	0,25	0,20	0,20
	N.mm^{-2}	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8

BS = Bending Strength ; MOE = Modulus of Elasticity ; IB = Internal Bond

The requirements are different for load-bearing boards for use in dry conditions according to EN 312 - 4 are presented in table 3.1.1.5.

Table 3.1.1.5: Requirements for mechanical and hygroscopic properties for load bearing boards used in dry conditions

		Thickness range (mm)							
Property	Unit	>3 to 4	>4 to 6	>6 to 13	>13 to 20	>20 to 25	>25 to 32	>32 to 40	>40
BS	$N.mm^{-2}$	15	17	17	15	13	11	9	7
MOE	$N.mm^{-2}$	2.300	2.600	2.700	2.500	2.250	2.000	1.750	1.500
IB	$N.mm^{-2}$	0,45	0,45	0,40	0,35	0,30	0,25	0,20	0,20
TS_{24h}	%	< 23	< 19	< 16	< 15	< 15	< 15	< 14	< 14

BS = bending strength ; MOE = modulus of elasticity in bending ; IB = internal bond ; TS_{24h} = thickness swelling

The requirements for load-bearing boards for use in humid conditions according to EN 312-5 are presented in table 3.1.1.6.

Table 3.1.1.6: Requirements for mechanical and hygroscopic properties for load bearing boards used in humid conditions

		Thickness range (mm)							
Property	Unit	>3 to 4	>4 to 6	>6 to 13	>13 to 20	>20 to 25	>25 to 32	>32 to 40	>40
BS	$N.mm^{-2}$	20	19	18	16	14	12	10	9
MOE	$N.mm^{-2}$	3.000	3.000	3.000	2.800	2.500	2.200	2.000	1.800
IB	$N.mm^{-2}$	0,50	0,50	0,45	0,45	0,40	0,35	0,30	0,25
TS_{24h}	%	< 13	< 12	< 11	< 10	< 10	< 10	< 9	< 9

BS = bending strength ; MOE = modulus of elasticity in bending ; IB = internal bond ; TS_{24h} = thickness swelling

The requirements for heavy-duty load-bearing boards for use in dry conditions according to EN 312-6 are presented in table 3.1.1.7.

Table 3.1.1.7: The requirements for mechanical and hygroscopic properties in heavy duty load-bearing boards for use in dry conditions

		Thickness range (mm)					
Property	Unit	>6 to 13	>13 to 20	>20 to 25	>25 to 32	>32 to 40	>40
BS	$N.mm^{-2}$	20	18	16	15	14	12
MOE	$N.mm^{-2}$	3.150	3.000	2.550	2.400	2.200	2.050
IB	$N.mm^{-2}$	0,60	0,50	0,40	0,35	0,30	0,25
TS_{24h}	%	< 15	< 14	< 14	< 14	< 13	< 13

BS = bending strength ; MOE = modulus of elasticity in bending ; IB = internal bond ; TS_{24h} = thickness swelling

Finally the requirements for heavy-duty load-bearing boards for use in humid conditions EN 312-7 are given in table 3.1.1.8.

Table 3.1.1.8: The requirements for mechanical and hygroscopic properties in heavy-duty load-bearing boards for use in humid conditions

		Thickness range (mm)					
Property	Unit	>6 to 13	>13 to 20	>20 to 25	>25 to 32	>32 to 40	>40
BS	$N.mm^{-2}$	22	18	16	15	14	12
MOE	$N.mm^{-2}$	3.900	3.000	2.550	2.400	2.200	2.050
IB	$N.mm^{-2}$	0,60	0,50	0,40	0,35	0,30	0,25
TS_{24h}	%	< 15	< 14	< 14	< 14	< 13	< 13

BS = bending strength ; MOE = modulus of elasticity in bending ; IB = internal bond ; TS_{24h} = thickness swelling

3.1.1.4. Research Needs

- Utilization of annual plants, waste or residual wood as raw material resource.
- Developing of “Bio-based” glue resins based on natural resources.
- Developing of fortified and modified resins to enrich boards resistance to humid conditions.
- Developing on line control methods for measurement of surface quality.
- Non-destructive testing methods to detect possible defects occurring during laminating process of particleboards with surface materials (melamine films, decor foils, veneer).
- Developing an emission-free technology of powder coating.
- Further research for lowering the limiting values of emissions (gaseous, dust) and for heat recovery during wood-particles drying.

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EN 312-4 “Particleboards - Specifications - Part 4: Requirements for load-bearing boards for use in dry conditions” prEN 312-4: 1992

EN 312-5 “Particleboards - Specifications - Part 5 :Requirements for load-bearing boards for use in humid conditions” prEN 312-5 :1993

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3.1.2 M.D.F

Frederic Pichelin

3.1.2.1. Description - Application

MDF are sheet materials with nearly isotropic in-plane properties consisting of fibres (wood cells) and fibre bundles, respectively, which are glued together. MDF have an average density of 750 to 850 kg/m³ and are produced in a dry process comparable to the manufacture of particleboard.

The development of MDF technology took place in the 1960s in the USA and Europe.

Industrially, MDF was firstly produced in the USA in 1963, in Europe in 1973, in Germany in 1987. MDF production and consumption is characterised by a standing worldwide increase over the past 20 years. Figure 3.1.2.1 gives an overview of the production of MDF in Europe.

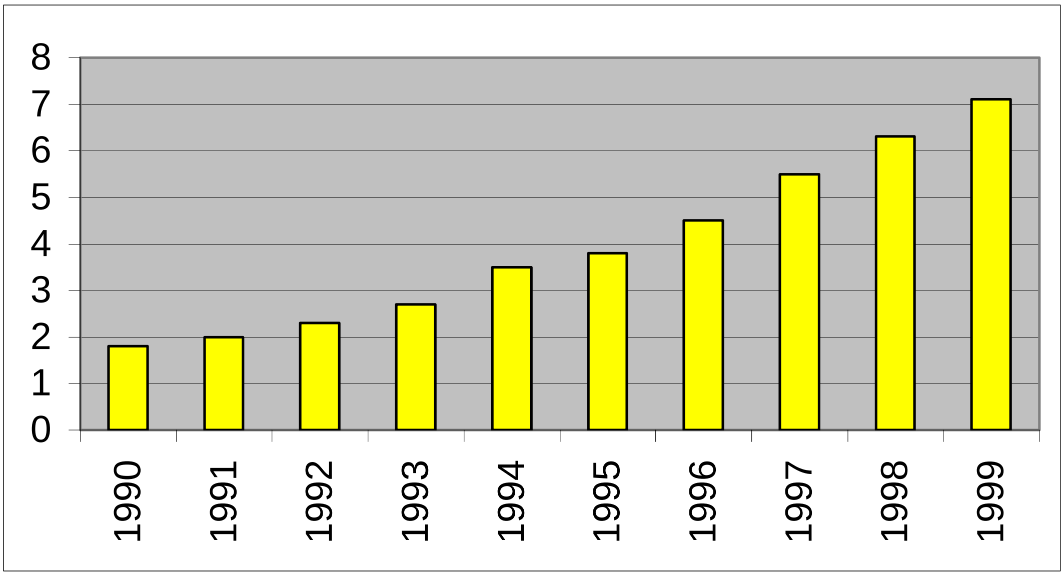


Figure 3.1.2.1: MDF production in Mio m³ (source EPF) - Average annual increase 16,5%.

The price of MDF in Europe is about 20% higher than that for particleboard of equal thickness.

Due to the relative homogeneous structure of MDF perpendicular to the surface, edge quality is distinctly higher than that of particleboard. Hence, edge banding and profiling results are much better than for particleboard.

Sanded MDF shows excellent surface smoothness and homogeneity of colour. For this reason MDF boards can be easily overlaid with films or lacquers even if surface or edges are profiled.

MDF are typically used for high quality furniture, decorative mouldings, wall panelling, and laminated flooring.

The MDF product line is extended into three directions:

- Especially by further optimising continuous presses, it is possible to produce thin boards with high physical properties; these boards do not require sanding as their high-density surface are well sealed. The type of product is used by the furniture industry, for indoor purposes, as door surfaces and in the automobile industry.
- Being a substitute for solid wood, thick MDF are going to gain importance. In the Siempelkamp steam pressing method, steam is evenly injected over the entire mat surface. This results in a homogeneous product with excellent processing characteristics.
- The third trend to be observed on the market is the production of light boards. This does not only affect the exploitation of the possibilities provided by the use of light board species (e.g. Pinus radiata), but also the production in Europe using wood species available there.

3.1.2.2. Process

a) Wood species

All plant containing cellulose and lignin may be used for MDF manufacture.

The structure of the fibres (dimension, strength, quality) is most important for the achievement of good panel properties. In this respect many similarities between MDF and paper manufacture exist.

Today's advanced technology makes it possible to design the plant to cope with the various raw materials available and still produce high-quality panels.

Many of the plants projected today are based on the use of young roundwood from clearings of growing plantation forests, cut at young age and debarked before use.

- Softwoods are easy to process and make a light - almost natural pine wood- coloured board. Due to the relatively long fibre, the mat has a higher internal integrity and it is possible to obtain good physical board properties with around 8% resin.

  However, one drawback of softwoods is that they require more electric energy for fiberizing. This consumption can be 50 percent higher than for hardwoods.
- Hardwoods have shorter fibres and require less energy in the fiberizing. The fibre web integrity is lower. The lower mat integrity is also compensated with 1-2 percent more resin and perhaps a slight increase in density in order to maintain the physical properties.

Moreover experience has shown that:

- Long fibres give better panel properties parallel to the panel's surface and lower swelling due to better and stronger glue bonds.
- Low-density wood (350 to 550 kg/m^3) give high-density panels (850 kg/m^3) with good properties since fibres are intensively compressed and favourable contact areas between fibres are present.
- Light colour species render light-coloured panels that are desirable as regards overlaying and coating. Low digesting and pulping temperatures ensures light fibre colour.
- Round wood should be debarked as bark renders low fibre quality, contains high amount of extractives (e.g. minerals) and has a low pH value due to a high acids content.
- Mill residues (like sawdust) have unfavourable particle dimension and therefore give low fibre quality and consequently panel quality.

Currently, there are more than 20 wood and annual plant species being used in MDF production.

b) Wood preparation

Logs are debarked in a ring or drum-type debarker. Round wood is then chipped in a drum-type or disc chippers. Chips are washed in water to remove metal, minerals and other impurities.

c) Preheating

In the chip silo pre heater and in the feed screw to the digester the action of steam provokes wood plasticization through simultaneous moisture and temperature increase. The chips reach about 80°C in the feed screw.

d) Digesting

The plug feed screw compresses the chips and presses them into the digester vessel. In the digester, wood chips are further plasticized at temperatures levels ranging between 160 to 200°C corresponding to a steam pressure of 6 to 10 bars.

The digesting process for MDF manufacture is almost the same as in a pulp mill with the exception that no chemicals are added to the chips. Some trials including biological and chemical (CTMP) treatments of the chips have nevertheless been conducted to reduce the energy required during the refining process.

About 0,5 to 0,8 tons steam are needed to preheat each ton of bone-dry fibres.

The action of temperature and moisture on wood chips results in the softening of the middle lamella between the individual wood cell walls. This middle lamella primarily consists of lignin and other amorphous substances and acts as a bond line between the multi-layered wood cells. The softening of the middle lamella facilitates the refining process and reduces destruction of fibres during refining.

e) Refining

After preheating and digesting, the plasticized chips are transferred into the single disc refiner by mean of a plug conveyor screw. Excess water is squeezed out of the chip.

A steam pressure of up to 10 bars in the refiner is maintained (Suchsland and Woodson 1991) so as to facilitate defiberization. High-pressure refines operate at 20 bars steam pressure.

The chips are fed into the centre of the refining disc and move radially outward within the gap between the discs equipped with profiled refining elements. The profile of the refining elements becomes finer toward the periphery of the disc to render isolated fibres and fine bundles in the machine housing.

The quality of fibres depends on refining conditions, i.e. preheating, defiberising time, disc geometry, refining temperature, and sharpness of the profiled refining elements.

The fibres leave the refiner housing through a valve through which instantaneous expansion of fibres and steam occur, leading to further defiberization.

f) Gluing

MDF is most commonly glued with UF resins at a percentage of 10 to 12%. New formulations based on PMDI/PUR and Tannin have been tried and show a very good dimensional stability. In order to avoid any plugging of the blow-line, blowing with PMDI occurs directly at the output of the blow-line (Glunz AG Deutsche Patentanmeldung 4 312 564.6).

Gluing may be achieved according to two different processes:

- In the blow-line, which ensures a very intensive, turbulent mixing of adhesive and fibres. It must be stressed that the temperature of fibres during the drying process should not exceed a temperature of 60°C, which could provoke a precuring of the adhesives.
- Another process relies on the blending in a separate blender like in the particleboard industry (Walter 1999).

Most MDF mills use the blow-line principle, as this one enables an optimal distribution of liquid glue droplets on fibres, thus avoiding dark spots at the board surface, which is a determinating factor for coating.

To avoid pre-curing of the glue droplets on the fibres during drying, special MDF adhesive formulations of a lower reactivity have been developed. Losses of formaldehyde on the way from the blow-line to the hot-press are compensated by a high U/F ratio of 1:1,4.

In general, due to the unavoidable precuring of the adhesive, 1-2% more adhesive is required with the blow-line process.

g) Fibre drying

Fibres are blown from the blow-line directly into single- or two-stage tube dryers. Drying temperature reaches 160°C for drying times between 2 and 5 min. that leads to final fibre moisture contents between 5 and 8%. A fibre temperature should not exceed 60°C so as to avoid any precuring of the adhesive.

h) Mat forming

Directly before mat formation, the fibres are screened in an air sifter to remove any impurities like coarse fibre and glue bundles, metal.

In the sifter the fibres may be conditioned to 40 to 50°C to accelerate the pressing process.

Because most of MDF mats are single layer mats, air stream and casting formers are not required. Relatively simple metering bins with mechanical or pneumatic fibres spreaders and gravity forming heads are used.

MDF mats are up to 50 times as thick as the final panel. For panels thicker than about 16 mm, two forming heads are necessary to achieve satisfactory production speeds.

i) Pressing

Due to the enormous height of the mat directly after forming, all MDF mills use belt-type pre-compressors to press air out of the mat and consolidate the mat for the transfer onto the press belt.

Due to the relatively low mat permeability, heat transfer in the core layer occur very slowly, press times are consequently 1,5 to 2 times as those for particleboards.

A multi-opening press is a good choice for production of panels from 8 mm to 40 mm. The press has a very flexible operating control system, which makes it possible to custom-design all panel properties. It can also operate with special types of resins requiring higher curing temperatures, such as phenolic resin, and thereby allow production of special moisture resistant or exterior-grades panels.

The steam-injection press developed by Siempelkamp enables the production of panels of thickness up to 40 mm with a homogenous density profile and at very short press times.

A continuous press can produce panels from 2,5 mm to 25 mm. The ContiRoll press (Siempelkamp) makes it possible to easily control the density profile. Moreover the continuous pressing has the advantage of substantially lower trimming and sanding losses.

To conclude, figure 3.1.2.2 gives a comparison of the material costs for the manufacture of particleboard and MDF.

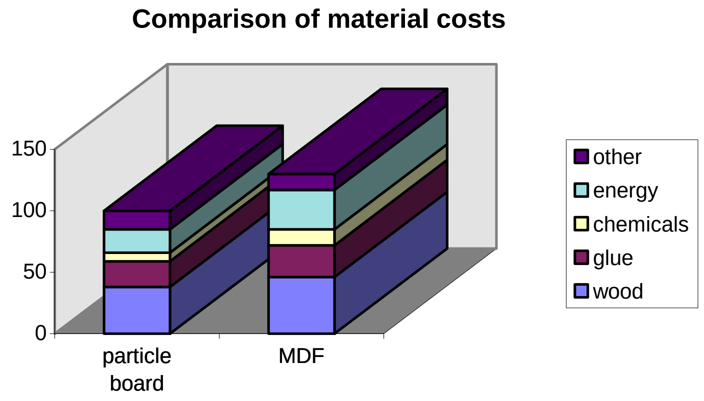


Figure 3.1.2.2: Comparison of material costs for the manufacture of particleboard and MDF (source Siempelkamp).

As can be seen, the high manufacturing costs of MDF are mainly due to the high level of energy required to defiberize the wood chips. The other drawback of MDF production as regards costs is the higher glue consumption required by the blow line process.

3.1.2.3. Properties

MDF is a product with excellent mechanical properties. Figure 3.1.2.3 shows a comparison between MDF and particleboard properties.

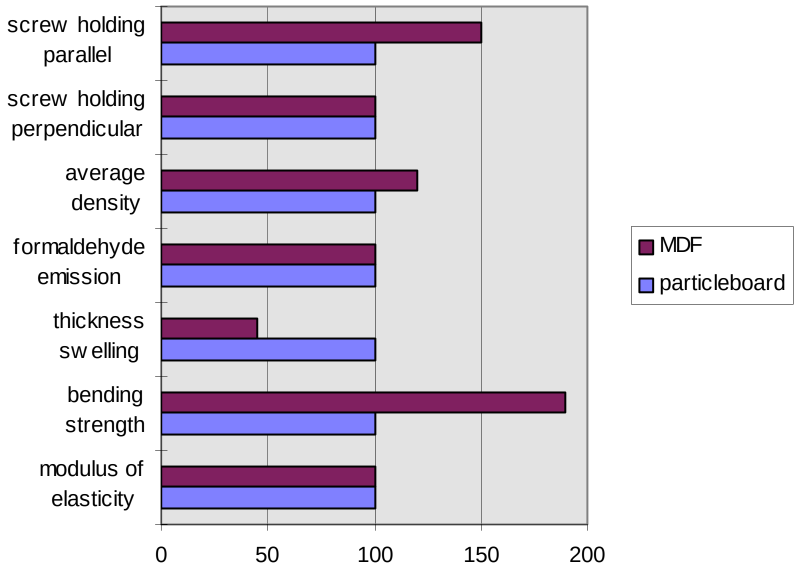


Figure 3.1.2.3: Comparison of MDF and particleboard properties (source Siempelkamp).

From this figure, it can be seen that at the same density level, MDF has a higher bending strength, a higher screw holding and a lower thickness swelling than particleboards. These performances can be explained by the very good contact existing between each fibre.

3.1.2.4. Research Needs

a) Thin MDF:

MDF producer are confronted with an increasing demand for thin MDF (< 2 mm) with a high forming accuracy (± 2%). Such thin boards can be used in the furniture industry. The high forming accuracy requires the development of new forming systems. The pressing technology should equally be adapted to the low thickness.

b) Reduction of resin spots on the board surface

Resin spots are always a drawback for the laminating of panels. Up to now there are very few information as regards the formation of resin spots. Investigation of the physical parameters involved in the blow-line process should help solving this problem.

c) Manufacture of MDF with tannin-based adhesives

Tannin-based adhesives have proven to be suitable for the production of exterior grade particleboard. Some investigations have been conducted in order to produce exterior MDF. Further research is needed in this area.

The formulation based on the use of hexamine as a hardener should enable to produce MDF panel specifically for use in environmentally sensitive interior applications where formaldehyde emissions need to be kept to the minimum. Until now such panels are produced with pMDI adhesives, which is not economical.

d) Manufacture of MDF with recycled wood

Recycled wood has been successively used in the particleboard industry. Some research is needed in order to improve the fibre quality gained from recycled wood.

e) Gluing of fibre in a mechanical blender

The blow-line process has the big disadvantage that resin pre-curing occurs during the drying of fibres. The consequence of this is a very high adhesive consumption.

An alternative to the blow-line system consists in gluing fibres after drying in a mechanical blender. This avoids the problem of pre-curing. Such a system has been successfully tried in semi-industrial trials in combination with a blow-line resination. Results have shown a reduction of 30% of adhesive consumption. Further research is required in order to achieve 100% of the resination with the mechanical system.

3.1.2.5. Standards

Table 1 summarises panel properties values required by the European standard EN 622-5 (1997). This standard distinguishes four classes of MDF:

- **MDF** boards for use in dry conditions
- **MDF.LA** load-bearing boards for use in dry conditions
- **MDF.H** boards for use in humid conditions
- **MDF.HLS** load-bearing boards for use in humid conditions

Table 3.1.2.1: EN 622-5 “Requirements for MDF”

Example : board thickness 16 mm	Testing method	EN 622-5 MDF	EN 622-5 MDF.LA	EN 622-5 MDF.H	EN 622-5 MDF.HLS
IB (N/mm²)	EN 319 (1993)	≥ 0,55	≥ 0,60	≥ 0,75	≥ 0,75
Boil test (N/mm²)	EN 1087-1 (1995)	-	-	≥ 0,12	≥ 0,12
MOR (N/mm²)	EN 310 (1993)	≥ 20	≥ 25	≥ 24	≥ 30
MOE (N/mm²)	EN 310 (1993)	≥ 2.200	≥ 2.500	≥ 2.400	≥ 2.700
24 h thickness swelling	EN 317 (1993)	≤ 12	≤ 12	≤ 8	≤ 8

Literature:

EN 310 (1993) “Wood-based panels: Determination of modulus of elasticity in bending and of bending strength”, European Committee for Standardization

EN 317 (1993) “Particleboards and fiberboards: determination of swelling in thickness after immersion in water”, European Committee for Standardization

EN 319 (1993) “Particleboards and fiberboards: determination of tensile strength perpendicular to the plane of the board”, European Committee for Standardization

EN 622-5 (1997) “Faserplatten - Teil 5 : Anforderungen an Platten nach dem Trockenverfahren (MDF)”

EN 1087-1 (1995) “Anhang A in EN300 (1997): Abgewandelter Arbeitsablauf”, European Committee for Standardization : 8

Suchsland, O. and G.E. Woodson (1991) “Fiberboard Manufacturing Practices in the United States”, Forest Products Research Society, Madison

Walter, K. (1999) Siempelkamp, private communication

3.1.3 OSB

Frederic Pichelin

3.1.3.1. Description - Application

Oriented Strand Board (OSB) is a 3-layer wood particleboard with longitudinally and transversely oriented strands.

The development of this board type occurred essentially in America during the 60’s, and particularly through Elmendorf in Palo Alto, California (Boehme 1998).

This new product came later to Europe. A first plant was erected by Bison in Bevern, and two other mills were built in 1985, Norbord in Scotland and Isorex in France.

At present five mills are running in Europe and a total production of 870.000 m³ is foreseen for the year 2000 (EUWID 1996a).

Standard European OSB mills have a capacity of 500-800 m³ / day, which is less than US/Canadian mills that are planed for a capacity of 1.000-1.500 m³ / day.

Figures 3.1.3.1 and 3.1.3.2 are giving an overview of the OSB market.

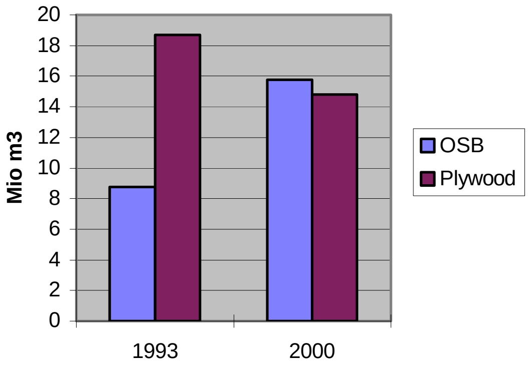


Figure 3.1.3.1: Growth of structural panels in North America (source EUWID HOLZ N° 42)

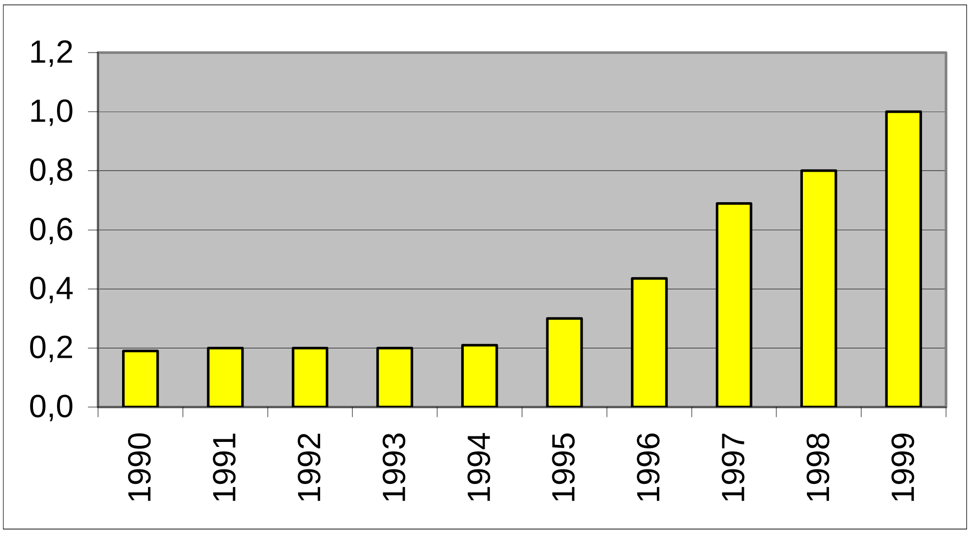


Figure 3.1.3.2: European OSB production in Mio m³ (source EPF). Average annual increase 19.6% (>1995: 35.1%)

The MOR and the E-module as well as internal bond and thickness swelling are similar to plywood, which means that this product can find numerous applications mainly in housebuilding.

In Europe, a huge proportion of OSB is used for packaging or structural application. However, owing to the anticipated increase in the production over the next year, it is believed that (similarly to particleboard and MDF) applications and uses for OSB in Europe will diversify (Woestheinrich 1999). For example, OSB will play a more important part in the fields of:

- Laminated products e.g. concrete shuttering or furniture parts
- Engineered wood products (substituting solid wood)
- Decorative applications e.g. shop fittings

3.1.3.2. Process

a) Wood species

OSB is made from freshly harvested aspen poplar, pine or other mixed hardwood and softwood logs. In Europe, pine (Pinus sp.) is mainly used. Spruce (Picea sp.) or Douglas (Pseudotsuga menziesii) and a few hardwood species may also been used as well.

In North America, the industry is concentrated in two regions: the Northern and the Southern/Eastern States. This regional separation represents a distinction as regards the raw material. In the Northern States (e.g. Alberta, Ontario, Quebec, Minnesota) Aspen (Populus grandidentata, P. tremuloides etc.) is mainly used. In Southern/Eastern States (e.g. Texas, Tennessee, Louisiana) mixture of softwood and hardwood (up to 20 different species) is used.

b) Debarking

The logs are debarked and cut to shorter lengths before being processed in the strander. The fines and bark become fuel for the mill’s energy system.

c) Flaking

The strander slices the logs into strands along the direction of the grain. Strand dimensions are predetermined for the process and have uniform thickness. The industry tends to favour longer (up to 150 mm) and thinner strands (0,5 mm), especially for the surface layer.

d) Drying

The strands are then dried. Modern single-pass dryers guarantee an accuracy of at least ± 1% in moisture content. This is so because the retention time is longer (up to 20 minutes) and strands (predominantly mechanical conveying) and fines (predominately pneumatic conveying) are handled separately. The older three-pass dryers only work on the pneumatic conveying principle. As a consequence, retention times are shorter, in-feed temperatures are higher and the resultant moisture content of the dried strands is more variable.

After being dried, strands have a moisture content of 2%.

e) Screening

Long strands are used for the surface layer whereas shorter strands are used for the core layer. Fines are removed with drum-screens. Fines increase resin consumption and have a detrimental influence on surface quality. In North America, these fines are usually used as fuel for dryers, heating etc. In Europe, fines are a crucial cost factor, because wood is an expensive fuel. It is for this reason that nearly every new OSB plants in Europe are placed adjacent to particleboard or MDF plant, so that fines from the OSB process can be used in the manufacture of these other products.

f) Gluing

After sorting, surface and core layer strands are blended in a rotary drum blender. Standard adhesives used for OSB production in North America are liquid or powder phenolic resins and isocyanate-based adhesives (EUWID 1996b). Since the specification requirements are not high (OSB/2 is used for house building), very low resin contents (2,5-5%) are sufficient to achieve values satisfying the ASTM standard (Kieser 1987). This is the reason why the North American OSB-boards do not have as good a moisture resistance as required elsewhere.

The situation is very different in Europe with the newly introduced EN 300 standard. The quality 4 can only be reached with Melamine-Urea-Phenol-Formaldehyde (MUPF) or isocyanate (Kieser 1987). A combination of 12% MUPF in the surface layer and 4,5% isocyanate in the core layer is often chosen by European manufacturers (EUWID 1996b; Kieser 1987).

Wax is equally spread onto the strands (2% based on dried wood) in order to reduce the thickness swelling of the boards.

g) Mat forming

In Europe OSB board are typically composed of three layers. Surface layer strands are oriented in the direction of the production, whereas core layer strands are crosswise oriented. This results in very good bending properties.

Sometimes all layers are aligned in the long direction of the panel in order to obtain very high stiffness.

h) Pressing

After forming, the mat of strands is pressed at a high temperature and pressure to form a rigid, dense structural panel. Thickness is ranging from 5 mm to 40 mm for a density comprised between 650 kg/m^3 and 680 kg/m^3.

Multi-daylight presses are widely used in America. In Europe on the contrary the continuous pressing has been successfully practised. The advantages of the continuous pressing for OSB are numerous: better surface quality, lower sanding allowance and optimised density profile (Mayner 1990).

For board thickness above 40 mm, the use of a preheater becomes necessary. The long time required to reach a high temperature in the core without preheating would lead to very long press times, which is not economical. A preheater like the Siempelkamp Contitherm® enables to warm up the core layer up to 80°C before pressing. The system consists of injecting of a controlled steam/air mixture thought the mat. When condensing, the steam liberates its energy, which increases the mat temperature.

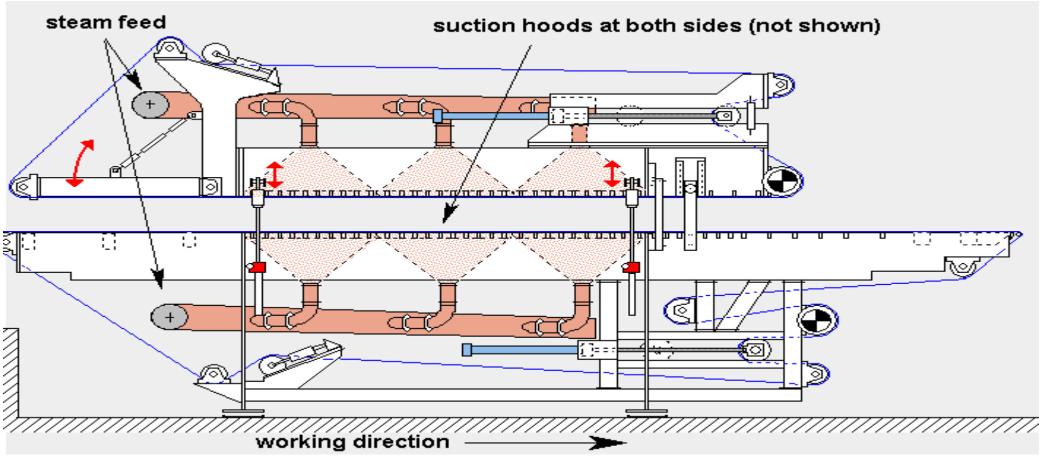


Figure 3.1.3.3: The Contitherm® system (source Siempelkamp)

The Contitherm® has proved to be a be a very good device not only for the production of 40 mm panels but equally for the pressing of conventional panels at very short press time (Reduction of 20% of the press time). Other advantages of the Contitherm® system are:

- Reduced specific pressure
- Possibility to humidify the mat
- Reduction of the thickness swelling
- Improved modulus of elasticity
- Improved modulus of rupture
- Improved internal bond

After pressing the panels are then cooled, cut to size, grade stamped and stacked in bundles for shipping.

3.1.3.3. Properties

In Europe OSB is a new product that can compete with plywood. Table 3.1.3.1 gives a comparison of the properties of OSB and plywood (Woestheinrich 1999).

Table 3.1.3.1: Comparison of OSB and plywood properties

Board type **Wood species**	**Plywood** **Beech**	**Plywood** **Pine**	**OSB** **Pine**	**OSB** **Aspen**
Density (kg/m³)	750	560	660	630
Thickness (mm)	18	9.5	18	18
Resin	PF	PF	MUPF/MDI	PF
MOR ψ (Mpa)	85	50	45	26
MOR δ (Mpa)	70	15	23	14
MOE ψ (Mpa)	9.000	8.000	7.500	5.000
MOE δ (Mpa)	6.500	1.200	3.200	1.850
IB (Mpa)	6	0,85	0,70	0,28
Thickness swelling (%) 24h	10	7.6	10	17

PF : Phenol-Formaldehyde resin / MUPF : Melamine-Urea-Phenol-Formaldehyde resin /
ψ : parallel / δ : perpendicular

3.1.3.4. Research needs

a) Improvement of the thickness swelling of OSB

OSB is a product that can be used for many exterior applications. Such applications require a very good dimensional stability. The problem is that a low thickness swelling can only been reached with PMDI adhesives. These adhesives are very expensive and not friendly for this environment.

Recent researches with tannin-based adhesives (Pichelin 1999) have proven that pressing at high moisture content enables to considerably reduce the thickness swelling. This route should be further investigated.

b) Use of tannin-based adhesives for the manufacture of exterior grade OSB

Pine tannin has been successfully used for the production of OSB/4 (Pichelin 1999) at a semi-industrial scale.

This new technology has to be further optimised with an industrials partner.

c) Improvement of stands alignment

Strands alignment is a determinant factor for the mechanical properties of the board.

Improving strands alignment would result in a better bending strength.

d) Reduction of VOC emission during the drying

Modern OSB plants have to be environmentally friendly. The drying process is responsible for VOC emission. Reducing the drying temperature should help to lower the emissions from the dryer.

e) Improvement of stands quality

Longer and thinner strands are expected to improve board mechanical properties.

f) Use of high density species

The use of high-density wood species would enable to build plants in areas where softwood is not present. Pressing at high moisture content could be the solution.

g) Development of adhesives for the steam injection

The steam injection process requires adhesive with a high molecular weight. Unfortunately very few wood adhesives are suitable for the steam injection. Because of their natural high molecular weight tannin-based adhesives should be further investigated for this purpose.

3.1.3.5. Standards

In Europe considerably higher characteristics are required for OSB in comparison with Waferboard and OSB produced in North America, in particular as regards their thickness swelling. A recent standard EN 300 with four classes has been especially developed for the European market (EUWID 1996a; EN 300 1997):

- OSB/1 for use in interior fittings (including furniture) in dry conditions
- OSB/2 load-bearing boards for use in dry conditions
- OSB/3 load-bearing boards for use in humid conditions
- OSB/4 heavy duty load-bearing boards for use in humid conditions

Table 3.1.3.2 summarises panel properties values required by the European standard EN 300.

Table 3.1.3.2: EN 300: requirements for OSB

Example: Board thickness 16 mm	Testing method	EN 300 OSB 1	EN 300 OSB 2	EN 300 OSB 3	EN 300 OSB 4
IB (N/mm²)	EN 319 (1993)	≥ 0,28	≥ 0,32	≥ 0,32	≥ 0,45
Boil test (N/mm²)	EN 1087-1 (1995)	-	-	≥ 0,13	≥ 0,15
MOR parallel (N/mm²)	EN 310 (1993)	≥ 18	≥ 20	≥ 20	≥ 28
MOE parallel (N/mm²)	EN 310 (1993)	≥ 2.500	≥ 3.500	≥ 3.500	≥ 4.800
24h thickness swelling (%)	EN 317 (1993)	≤ 25	≤ 20	≤ 15	≤ 12

Tolerance on the mean density within a board = ± 10%

Literature:

Boehme C. (1998) "OSB in Europa - große Chancen in naher Zukunft", Holz-Zentralblatt 142

EUWID (1996a) "Steigende Zahl von OSB-Produzenten auf dem europäischen Markt", EUWID Holz 42: 17

EUWID (1996b) "Entwicklungstendenzen bei der Produktionstechnick für OSB", EUWID Holz 44: 14

Kieser J. (1987) "OSB-Entwicklung in Europa", Holz als Roh- und Werkstoff 45: 405-410

Mayner J.A. (1990) "The economics of continuous pressing", Proceedings 24th international particleboard symposium W.S.U : 167-183

Pichelin F (1999) "Manufacture of OSB with high moisture tolerant adhesives", Doctoral thesis, University of Hamburg, Germany

Woestheinrich A (1999) "Experiences with OSB produced on ContiRoll systems", Proceedings of the third European Panel Products Symposium, Llandudno, Wales

EN 300 (1997) "Oriented Strand Boards (OSB) - definitions, classification and specification", European Committee for Standardisation

EN 310 (1993) "Wood-based panels - Determination of modulus of elasticity in bending and of bending strength", European Committee for Standardization

EN 317 (1993) "Particleboards and fiberboards - determination of swelling in thickness after immersion in water", European Committee for Standardization

EN 319 (1993) "Particleboards and fiberboards - determination of tensile strength perpendicular to the plane of the board", European Committee for Standardization

EN 1087-1 (1995) "Anhang A in EN 300 (1997) - Abgewandelter Arbeitsablauf", European Committee for Standardization : 8

3.1.4 Plywood

Eva Martinez

3.1.4.1. General

This chapter is dedicated to one of the most used type of wood-based panels: plywood. The technology to manufacture plywood is one of the ancients because it is known since before 1500 b.c.

3.1.4.2. Definition

Plywood is a wood-based panel composed by an uneven number of layers (plies), bonded together with an adhesive and assembled under pressure to obtain an angle of 90° between the grain direction of one layer an its adjacent one.

A ply generally is made bonding together veneers that are thin sheets of wood (0,3 mm to 6,5 mm) having the grain direction of the wood parallel to the surface.

One surface ply is called face (the one which is shown) and the other is called back. The inner plies conform the core. The core may also be manufacture from solid wood, particleboard, fibreboard or another material, so nowadays plywood is divided into two classes: veneer plywood and core plywood.

Another classification of plywood is made according to the characteristics of the adhesive employed in its manufacture:

- Interior type plywood: the adhesive used does not resist exposure to humidity.
- Protected exterior type plywood: the adhesive employed resists long periods of exposure to high humidity and water leakage.
- Exterior type plywood: the adhesive employed resists weather conditions and plywood is intended for permanent exterior use.

Plywood may be also divided into two main categories due to its final use:

Decorative plywood: it is the one employed for decorative purposes. The classes are the following:

- **Class E**: The face of the panel is made by one-piece veneer (100% hardwood or 100% sapwood), free from knots, knotholes open defects and stain. Synthetic fillers could be employ to fill small cracks and splits. Repairs should not exceed a number of six and must be made with wood.
- **Class A**: The face can be made form trimmed veneer, well joint, free from knots, knotholes and open defects. Synthetic fillers could be employ to fill small cracks. Repairs (with wood or synthetic patching material) should not exceed a number of eighteen.
- **Class B**: The face can be made form trimmed veneer, well joint, free from big open defects and broken grain but not from discoloration. Synthetic fillers could be employ to fill small cracks, splits or openings. Knots are permitted if they do not exceed 2,54 cm width (measured across the grain) and must be both sound and tight. Wood repairs must not exceed 7,62 cm width. Synthetic panel repairs must not be bigger than 5,72 cm width.
- **Class C**: The face can be made form trimmed veneer, well joint. Sanding defects are allowed. Splits, knotholes and voids are permitted if they do not exceed 1,27 cm and 2,54 cm width, respectively. Wood repairs must not exceed 7,62 cm width. Synthetic panel repairs must not exceed 7,62 cm width. Synthetic panel repairs must not be bigger than 5,72 cm width.
- **Class D**: The face can be made form trimmed veneer. Sanding defects are allowed. Splits, knots, knotholes, voids and white pocket are permitted if they do not exceed 0,64 cm and 8,9 cm width, respectively. There is no limitation in the number or size of repairs.

Structural plywood: This kind of plywood is used mainly for building purposes, where strength and durability is required. There are four types of structural plywood: **Technical**, **Type I**, **Type II** and **Type III**. The first is the most resistant and the one with the best quality.

3.1.4.3. Uses

a) Uses of interior type plywood:

- Furniture: cupboards, wardrobes, chests, trunks, desks, tables, chairs, armchairs, shelves, children's furniture, etc.
- Doors: door's frames, flush doors, etc.
- Packaging: packaging for fruits and vegetables, cases, crates, etc.
- Toys
- Accessories: sewing boxes, folding screens, flowerpot stands, trays, etc.
- Do-it-yourself
- Wall panelling: e.g. the sound proofing of a building

b) Uses of protected exterior type and exterior type plywood:

- Beams
- Floors, roofs and walls of light building constructions such as greenhouses, kennels, granaries, henhouses, etc.
- Doors and fences
- Hulls and decks of boats
- Sports: tennis rackets, hockey sticks, etc.

3.1.4.4. Production

In the following points, all the items related to the manufacturing of plywood are going to be discussed.

a) Raw materials

The raw materials involved are veneers and adhesives.

(1) Veneers

As mentioned before, veneers are thin sheets of wood. Many wood species (softwood and hardwood) are employed to produce veneers; they are listed in hereunder:

Table 3.1.4.1: List of wood species

Beech	*Fagus sylvatica*
Poplar	*Populus ssp*
Birch	*Betula pendula & Betula pubescens*
Pine	*Pinus ssp*
Douglas fir	*Pseudotsuga menziesii*
Okoume	*Aucoumea klaineana*
Obeche	*Triplochiton scleroxylon*
Limba	*Terminalia superba*
Meranti	*Shorea ssp*
Indigbo	*Tenninalia ivorensis*
Ilomba	*Pycnanthus angolensis*
Utile	*Entandrophragma utile*
Red river gum	*Eucalyptus camaldulensis*

Veneers may be classified according to their quality and aspect. This classification is well related to the one mentioned before for the decorative plywood panels:

- **Grade N** or **Premium**: This grade should meet the requirements of the face of decorative plywood class E
- **Grade A** or **Good (l)**: This grade should meet the requirements of the face of decorative plywood class A
- **Grade B** or **Sane (2)**: This grade should meet the requirements of the face of decorative plywood class B
- **Grade C** or **Utility (3)**: This grade should meet the requirements of the face of decorative plywood class C
- **Grade D** or **Last (4)**: This grade should meet the requirements of the face of decorative plywood class D

When veneers must be joined, this is often used to obtain decorative figures, giving the following classification:

(2) *Adhesives*

There are many types of adhesives in the market to join pieces of wood. This work focus its attention in the three main classes employed to manufacture plywood:

- Phenol-formaldehyde resins
- Urea-formaldehyde resins
- Melamine-formaldehyde resins

They are called thermosetting resins because they need the combined action of heat and pressure to develop the polymerisation reaction and consolidate the union.

Phenol-formaldehyde resins are obtained from the controlled reaction between phenol and formaldehyde. There are to types: when the reaction is carried out under acid conditions in an excess of phenol, the resin is called novolak. If the reaction is developed under alkaline condition in an excess of formaldehyde, the resin is called resol. The adhesives used to manufacture plywood are resols.

The principal characteristic of these resins is their stability and resistance against humidity when cured. The only inconvenient is their dark brown colour.

Resorcinol is a derivative from phenol employed in the manufacture of phenolic resins when the curing reaction is carried out at ambient temperature. These resins are more reactive but they lose part of the resistance against humidity. It is also possible to find phenol-resorcinol-formaldehyde resins with intermediate properties.

Urea-formaldehyde resins are poly-condensation products from urea and formaldehyde. They are the most employed in the manufacture of plywood.

Their main advantages are their low cost and the absence of colour when cured. However, they have little stability and resistance against humidity that is why their employment is restricted to interior type plywood.

Melamine-formaldehyde resins are poly-condensation products from melamine and formaldehyde. Their characteristics are similar to urea-formaldehyde resins but these ones show more stability and resistance to humidity and they are more expensive. In the market it is possible to find melamine-urea-formaldehyde resins.

b) Manufacturing process

The production of plywood implies two main processes: veneering and plywood manufacturing.

(1) *Veneering*

These are the steps to follow:

- Selection and felling of logs from trees: this action is carried out in the forest and after that the logs are transported to the veneer factory.
- Cutting the logs to the length desired. The pieces obtained are called blocks.

- Debarking, employing a knife or hammer debarker.
- Heating the blocks by the action of steam or hot water. This operation is not essential but softens the block surface and makes the wood more plastic for easier cutting into veneer, increasing the quantity obtain in a 15%.
- Cutting to obtain veneers. There are three main methods: sawing, slicing and rotary peeling.
- Sawing to obtain veneers is rarely used, because much of the wood is wasted and the cutting is not precise.
- Slicing is employed when the quality of the wood is high to manufacture beautiful face veneers.
- The rotary peeling is the most common method to produce veneers. To carry out this technique the block is centred in a lathe and revolved against a block long sharp knife. A continuous ribbon of green wood is obtained. After that the ribbon is cut into sheets and trimmed to the desired widths (veneers).
- Drying to reduce the veneers moisture content. There are also three main methods: ambient drying, climate chamber drying and mechanical dryers. The first two methods are rarely employed because they need too much time and space and it is difficult to achieve the reduction of veneer moisture content required.

  The mechanical dryers have several sections at different temperatures: the first one is only to make the veneers "sweat". The second section, at higher temperature is prepared to reduce the veneers moisture content to the values desired by water evaporation and the third section that is called cooling section prepares the veneers to avoid thermal shock when they leave the dryer.

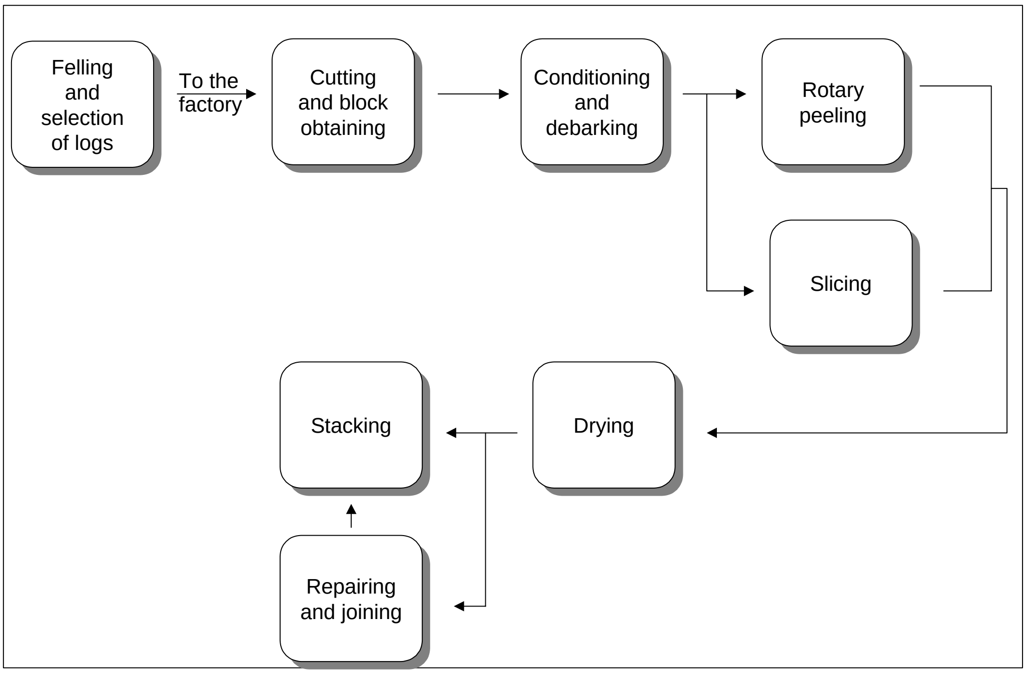


Figure 3.1.4.4: Veneering process

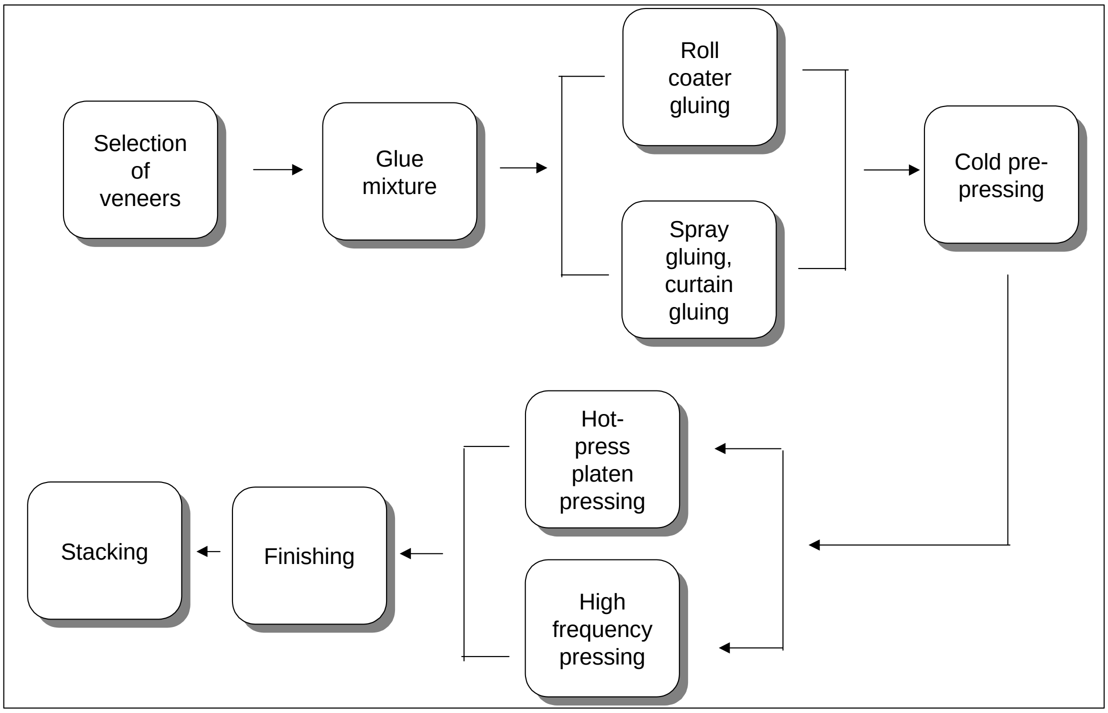
- Repairing when needed and joining to obtain bigger pieces employing a line of hot-melt adhesive or nylon strings (sewing).

(2) Plywood manufacturing

These are the steps to follow when manufacturing plywood:

- Glue mixture: after choosing the type of resin that is going to be employed to join the veneers, a glue mixture is prepared. A quantity of resin is beaten with flour (wheat flour, rye flour, etc), water and a catalyst (ammonium salts).
- Choosing veneers: the wood species, the quantity and quality of the veneers are chosen before the manufacturing of plywood starts.

- Gluing process: thought there are several methods to apply the adhesive, such as spray coater or curtain coater, the most popular is the double roll coater. The basic applicator has two rollers that are adjusted with an opening between them to the thickness of the veneer. The rolls pull the veneers through by a rotating action and transfer a quantity of glue to the faces of the veneer.
- Assembling: after gluing the veneer are assembled. Generally this process involves hot pressing but employing very reactive adhesives, a cold pressing is possible. It is also common practice to carry out a cold pre-pressing before hot pressing. Press temperature and press time depend of the thickness of plywood and the type of resin used.



- Finishing: Sawing, sanding, grading and sorting.

Figure 3.1.4.5: Plywood manufacturing process

c) Production volume

In Europe the production volume of plywood has been increasing during the last few years. This increment is similar to the one shown by particleboard but very little compared to the fibreboard rise.

From 1993 to 1998 the manufacture of plywood and particleboard raised in a 26% and a 23% respectively, while the production of fibreboard increased in an 88%.

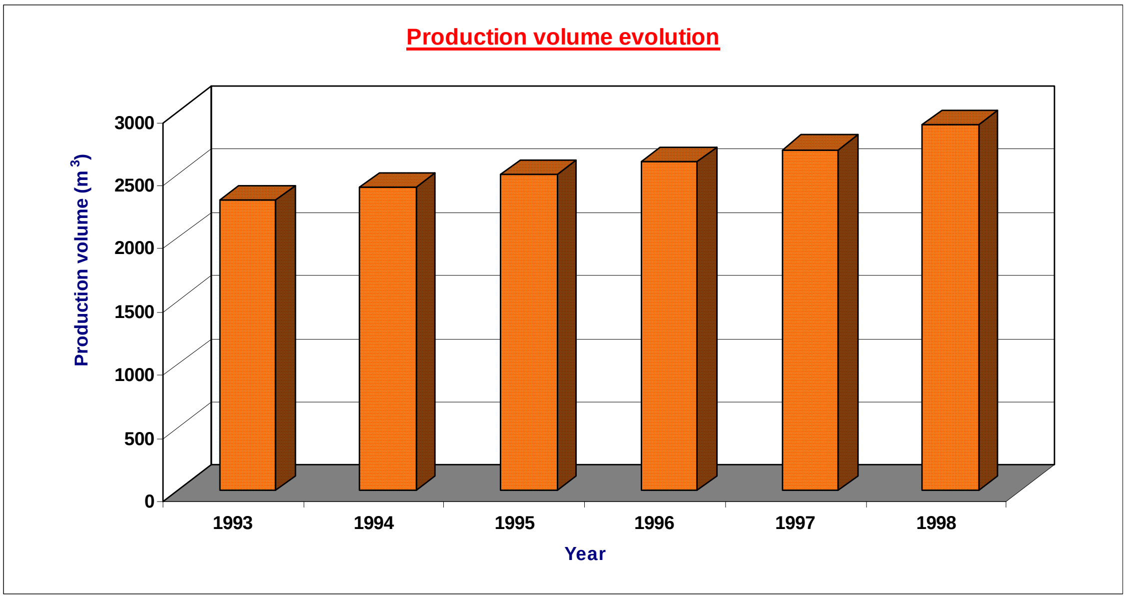


Figure 3.1.4.6: Plywood production volume evolution in Europe (Source EIC)

In the following table it is also possible to see the overseas trade of plywood in Europe and the rest of the world in 1998 and during the first five months of 1999.

Table 3.1.4.2: Overseas trade of plywood

Country	Imports (m^3)		Exports (m^3)	
	1998	1999	1998	1999
Austria	222	39	672	576
Belgium	30	-	2.280	-
Denmark	11	6	269	
Finland	12.531	11.109	-	-
France	13.288	6.833	16.107	7.437
Germany	2.052	1.452	17.481	12.066
Greek	34	-	1.015	737
Holland	217	91	3.752	2.015
Ireland	-	-	39	26
Italy	306	158	12.774	5.771
Portugal	613	636	6.313	3.396
Sweden	824	40	-	-
United Kingdom	1	158	17.984	3.087
Subtotal	**30.129**	**20.552**	**78.650**	**35.111**
Poland	603	502	-	-
Russia	5.904	3.654	-	83
Slovenia	34	41	332	-
Switzerland	-	-	463	-
Others	1.128	584	715	435
Subtotal	**7.669**	**4.781**	**1.510**	**518**
Africa	1.875	975	4.122	2.874
America	2.051	1.370	3.468	1.329
Asia	464	351	16.477	5.688
Australia	-	40	-	-
Subtotal	**4.390**	**2.736**	**24.067**	**9.871**
Grand total	**42.188**	**28.039**	**104.277**	**45.500**

3.1.4.5. Properties and Requirements

a) Test methods

There are a lot of tests that can be applied to determine the quality of plywood. Some of them are use to define and describe plywood, others to establish its mechanical characteristics and durability and there are also methods to know its toxicity.

The following list shows the standardised methods:

EN 120 “Wood-based panels - Determination of formaldehyde content - Extraction method called the perforator method”

EN 310 “Wood-based panels - Determination of modulus elasticity in bending and of bending strength”

EN 313-1 “Plywood - Classification and terminology - Part 1: Classification.”

EN 313-2 “Plywood - Classification and terminology - Part 2: Terminology.”

EN 314-1 “Plywood - Bonding quality - Part 1: Test methods”

EN 314-2 “Plywood - Bonding quality - Part 2: Requirements”

EN 315 “Plywood - Tolerances for dimensions”

EN 322 “Wood-based panels - Determination of moisture content”

EN 323 “Wood-based panels - Determination of density”

EN 324-1 “Wood-based panels - Determination of dimensions of boards - Part 1: Determination of thickness, with and length”

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EN 325 “Wood-based panels - Determination of dimensions of test pieces”

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EN 635-4 “Plywood - Classification by surface appearance - Part 4: Parameters of ability for finishing, guideline”

EN 636-1 “Plywood - Specifications - Part 1: Requirements for plywood for use in dry conditions”

EN 636-2 “Plywood - Specifications - Part 2: Requirements for plywood for use in humid conditions”

EN 636-3 “Plywood - Specifications - Part 3: Requirements for plywood for use in exterior conditions”

EN 717-1 “Wood-based panels - Determination of formaldehyde release - Part 1: Formaldehyde emission by the chamber method”

EN 717-2 “Wood-based panels - Determination of formaldehyde release - Part 2: Formaldehyde release by the gas analysis method”

EN 717-3 “Wood-based panels - Determination of formaldehyde release - Part 3: Formaldehyde emission by the flask method”

EN 789 "Timber structures - Test methods - Determination of mechanical properties of woodbased panels"

EN 1058 "Wood-based panels - Determination of characteristic values of mechanical properties and density"

EN 1072 "Plywood - Description of bending properties for structural plywood"

EN 1084 "Plywood - Formaldehyde release classes determined by the gas analysis method"

ENV 1099 "Plywood - Biological durability - Guidance for the assessment of plywood for use in different hazard classes"

3.1.4.6. Research Needs

The main research needs are:

- The necessity of manufacturing plywood with low formaldehyde emission and content. In that field more research is needed on resins and production process.
- The employment of glues obtained from natural resources.
- Plywood manufactured using glues that cure at ambient temperature.
- Bent plywood: research is needed on the manufacturing process in order to understand the factors that affect plywood final properties. The technique usually employed is high/low frequency to cure the glue and in this case the hardening is rarely known.

3.1.5 Solid wood panels and plate structures

S. Tobisch, D. Krug, A. Teischinger

3.1.5.1. Description and Applications

Solid wood panels (as described in EN 844-3) are panels that consist of pieces of timber of uniform thickness glued together on their edges and, if multi-layer, on their faces.

Solid wood panels have – depending on the type of wood, wood quality, panel structure, format and panel quality, multiple fields of application in furniture making, interior design and construction (Wiesner 1990; Herrmann 1996; N.N. 1997a; 1998b). The industrial manufacture of furniture has been characterized over the recent years by moving towards the application of solid wood panels (Deppe 1996). Very low formaldehyde emission thus encourages the use of solid wood panels in furniture front design and in ecologically minded interior design (Kehr 1998). No doubt, that the "solid wood" character adds to the advantages of the material. In interior design, too, the share of solid wood panel application for making door, ceiling, wall and staircase elements has risen clearly as summarized by Teischinger 2000.

Along with wood construction gaining image, with undiminished growth and with upward economy in pre-fabricated and wooden house construction as well as with the increasing application of wood pillar and wood frame construction, the demand for solid wood panels for application in construction (e.g. for wooden houses in slab construction) has especially increased. As a result, various manufacturers determined their sales increase in this field between 10% and 30% (N.N. 1998a).

The production volume for single and multi-layer solid wood panels in Germany, Austria and Switzerland increased from about 450.000 m³ in 1993 to about 750.000 m³ in 1997. A closer look at the 1997 solid wood panel production in Germany shows, that 94.890 m³ hard wood panels and 266.110 m³ soft wood panels were manufactured (N.N. 1998a,c).

As a rule, solid wood panels are manufactured by the saw-mill industry or special solid wood panel plants respectively; the only exception to this rule, known so far, makes the successful reconstruction of a small Italian chipboard plant into a modern solid wood panel plant (Rüter 1993).

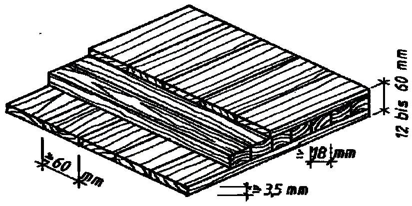

Figure 3.1.5.1: Three-layer solid wood panel according to ÖNORM B 3022Process

A principal differentiation is made between single-layer and multi-layer solid wood panels (prEN 12775). Single-layer solid wood panels are products from several solid wood lamellas, laid parallel at their long sides and joint-glued. Depending on the required panel quality, uninterrupted or bluntly or finger-jointed lamellas respectively are put in. Multi-layer solid wood panels consist of two parallel oriented outside surface layers, which are glued with intermediate or inner layers, set at 90° to each other and often pre-fabricated, in single-daylight or multi-daylight presses with partly additional pressing elements for horizontal compaction of the outer surface layers (figure 3.1.5.1). This plying adds to the stiffness in the panels in the cross direction, improving their form stability.

When laying the lamellas (wood processing moisture 8 – 12%) it is basically taken care, that the side of the outer surface layers showing to the kernel is placed outside. The thickness of the two outer layers is generally identical, while intermediate and also inner layers may be thicker, in exceptions also thinner in their dimensions. The multi-layer solid wood panel with rods as the intermediate layer is rather widespread as a special form in the interest of shorter pressing times and of very economic use of wood material. These intermediate layers are often produced in special continuous gluing operation plants.

The production of lamellas differentiates between cutting and non-cutting processes (Ehrentreich 1991; Soiné 1995). The non-cutting manufacture of lamellas by means of special cutting-blade machines, as compared to the cutting process (e.g. multi-blade cutting, thin frame-sawmill) is almost free of cuttings (Leible 1996). Apart from the optimal use of wood, this cutting process characterized by high flow rates, whereas the higher energy consumption for the necessary pre-steaming of the wood can be balanced off in the manufacturing process. The cracks and faulty marks are considered as disadvantageous, which are caused by pre-splitting the wood and which become even more visible in the subsequent machine processing (e.g. milling), and which may result in unfavourable surface properties (e.g. in coating).

Cutting the wood up into single lamellas generally reduces wood-inherent tension.

About three quarters of solid wood panels produced are made from lamella qualities A and B (acc. to ÖNORM B 3021, B 3022 resp. prEN 13017, Parts 1 and 2). As a tendency, a further increase in the application of C qualities may, however, be expected due to an increasing production volume in softwood panels for construction purposes. (N.N. 1998a).

The raw material for the lamellas is found, apart from high-value sawn timber, in side-cuts (Johansson 1997) and other low-value wood material assortments (e.g. small-sized wood). Small-sized wood in its turn tends to show twisted growth becoming especially visible in drying the wood (Vanek, Olbrich 1995).

There is a wide range of solid wood panel manufactoring. Soft wood panels are preferably made of pruce, fir, pine and larch as well as of Douglas fir. Hard wood panels are mainly made of beech, alder, as well as maple, cherry, oak and birch recently.

While in soft wood panels, the outside surfaces are mainly made of uninterrupted lamellas, the high wood costs and the different wood quality lead to the technology of finger jointing and gluing of single lamellas lengthwise in hard wood panels.

Bonding agents for the industrial gluing of single-layer solid wood panels are mainly dispersion glues based on polyvinyl acetate (PVAc) (Bierwirth 1994). Their advantages, apart from their simple applicability, are above all the ready-to-use availability and formaldehyde-free gluing. Regarding their climatic stability, PVAc-based bonding agents have, however, got some disadvantage, although adding the respective hardeners enable relatively moisture-resistant D3 or D4 glue-joints respectively (acc. to EN 204, EN 205). With regard to better handling, manufacturers of multi-layer panels partly pre-fabricate intermediate or inner layers. PVAc dispersions (e.g. as D2 quality) are applied there as a rule.

Better climatic and thus moisture stability is obtained by melamine urea formaldehyde (MUF) resins, phenol urea formaldehyde (PF) resins, as well as isocyanate bonding agents. Mainly the application of MUF resins is widespread in the manufacture of multi-layer solid wood panels, whereas strict obedience of the processing regulations assures quality gluing (Stoiber 1992). Apart from technological process parameters, such as pressing temperature, pressure and duration, the resulting gluing quality is decisively determined by the kind of wood, wood moisture, bonding agent and amount applied (Bierwirth 1994; Deppe, Schmidt 1995).

3.1.5.2. Requirements and Testing-Properties

Along with European standardization, WG 9 „Solid Wood Panels“ of the CEN/TC 112 is currently busy establishing a standard series for single and multi-layer solid wood panels:

- prEN 12775 “Solid wood panels - Classification and Terminology”
- prEN 13017-1 “Solid wood panels - Classification by Surface Appearance - Part 1: Softwood”
- prEN 13017-2 “Solid wood panels - Classification by Surface Appearance - Part 2: Hardwood”
- prEN 13353 “Solid wood panels – Specifications for use in dry, humid and exterior conditions”
- prEN 13354: “Solid wood panels – Bonding quality – Test method”

The establishment of characteristic properties by WG 9 is currently only being done for three-layer solid wood panels from soft wood. The values shown in tables 3.1.5.1 and 3.1.5.2 have been set up as the result of substantial testing (Tobisch, Krug, Mauritz 1999). They are, however, under discussion in WG 9 at this time.

Table 3.1.5.1: Characteristic density [kg/m³] and strength [N/mm²]

Thickness mm	Density ρ	Bending f_m		Tension f_t		Compression F_c		Panel Shear f_v	Planar Shear f_r
t_{nom}		0	90	0	90	0	90		
≤ 20	430	40,0	5,3	23,0	12,1	10,0	12,7	4,9	1,7
> 20 - 30	430	29,0	3,8	13,2	12,2	11,0	11,4	4,9	1,7

Table 3.1.5.2: Mean stiffness values [N/mm²]

Thickness mm	Density ρ	Bending E_m		Tension E_t		Panel Shear G_v		Planar Shear G_r
t_{nom}		0	90	0	90	0	90	
≤ 20	430	12.000	600	8.500	4.500	1.200	910	110
> 20 - 30	430	9.000	400	6.700	5.400	1.200	910	110

From the above values, the following requirement data for three-layer solid wood panels from soft wood in the nominal thickness range of up to 30 mm, according to prEN 13 353 for panels for bearing purposes, to be proved in self-monitoring, would result:

Table 3.1.5.3: Required values for three-layer solid wood panels from softwood

		Orientation of the surface layer lamella			
		Parallel		Perpendicular	
		Nominal thickness in mm			
Property	Quantile	≤ 20	20-30	≤ 20	> 20-30
Bending strength σ_{Bxy} [N/mm²]	5%	40	29	5,3	3,4
Bending MOE E_{Bxy} [N/mm²]	5%	10.000	7.500	370	270
Density [kg/m³]	5%	430			

In applying solid wood panels as bearing and stiffening planking in Germany, the type of panel used needs to have general approval by the building authorities issued by Deutsches Institut für Bautechnik (DIBt) and must correspond with the regulations according to DIN 1052, Parts 1-3, DIN 4074, Part 1 and DIN 68800, Parts 2-3. In Europe, currently seven manufacturers of solid wood panels have been granted a relevant approval, further approvals have been applied for (N.N. 1998a). Multi-layer solid wood panels from soft wood of medium wood qualities are preferably used, whereas for a general approval by the building authorities there is the requirement to manufacture the lamellas from quality-assorted material according to DIN 4074, Part 1, which, by at least 90% may be classified as assortment class S10 and by 10% as assortment class S7.

Quality requirements for solid wood panels to be applied in Germany are exclusively defined for specific types in the documentation of the building authority approvals.

Subsequently, solid wood panel manufacturers orientate themselves by Austrian standards (ÖNORM B 3021, B 3022, B 3023 and B 3024), in which kinds, requirements and tests for single and multi-layer solid wood panels as well as concreting boards are laid down. Requirements for solid wood panel stability in Austrian standards only exist for multi-layer solid wood panels (at no restrictions towards nominal thickness) and for three-layer concreting boards (cf. tables 3.1.5.4 and 3.1.5.5)

Table 3.1.5.4: Characteristic strength [N/mm²] of multi-layer solid wood panels (ÖNORM B 3022)

Wood species	Bending strength σ_{Bxy}	
	0	90
Softwood	30	10
soft Hardwood	30	10
Hardwood	50	25

Table 3.1.5.5: Characteristic Strength and mean Stiffness Values [N/mm²] of three layer form boards made of softwood (ÖNORM B 3023)

Nominal thickness t_{nom} [mm]	Bending strength σ_{Bxy}	Bending MOE E_{Bxy}
	0	
21	40	8.000
27	35	7.200

3.1.5.3. Future of the Product

Solid wood panels are going to enjoy an increasing use in the building industry. The solid wood structure, always asked for, plays an important role in their application for bearing and stiffening. Improved sorting and purposeful influence on the structure will enable solid wood panels to get adapted to highly differentiated fields of application.

But also solid wood panels as furniture components parts as well as indoor design elements will find a larger field of application in the future.

3.1.5.4. Research Needs

A study, carried out by Krug and Tobisch in 1997 concluding a questionnaire for further needs of research came to the following conclusions:

1. It is necessary to investigate the influence of the structure (i.e. ratio of lamellas) of solid wood panels on the strength and stiffness values to be achieved. This knowledge enables you to estimate the further properties of the boards for the use in special structures.
2. In addition it is useful to analyse the procedure of drying the lamellas so as to save time and money and to increase the drying quality of the lamellas.
3. Due to a limited pressing area it is useful to develop joining methods for entire boards (dimensions normally 2 × 5 m) to form larger dimensions (e.g. complete wall elements). This joining / fixing of plane boards have to be examined for mechanical properties.
4. Pressing time is a limiting factor for the manufacture of multi-layer solid wood panels. It is therefore necessary to find new pressing technologies (e.g. new heating systems) and/or new faster hardening adhesives that meet the requirements for moisture-resistant glueings.
5. Development of a more appropriate panel for facades (complete impregnation of the outer layer with glue, using thermal modified wood etc.)
6. Development of a solid wood panel „light“ for special furniture purpose (extreme light middle layer)

3.1.5.5. Glued Solid Wood Plates Used for Construction Elements

There is a various number of new glued solid wood plates which are mainly used for construction elements. These construction elements comprize plates such as glued box elements, staked board construction, cross-glued block panels in various performances and are produced under different trade marks as “Lignotrend”, “Dickholz”, “Kreuzlagenholz (KLH)”, “LFE”, “LME” etc. (N.N. 1997b, 1997c).

With glueing systems it is possible to transform thin and narrow boards into large wall and ceiling panels. Their technical details may differ, but most systems have one thing in common – the boards are arranged in criss-cross layers to achieve a cross-band effect. The number of layers varies from three to seven.

The oldest representatives of these systems allow for relatively wide air ducts between the boards of a single layer (figure 3.1.5.2). This does not only save material and weight, it also provides a convenient and effective possibility for laying cables and lines. To date these panels have been manufactured als wall elements for heights of up to three storeys.

A variation of this basic system shows the criss-cross layers diagonally and grooves are cut into the board before they are glued together. This results in smaller air ducts, but it helps to reduce the stresses that could cause the finished panels to warp.

MUF and PUR glues are most frequently used and MUF glues are often cured with high-frequency heating because of the thickness of the elements (N.N. 1998d). For not load bearing structures also PVAC glues may be used.

Figure 3.1.5.2: Lignotrend elements with criss-cross layers and air ducts

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prEN 13354 “Solid wood panels – Bonding quality – Test method”

prENV 717-1 “Wood-based panels – Determination of formaldehyde release – Part 1: Formaldehyde emission by the chamber method”

3.1.6 Wood based panel quality control

Wilfried Haelvoet

3.1.6.1. Introduction

Panel industry in Europe is performing quality control on panels since the start of the panel production. Quality control implies that properties of the panel are measured and that the production process is corrected taking into account the results of this quality control.

Quality has to be seen as the extent to which the properties of a panel are responding to the needs.

Properties of a wood based panel are of physical, mechanical or chemical nature. Customers can describe the properties of a panel by means of specifications. Specifications always are related to test methods. A property of a panel can be measured according to certain procedure. The result is a figure that gives an idea of the quality of the panel and that permits to compare it with the quality of other panels.

Some properties of a panel can be expressed by specifications resulting from a test procedure that is rather simple and used all over the world. Talking about length, width, thickness and weight generally does not give rise to misunderstanding if the units are clearly defined.

Other properties are measured according to more complicated and conventional (national) methods. The ageing properties of a panel e.g. can be measured according to totally different methods, giving results that cannot be compared with each other. In spite of the fact that the performance of a panel in real applications is perceived in more or less the same way everywhere, the way of expressing this performance is very different.

This problem e.g. is felt in international standardisation working groups. Generally agreement about standards describing how to measure length and width of a panel is obtained quickly. Standards describing how to measure a characteristic strength value that has to be used in design calculations is much more complicated. Producers, designers, legislators and consumers need time to become familiar with it. Not so much new test methods are a problem but the significance of the obtained result.

When producer and customer meet difficulties in mutual understanding of the significance of specifications expressing the quality level of a panel, it is of the responsibility of the producer to translate his specifications in understandable terms to the customer. Since panel trade is not anymore a national business, even not a European one but a world event, quality service has to build up experience with different test methods and correlation between them. To inform consumers using their language (specifications) is part of the quality of the product.

3.1.6.2. European Normalisation of Test Methods and Classification of Wood Based Panels

Since the late eighties the EC launched a big normalisation programme in view of the opening of the borders and the unified market. CEN got the mandate to provide the facilities to get the work done.

TC 112 was the committee responsible for creating standards with regard to wood based panels. Initially, 4 working groups were created, WG1 for particleboards, WG2 for plywood, WG3 for fibreboards and WG 4 for test methods common to two or more board types. Later on different WG's were added WG5 – formaldehyde, WG6 – cement bonded boards, WG7 - finished boards, WG8 – OSB, WG9 – solid wood panels and WG10 – laminated veneer lumber. Finally two groups, WG 1 and WG 2 merged to WG 11 – particleboards and fibreboards. The reason for this is that most test methods for both types are common. Since that time a lot of standards have been produced, most of them already put into practice. The work of some WG's is more or less finished, where others, more recently started WG's, still have a lot to do. This is more exactly the case for the WG's 7, 8, 9 and 10.

Long before the start of the European normalisation work industry as well as institutes tried to tune to the neighbouring countries with regard to test methods and specifications. This made that finding out which classes of boards were needed was less difficult. In fact most of the participating countries had more or less the same test methods and classes of construction boards.

The normalisation work has been accompanied by some research work. One of the research programmes was the ring test pertaining to formaldehyde. This research programmes showed that correlation between emission measurements, performed by European institutes by means of the chamber method, was very low. This resulted in the decision not to accept EN 717-1 as a full standard but to give European producers sufficient time to gain experience by editing it as an experimental standard that becomes a full standard after a well-defined period. Another research programme was the programme co-ordinated by TRADA "Characterisation, evaluation and development of performance based tests for wood based panels for structural and non structural purposes", AIR-CT92-0291.

One of the subprograms was aimed to cope with the problem of testing the moisture resistance of particleboards and fibreboards. The outcome of this part of the research programme was not one test, independent from glue and board type, but different test methods for the different types of board. Actually no further proposal of changing existing standards, the cyclic test and the boil test, have been made by the industry. In the meantime the situation is such that the boil test (EN 1087-1) (V100 – German test) and the cyclic test (EN 321) (V313 – French test) are considered as equivalent. The more important part of the research programme was the elaboration of test methods for performance tests on wood based panels. As far as this part of the programme is concerned, dissemination of the knowledge still is going on.

In general we can subdivide the European standards in three classes:

1. Test methods
2. Specification/classification (See lower)
3. Sampling procedures and elaboration of test results (statistical standards) (See chapter on third party control)

To become an overview about the specifications produced by the different WG's of CEN tc 112 a decision tree has been developed (see figure 3.1.6.1).

The upper part of the drawing represents the decision process; the lower part represents a matrix with the different standard types of panels available on the market. The description of the panel types is given in the EN standard the reference of which is mentioned in the cell. References to standards of the same panel type are in the same row; different panel types of comparable quality are in the same column. In principle, mechanical and physical properties of one panel type are becoming higher going from the right side of a row to the left. After having answered the relevant questions the table is indicating the column in which the references to the quality standard of panels of suitable quality are mentioned. Sometimes one has the choice between different panel types in one column, sometimes only one type is mentioned. An empty cell does not mean that it is forbidden to use this type of board. The cell is left empty because the experts of TC 112 did not create a standard describing this quality level for this board type. In reality it is not excluded that, even if the quality level has not been defined for this panel type, such quality level is or can be produced.

The quality levels described in the product standards strongly depend on market at the moment the standards have been produced. In principle, if a cell is empty, one always can choose the better quality (if one), which is mentioned at the left side of the empty cell.

The basic questions to be asked have to do with the climate (humidity) in which the board will be applied and the kind of load the boards in service will have to bear. The three climate circumstances are those taken from ENV 1995, which are service class 1, 2 and 3 (SC1, SC2, SC3). Service class 1 stands for dry conditions. The moisture content of the board corresponds to an average humidity of the air of 20°C, 65% RH. Service class 2: the moisture content of the panel corresponds with a climate where the humidity of the air can be higher than 85% for a few weeks pro year. Service class 3 corresponds with climates leading to higher humidity, e.g. external use.

As far as the load is concerned there has been made distinction between load bearing and not load bearing in the first place. Among the load bearing boards a further distinction has been made between heavy-duty load bearing (industrial application) and normal load bearing (private construction). The non-load bearing panels have been subdivided in boards with high mechanical properties and boards for general applications.

This decision tree is limited to the basic quality aspects of construction boards, the moisture resistance and the mechanical strength.

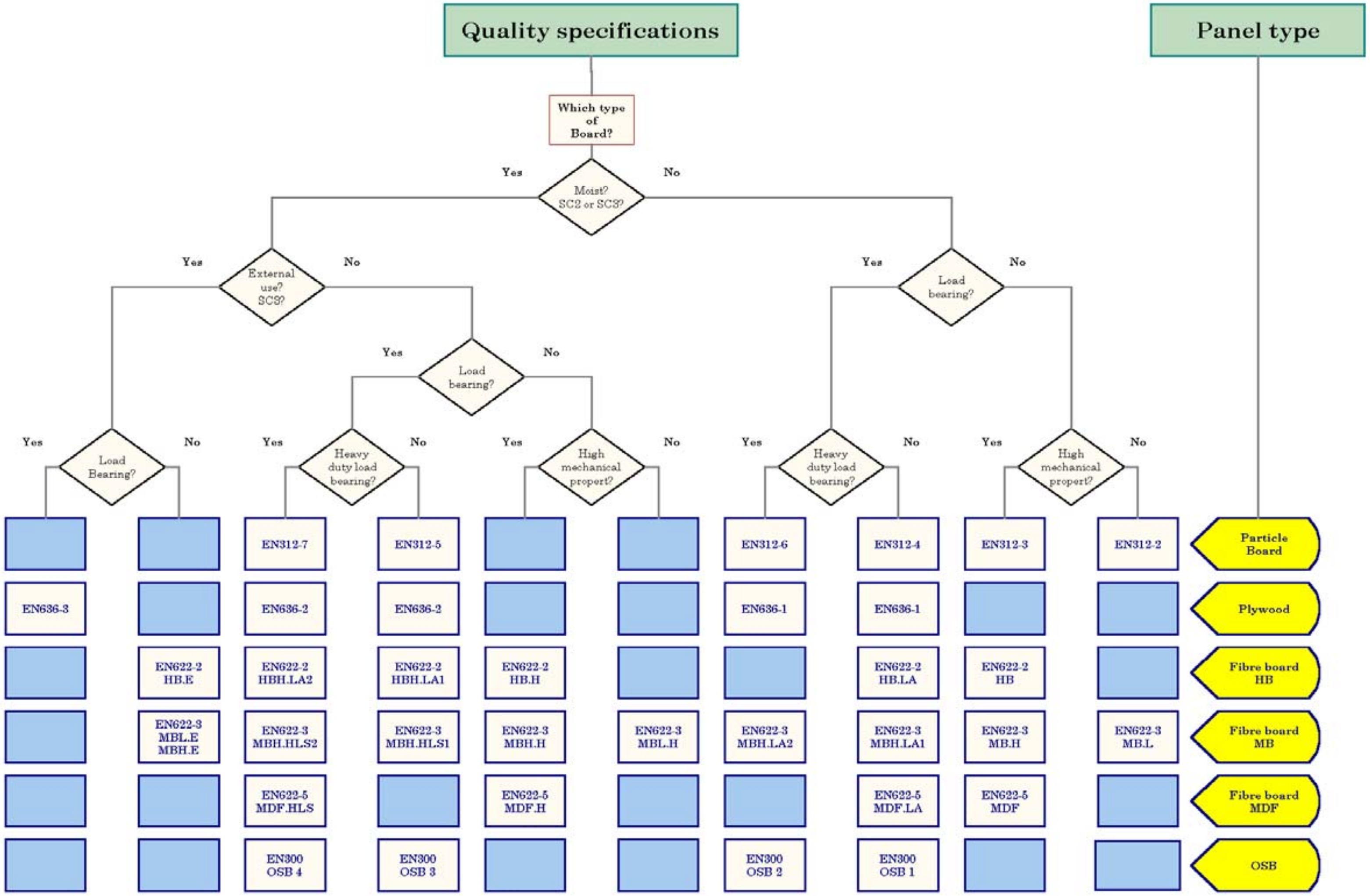

Figure 3.1.6.1: Decision tree; help for the selection of the correct panel specifications

3.1.6.3. Quality Control in the Factory:

Talking about quality control, we have to make distinction between quality control in the factory and third party quality control in an independent laboratory. The objectives of both are somewhat different.

Quality control in the factory must have following properties, the highest priority coming first:

- Low cost
- Speed/reaction time
- Simple manipulation/automatic
- In line
- Non destructive
- 100% testing
- Accuracy/Reproducibility

The list and the sequence of test properties is somewhat different for third party quality control:

- Accuracy/Reproducibility
- Speed/reaction time
- Low cost
- Non destructive
- Simple manipulation/automatic
- 100% testing

When looking at the priorities for the quality control in the factory, it becomes clear that an evolution takes place towards test methods at lower costs, giving relevant information as quickly as possible. Initially the factory relied essentially on the results of tests in the laboratory performed on the final product. These tests are rather expensive, are based on a limited sample, and oft results only are available when production has come to an end.

This gives issue to:

- Loss of material (scrap)
- Loss of productivity.
- Delivery delay

The quality control in production is performed on three different levels:

1. The measurement in line of raw and intermediate material properties and of process parameters to control and steer different sub processes
2. The measurement in line of properties of the board (length, width, weight, density, density distribution, blisters, etc.)
3. The end control of the final product in the laboratory.

The measuring techniques commonly used in today's panel production are (not exhaustive list):

Table 3.1.6.1

Process parameters	In line control of panels	In laboratory control of panels
Information on wood mixture	Weight of panel	Thickness
Information on glue type	Thickness of panel	Length
Information on glue recipe	Blisters	Width
Information on glue reaction time	Density of the panel	Density
Glue concentration	Density variation within the plane of the panel	Moisture content
Humidity of particles	Density variation in thickness	Bending strength
Particle size	Visual quality control	Stiffness
Ratio of small and large particles		Internal bond
Mat weight		Ageing properties (swelling, hydrolysis in water)
Press pressure		Formaldehyde emission
Press temperature		Surface soundness
Pressure profile		Screw holding
Temperature profile		Shear strength
Pressing time		Impact/hardness
		Concentration of fire retardant salts
		Reaction to fire
		Electrical conductivity
		Thermal conductivity
		Sound insulation
		Sound absorption
		Vapour permeability
		Biological durability
		Chemical contamination

There is a tendency to minimise the effort put into measurements from type 3 and to maximise the number of measurements of type 2 and 1.

In a first stage alternative tests on panels have been implemented. These tests had a good correlation with the standardised ones; they were faster and less expensive.

Nowadays evolution is going in the direction of measuring in line. All registered data containing information on raw materials, intermediate products, final products and process parameters are gathered and put together in a large database. After a certain time the number of data has grown to an extentd that correlations can be calculated. The existing correlations can be used to establish a mathematical model with the help of which a prediction can be made on the quality of the final product.

When measuring in line and especially when using process parameters to predict the quality parameters of the end product, losses of material and productivity can substantially be reduced. This is a tendency the CEN working groups, establishing test methods, have recognised and they have taken it into account. Indeed EN 326-1 contains a statement that every method showing good correlation with the standardised method can be used for quality control in the factory when giving a sufficient correlation with that standard method.

Actually most of the industrial laboratories still perform a lot of end control according to national or European standards or variations thereof.

One could make an enumeration of a lot of panel properties. Not all of these properties are equally important. Some properties are valuable for all kind of panels, others only are important in case of special applications.

A rather complete list of panel properties can be found in the harmonised standard (which at this moment is still in the stage of prEN) for panel products.

The properties that are of over all importance are:

Table 3.1.6.2

Thickness
Length
Width
Density
Moisture content
Bending strength
Stiffness
Internal bond
Ageing properties (swelling, hydrolysis in water)
Formaldehyde emission

Dependent on the application of the board (furniture, fire resistant doors, etc.) additional properties could be of interest:

Table 3.1.6.3

Surface soundness
Screw holding
Shear strength
Impact/hardness
Electrical conductivity
Thermal conductivity
Sound insulation
Sound absorption
Vapour permeability
Biological durability
Chemical contamination
Reaction to fire

From those lists it becomes clear that quality control basically concerns the determination of the general properties of all boards. If this basic quality control has to be extended to the items of second list strongly depends on the contract. This contract could be a bilateral agreement with the customer; it could be the document describing the conditions to mark CE (Harmonised Standard), a third party certificate, etc.

In the future quality control, according to standardised methods in the producer's laboratory, will not be diminished dramatically and replaced by predictions of some mathematical model.

The reasons for that are:

- Mathematical models need to be build up using a lot of test results produced by the laboratory by means of standardised tests
- Even if a reliable model has been installed, one should continue to perform tests in order to actualise and to refine the model and the correlations it is based on.
- Evolution in raw material (e.g. glues with lower formaldehyde content, use of recycled wood, etc.) to day is so far reaching that correlations may evolve rather fast.
- More and more panel types are tailor made. This has been made possible by new and very flexible production techniques. The consequence could be that for a number of qualities reliable correlation can never be obtained because of lack of results.
- Customers are asking for results of end control according standardised methods (ISO 9000 systems).

The profit of models will not be so much the reduction of the costs of laboratory tests, but the reduction of costs caused by delays of delivery, diminution of productivity and loss of material. This will be obtained by the fact that quality information will be at disposal in an early stage of the production.

3.1.6.4. Third Party Quality Control

One of the hot items from WG4 of CEN TC 112, competent for the elaboration of test methods applicable to different types of wood based panels, was attestation of conformity and quality control. This discussion resulted in EN 326.

EN 326 contains three parts:

1. Part 1: Sampling and cutting of test pieces and expression of results.
   This standard describes how to take test pieces out of a panel and how many test pieces have to been taken for the different test purposes.
2. Part 2: Quality control in the factory.
   During the discussions this appeared to be the most critical part, due to the fact that a pure statistical quality control can result in very important expenses. The difficulty was to reconcile practice with the theoretical basis of statistics. Taking into account that specifications were expressed in terms of characteristic values, the manufacturer had to calculate characteristic values of the properties of his product types, using board averages and variations between boards.

   Using control charts, one has to produce an important number (30) of boards before being able to tell something meaningful about the process and the quality of the product. Due to the fact that quality control tests are destructive and labour intensive, hence very expensive, manufacturers have to restrict on the number of tested panels. The consequence is that only months after the production start of a new panel type, one will be able to obtain an accurate idea of the characteristic value of the board type.

   As already stated, today's production lines become more and more flexible and the possibility exists to change very quickly from one quality of board to another with a minimum loss of material and productivity. So tendency exists to make more and more different qualities and to produce boards almost on demand. In some cases even, quality of boards is evolving so quickly that producers never reach the stage that permits to make a good estimation of the over all average and variation between board means.

   To obtain a quicker response of the tendency the proposal was to calculate the running mean and the variation of five consecutive results. Using this, a running characteristic value could be calculated and used as a decision tool for accepting or degrading the batch. An annoying consequence of this technique is the fact that sometimes one had to degrade a board due to the fact that variation became high (characteristic value low) as a consequence of a very good result.

   All this stood far from the practice that had been reality during many years. That practice was that producers took just one board to judge if the batch satisfies the specifications asked by the customer. On top of that, manufacturers in fact were not so much looking after a tool for process control but a means to judge quickly and with reasonable expenses if the produced batch had the required quality and if it could be delivered.

   After long discussions the WG finally accepted a compromise. This compromise consisted in testing one panel of a batch and to use the variation between the test piece of one board as an estimation of the variation between averages of boards. One restriction has to be observed, that is that one should not allow that the variation coefficient by chance is very low. Therefor 8% is the minimum coefficient to use in this calculation of the characteristic value. Experience shows that, as far as wood based panels are concerned, this is a fair way to estimate the characteristic value of the board. Even if, from the theoretical side, one could disagree, practical results prove that this method is rather severe and certainly on the save side. On term the gathered results can be used to make up control charts and to refine the quality control by using variation between boards.

3. Part 3: Inspection of a consignment of panels.
   From a lot of panels whose origin is totally unknown, or that has been produced by an unknown company, samples will be taken according to this standard. The number of panels to be sampled is taken from ISO 2859. This standard did not cause too many problems to be accepted

Glossary of Terms

Additive- Material introduced in particleboard prior to the final consolidation in order to give the board some special property. e.g. wax

Adhesive - Substance which binds materials, together by surface attachment. In this case we talk about Urea-formaldehyde, Melamine-formaldehyde etc.

Bark- Outer tissue of stem and branches of tree. It may cause discoloration to the end product and that’s the reason why we remove it .

Bending Strength- Common term for modulus of rupture.

Blending- It’s the phase where glue is applied to the particles together with the other additives.

Binder - Adhesive used to agglomerate particles.

Blender- Apparatus in whitch the glue applied to the particles in particleboard manufacture.

Bond- Adhesion of particles one to another.

Catalyst- Chemical substance that initiates the setting (curing, hardening) of a synthetic resin.

Core- The inner part of a board between the outer surfaces or layers.

Chips- It’s a small pieces of lignocellulosic material , particle.

Classifier- Equipment for separating particles according to size.

Cure- The change of the physical properties of an adhesive by chemical reaction, polymerization usually accomplished by the action of heat and catalyst.

Debark- Removal of the outer layer or bark from round timber.

Density - Specific gravity or weight per unit measure: expressed in g/cm^3

Disk flakers- A flaking machine with knives on a rotating disc.

Formaldehyde- A reactive organic compound ,HCHO

Former- Apparatus for laying resin - coated particles as a mattress in particleboard manufacture.

Glue- Adhesive or binder.

Hammer mill- Machine for breaking down solid wood to particleform by a grinding, breaking or tearing action.

Hot pressing- It is the process of pressing a mattress between hot platens of a press to compact and set the structure by simultaneous application of heat and pressure.

Internal bond- An overall measure of the panel’s integrity showing how well the core materials are bonded together. Tested by applying tension perpendicular to the panels surface.

Mat, **Mattress**- The mass of prepared particles deposited on a caul plate by the Former in particle board manufacture.

Multi opening press- A press having openings(Daylights) for pressing a number of boards simultaneously.

Outer layer- Surface layer of particleboard.

Particles- Small piece of wood or other lignocellulosic material mechanically produced for use in particleboard manufacture.

Phenolic resin- type of synthetic resin sometimes used in manufacture of hardboard and particleboard.

Pre-press- Pressure applied to a board prior to final consolidation in the main press.

Resin content- The weight of dry resin solids contained in a unit weight of oven dry particles expressed as a percentage.

Screwholding- A measure of the force required to withdraw a screw directly from the face or edge of a panel expressed in N.

Stability-Degree to which a board material is affected by changes in moisture content.

Unloader- Apparatus for removal of finished boards from the press.

Urea formaldehyde- Synthetic resin very commonly used as a binder in particleboard manufacture.

3.2 Glued Laminated Timber

Carl-Johan Johansson

3.2.1 General

3.2.1.1. Description of the Product

Glued laminated timber (often referred to by the generic term glulam), is a structural building material composed of adhesive bonded solid timber laminations. Glulam is normally in the form of beams, arches and columns with rectangular cross section. The lamination thickness is in the range 20 to 45 mm.

The advantages of glulam are

- The ability to manufacture larger structural elements from smaller timber sizes
- A better utilization of available timber resources
- The ability to achieve architectural effects through the use of curved shapes
- The ability to design structural elements with varying cross section.
- Minimizing of checking
- Dimensional accuracy
- The ability to optimise the use of timber by placing the high grade material in the highly stressed parts and the low grade material in the less stressed parts.

3.2.1.2. Use

Glulam was first used in the late 1900th century. Production on a larger scale started after World War I, when improvements had been made to the casein adhesive which the most common at that time. The material was used as structural members in aircraft and later as framing members for buildings. More durable adhesives that were developed during World War II permitted use also in bridges and marine constructions.

Today the predominant use is as structural members in buildings.

3.2.2 Production

3.2.2.1. Materials

The dominating lamination material in Europe is spruce timber, which is dried to a moisture content of about 12%, mainly in order to avoid checking of the glulam after it has been built in. Material of one or several strength classes is used. Grading of is performed by visual methods according to national standards either at a sawmill or at the glulam factory. In resent years non-destructive methods have been introduced and so called machine strength grading is common in particularly the Scandinavian countries.

The adhesives are almost exclusively of the phenolic or amino plastic type such as phenolic resorcinol and melamine urea formaldehyde adhesives. These have the supreme durability that is necessary for glulam exposed to outdoor climate. Most of the glulam is however used indoor under less demanding conditions, but for practical reasons most producers use the same adhesive regardless of the environment in which the glulam is going to be exposed.

Between 5 and 10 kg adhesive per cubic meter glulam is used. The amount depends on a number of factors such as type of adhesive, lamination thickness and curing method.

Since the mid 1990´s also one-component polyurethane adhesives have been used. In some applications it has advantages compared to the phenolic and amino plastic because it is easier to handle (no mixing of components) and because it gives light coloured adhesive bond lines.

3.2.2.2. Production Process

The production of glulam can be divided in to the following steps:

Step	Activity	Description
1	Selection and preparation of laminations	Timber can be delivered to the glulam producer graded and dried. Many producers, however, prefer to grade and/or dry the timber themselves. The thickness of the laminations may vary. Maximum is normally 45 mm after planning. For curved members the laminations need to be thinner. The smaller the radius of the member, the thinner the laminations need to be in order to avoid failure. Thicknesses below 20 mm are not uncommon.
2	End jointing	The timber is normally end jointed for the following reasons: • to obtain long enough laminations • to optimise the use of the timber and avoid cutting losses By far the most common type of end joint is the finger joint, see section 1.1.
3	Planning	This normally takes place when the finger joints have cured long enough to give the strength needed to withstand the forces acting on the timber during the planning.
4	Adhesive application	The adhesive is normally applied by running the laminations beneath an adhesive curtain.
5	Clamping	Pressure (0,6 to 1,0 N/mm²) is applied to the laminations. Here the members can be formed to for instance arches. The relatively high pressure is needed to overcome cup and twist. The laminations are kept under pressure in a controlled environment. Normally the temperature is raised to accelerate the curing. High frequency heating is also used.
6	Finishing	The wide faces of the members are planed and cut to proper length.

3.2.2.3. Standards

A European standard EN 386 has been established and is now being implemented in several countries. It gives performance requirements and minimum production requirements such as:

- Adhesives shall meet the requirement in EN 301.
- End joints shall be tested according to EN 385.
- Glue line integrity and strength shall be tested according to EN 391 (delamination test) and EN 392 (block shear test).

3.2.3 Properties and Requirements

3.2.3.1. Strength and Stiffness

Glulam is a structural material and therefore the most important properties are strength and stiffness. Both are controlled by the properties of the timber. The strength, in particular the bending strength and the parallel-to-grain tensile strength, are characterised by being less variable than for solid timber. This is an effect of the bonding together of the laminations. Strength reducing defects in one lamination is bridged over by defect free material in adjacent laminations. This is often called laminating effect and has a positive effect on the design values used by the engineers.

The stiffness of glulam expressed as modulus of elasticity is only slightly higher than that of the laminations.

The strength and stiffness properties are normally not controlled by testing of full sized members. Instead different calculation models have been established by which the strength properties of the glulam could be predicted with acceptable accuracy using strength data for the laminations as input. The European standard EN 1194 defines four strength classes. For each class are given so-called characteristic strength values and stiffness values. Compliance with EN 1194 may be based either on full scale test of glulam or on calculation. Table 3.2.3.1 shows example of beam lay-ups that fulfil the requirements in EN 1194. Glulam can be produced as homogeneous with the same quality in all laminations. Combined glulam is also common. In this case the outer sixth of the cross section have a higher lamination quality than the inner parts.

Table 3.2.3.1: Examples of beam lay-ups fulfilling the requirements in EN 1194. Lamination strength classes are according to EN 338 Solid timber strength classes. The strength class value is the characteristic bending strength, i.e. the lower 5th percentile.

	Lamination strength class		
Beam strength class	GL24	GL28	GL32
Homogeneous glulam	C27	C35	C40
Combined glulam	C27/C22	C35/C27	C40/C35

At strength tests glulam behaves similarly to solid wood. The failure is brittle and starts in the laminations in the tension zone at defects such as knots or at finger joints. The quality of the finger joints has a decisive effect on the strength of glulam. Therefore testing of finger joints is used to control the production of glulam.

Judging from table 3.2.3.1 the bending strength of glulam seems to lower than that of the laminations. Take for instance GL28 that can be achieved by using C35 laminations. The strength seems to drop from 35 to 28 and the reason for this is as follows: The bending strength of timber and glulam depends on the size of the member. The strength decreases with increasing

3.2.3.2. Dimensional Stability

The shrinkage and swelling of glulam is the same as for solid timber. Since glulam has a moisture content of about 12% at production the shrinkage in indoor applications is minimal.

3.2.3.3. Requirements on Adhesives for Glulam

Adhesives must be strong and durable. The adhesive bond line must not degrade during the expected lifetime of the glulam structure (50-100 years) to such a degree that the stability is jeopardised. Requirements with respect to these aspects can be found in EN 301 - Adhesives, phenolic and aminoplastic, for load-bearing timber structures: Classification and performance requirements. Adhesives fulfilling this standard give a bond shear strength that is normally higher than that of the timber. Two types (I and II) are defined. Type I adhesives are durable in full weather exposure, whereas type II adhesives can only be used in heated and ventilated structures.

In principle EN 301 is only applicable to phenolic and aminoplastic adhesives. For other types such as for instance one-component polyurethane a common European system for assessing adhesives is lacking.

Adhesives for load-bearing structures must be capable of withstanding sustained loading without creep and creep rupture occurring. These aspects are not covered explicitly in EN 301 but the phenolic and aminoplastic adhesives, which have been used for more than 50 years, have proved to have excellent properties in this respect.

3.2.4 Test Methods

Only methods relating to the adhesive bonding will be dealt with. Testing with respect to bonding quality is carried out in connection with certification of producers and continuously in the factory production control. Two methods are available:

EN 390, the block shear test: Sections are cut from the glulam members and from these shear specimens are prepared. Shear test are mainly used for glulam for indoor applications.

EN 391, the delamination test: Three methods are available, A, B and C. Sections, 75 mm long, are cut from the member. They are ”impregnated” with water in a pressure vessel and dried. In method A and B the drying temperature is at 60 to 70°C and 65 to 75°C respectively. After the drying openings in the bond lines are measured and based on that a delamination percentage is calculated as the ratio between open length and bond line length. For method B that is the most frequently used the delamination must not exceed 4% after one cycle.

The EN 391 delamination test method efficiently reveals gluing errors in the production. Most producers use this method even if the products are only for indoor use and shear testing would be sufficient. One important advantage is the easy specimen preparation.

3.2.5 Research Needs

There is an urgent need for a system for assessing new types of adhesives for load-bearing timber products like glulam. A set of standards that can be applied to all possible future adhesives is needed. A basis for such standardisation has to be created by further research on how to predict durability and creep/creep rupture behaviour. The methods in EN 302 and the classification in EN 301 have been developed based on experience from phenolic and aminoplastic adhesives and do not necessarily apply to other types of adhesive.

Literature:

Colling F. (1995) “Glued laminated timber - Production and strength classes” STEP A8

3.3 Structural Composite Lumber

S. Koponen, M. Kairi

The family of Structural Composite Lumber (SCL) belongs to *engineered wood products* (EWP) that combine veneers or strands with exterior structural adhesives to form lumber-like structural products. An important characteristic common to SCL products like *laminated veneer lumber* (LVL), *parallel strand lumber* (PSL) and *laminated strand lumber* (LSL) is that the grain of the wood elements is aligned parallel to the member's length to maximise longitudinal strength properties.

Especially in North America SCL is an alternative to larger dimension lumber. By utilising gluing technology, smaller logs and under-utilised wood species are produced to larger dimensions and high quality wood products. Shrinking, warping, bowing and splitting tendency of sawn lumber is reduced or eliminated. The variation of strength properties is minimised by grading raw material and mixing imperfections. Also, LVL, PSL and LSL all use wood fibre much more efficiently than sawn lumber (figure 3.3.1).

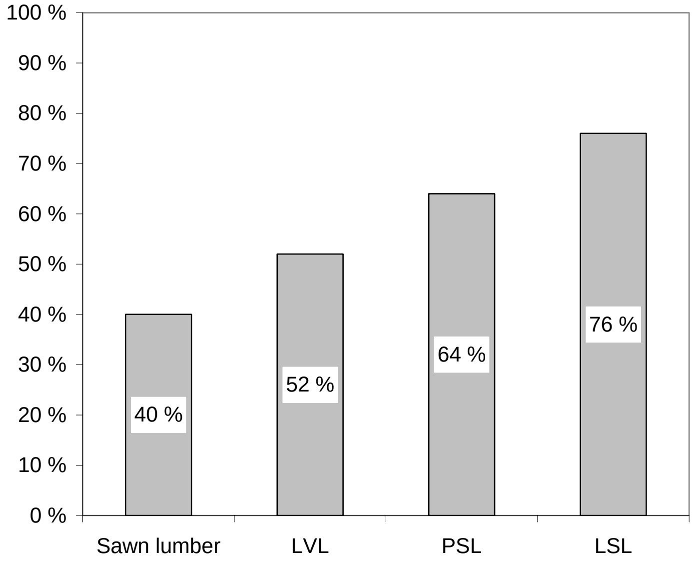

Figure 3.3.1: The wood fibre contained in a log is used more efficiently when it is converted into structural composite lumber than into sawn lumber (Nelson 1997).

These lumber-like products are often used for the same structural applications as sawn lumber and they substitute sawn lumber girders, beams, headers, joists, studs and columns (Nelson 1997). LVL, PSL and LSL are also used as larger members and components in commercial building constructions, e.g., trusses and portal frames. LVL has been used as slabs of roofs and floors.

Manufacturing of SCL requires an in-house quality assurance. Testing of glue bond quality and mechanical properties is done daily. Independent third party quality audits by a certification organisation carry out quality assurance inspections, which include random checks of process parameters and testing procedures as well as review of test results.

Wood species, wood element size and shape, adhesive and production parameters affect the engineering performance of SCL. Manufacturers shall be evaluated individually to determine their properties. ASTM D5456-99a Standard Specifications for Evaluation of Structural Composite Lumber Products cover initial qualification sampling, mechanical and physical tests, analysis, and design value assignments. Standard was established based on currently manufactured SCL products. Also in Canada there is SCL standard. So far there is no European standard concerning SCL products.

According to figure 3.3.2, the production of LVL and I-joist made of LVL will grow in the near future. PSL and LSL production will grow, but the production volume will remain smaller than LVL. The production volume of LVL in Europe is increasing now.

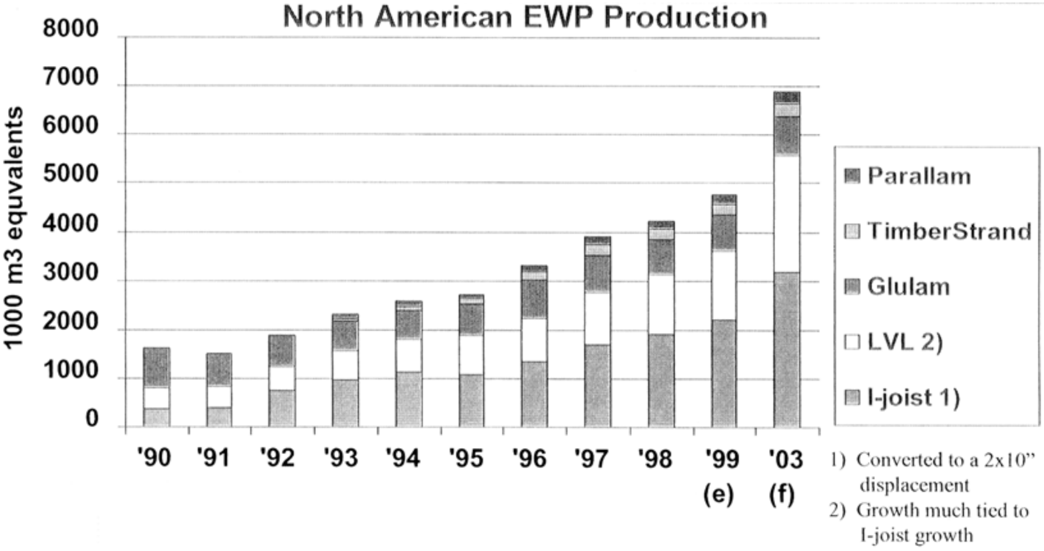

Figure 3.3.2: North American EWP production (Sandberg 1999)

3.3.1 Laminated Veneer Lumber (LVL)

3.3.1.1. General

LVL is manufactured in the United States, Canada, Australia, New Zealand, Finland, Sweden, Japan and Indonesia. In 1998 North American LVL production was 1,3 million m³, which indicated nearly 25 percent increase from 1997. The number of factories is 16. In 2002 the production is expected (APA) to be 2,0 million m³. Also in Europe the production has increased up to about 0,1 million m³, and there are 2 factories producing LVL, one in Finland and the other in Sweden. Third new LVL plant will be built in Finland.

3.3.1.2. Description of the Product

Laminated veneer lumber consists of layers of wood veneers laminated together with the grain of each veneer parallel primarily to the length of the finished product. For some end use purposes, about 20% veneers are added crossly in Finnish LVL factory (Kerto-Q-LVL). The thickness of veneers varies between 2,5 – 6,4 mm. Panel thickness is normally 19 – 45 mm, but thickness up to 89 mm can be produced. LVL is produced up to width of 1.800 mm. In the new Finnish LVL plant the width will be increased up to 2.500 mm. LVL is available in length up to the shippable maximum of 24 m.

3.3.1.3. Use

The application areas vary depending on continents and countries. LVL is used mostly for constructional purposes with structural and non-structural applications. In North America the most common application is joists, studs and flanges in I-joists. About 54 percent of LVL is used to make I-joist flanges, 36 percent for beams and headers. The other uses (10%) are scaffold planks and concrete form walers. At least one factory (Clear Lam) is coating LVL with a medium density overlay. Products are used as fascias and trims to obtain better durability to save installation and painting costs and to reduce construction site waste.

In Europe LVL beams and studs are common, but larger I-beams (Kerto-Q-LVL in webs) are also manufactured. In Germany very large engineered structures (figure 3.3.3) and renovation are important application areas. In Middle-Europe and especially in Switzerland Kerto-Q-LVL is used as a slab structure of roofs. In France portal frame structures are common application of LVL.

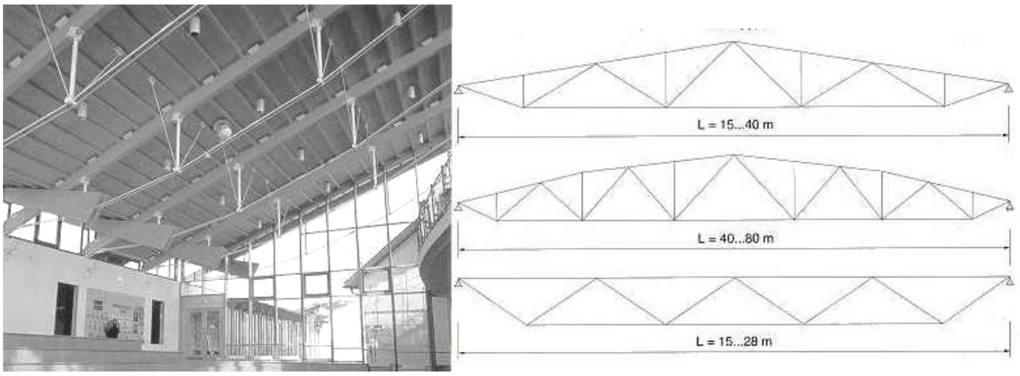

Figure 3.3.3: The use of LVL in roof structures as beams and trusses

Both in US and in Europe some bridges have been constructed using LVL decks. Concrete casting formwork beams can have LVL flanges and webs. Small amount of LVL goes to the furniture industry. LVL is also used as windows and doorframes. Truck floors and ladders for example are manufactured using LVL.

3.3.1.4. Production of LVL

Wood material and peeling: LVL is made of rotary peeled veneers. In North America standard plywood veneer sizes are used and LVL mills purchase veneers from plywood mills, but in Europe LVL factories peel veneers themselves. In North America Douglas-fir and Southern Pine are the most typical wood species used in LVL. European factories adopt Norway spruce and pine. Other possible wood species for LVL production are Sitka spruce, Radiata pine, Maritime pine, Yellow pine, Rubber wood, Eucalyptus, poplar and aspen. Different wood species can be combined in the production.

Veneers are graded based on density (ultra-sound for example) and visual defects. Veneers with lower quality are used mainly in secondary products or as core veneers. Up to three different strength classes have been distinguished. In addition, surface veneers can be graded based on colour and visual quality. At the ends of veneers a bevel is cut for scarf joint. Feeder stations transfer veneers to coater according to the required sequence. Typically the veneer handling rate is 3-4 s/veneer and thus the production rate is about 10 m^3/h.

Glues: Main adhesive is phenol formaldehyde (PF). Other possible glue is melamine formaldehyde (MF) and in the future maybe polyurethane (PU) glue. Typical glue spreading methods used for coating the veneers are roller or extrusion stripe spreading (curtain coater). Glue spraying and glue films are also possible. Adhesive solids content is 6-7% of the weight of the end product.

Hot pressing: LVL is manufactured either to a fixed length using stationary or to an indefinite length in a staging press or in a continuous hot pressing (figure 3.3.4). The press can have one or two daylights. Pressing time depends on the product thickness and the optimum thickness for the current production methods is about 40 mm. Pressing time can be reduced by microwave preheating. Hot pressing temperature is between 125°C - 150°C. Secondary gluing makes it also possible to produce thicker panels. Cold setting and gap filling resorcinol-formaldehyde glue (RF) is applicable for this purpose.

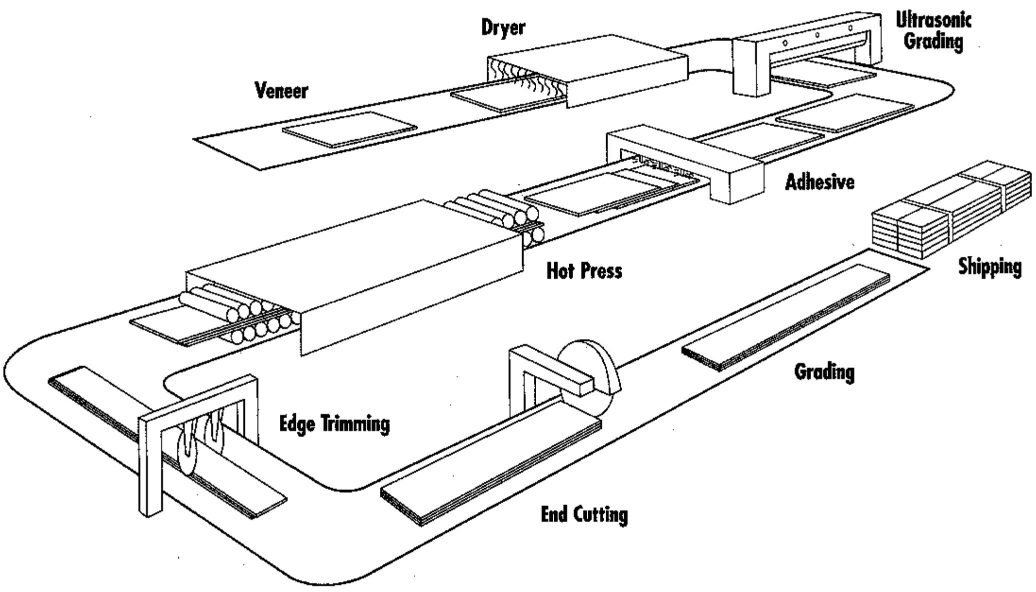

Figure 3.3.4: Schematic picture of LVL production (Nelson 1997)

3.3.1.5. Properties and Requirements

There are several different structural applications for LVL. Thus, lots of different type technical data and construction design instructions are required to support markets, to obtain technical approvals and for the design and use. In addition, veneer grades, lay-up and several wood species may be used and thus the product assortment is wide.

Each manufacturer has obtained technical approvals for his products. There have been slight differences in standards and in test methods, thus mechanical and physical parameters vary among countries. The Canadian Construction Materials Centre (CCMC) has issued product evaluations for LVL products marketed in Canada. In the United States, most manufacturers have obtained product evaluation reports from the Council of American Building Officials (CABO). In US the new ASTM D5456-99a standard outlines procedures for establishing, monitoring and re-evaluating structural capacities and will also detail the minimum requirements for establishment of quality control, assurance and audit. In Japan there is JAS-standard for structural laminated veneer lumber (1993). European standard concerning LVL is under development.

The exterior type glue should be used. European standards EN 301 and EN 302 give requirements for the glue and glueline strength (shear strength, wood failure percentage, shrinking and swelling resistance) and for the weather resistance of glue.

The manufacture of LVL requires an in-house quality assurance. Regular independent third party quality audit inspects manufacturers' quality assurance program. All manufactured LVL products that have been tested and approved should be marked with the name of certification agency, the manufacturer, date of manufacture, grade of LVL and reference to any applicable code or evaluation agency approval numbers.

LVL reacts to fire as the same as a comparable size of solid sawn lumber or a glued-laminated beam. Phenol-formaldehyde resin adhesive used in manufacture does not contribute to the fire load and the strength of the bond is not affected by heat. When LVL is used in fire-rated floor or roof assemblies, the performance of LVL is similar to solid sawn lumber or glued-laminated timber.

3.3.1.6. Advantages of LVL

LVL has many potential advantages over sawn lumber in strength, predictable performance, available sizes, dimensional consistency, dimensional stability and ability to be treated chemically. The need to increase process automation and efficiency of refining wood industry will lead to demand of high quality wooden raw materials. On the other hand, there is increasing lack of the resource of high quality timber.

The use of veneers in making LVL results in a re-distribution of the knots, slope of grain and other natural defects occurred in the logs. Further more when the veneers are graded, the higher-grade veneers can be placed to where they are more effective for strength, for example, product surfaces. Lower-grade veneers can be used for secondary products with lower strength requirements. Coefficient of variation in strength and stiffness for LVL typically ranges between 10 and 15% compared with 25 to 40% for structural grades of sawn lumber. It is more dimensionally stable than sawn lumber.

3.3.1.7. Disadvantages of LVL

Because the raw logs must first of all be peelable, this results in limitations on log size and quality. The tensile strength of peeled softwood veneers in thickness direction varies a lot, thus the strength of mechanical fasteners on the edge of panel may be reduced. The high capital investment and relatively low production rates demand higher value-added applications in order for profitable operations.

3.3.2 Parallel Strand Lumber (PSL)

Known generically as parallel strand lumber, Parallam® PSL is the unque PSL product currently available (figure 3.3.5). It is produced in three factories in North America. One factory is located in Canada and two in US.

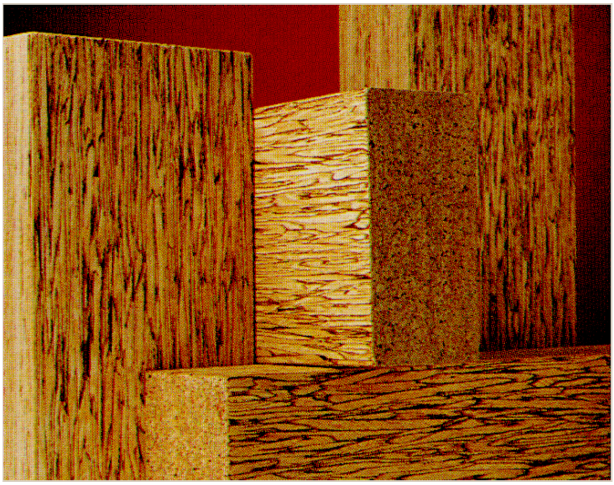

Figure 3.3.5: Parallel Strand Lumber (PSL)

As same as LVL, the manufacture of PSL begins with rotary-peeled and graded veneer about 3 mm thick. Veneer sheets are clipped into strands approximately 20 mm wide, thus permitting the use of roundup, fishtail and other pieces of less-than-full-width veneers. The fibre in these veneers is mostly clear sapwood from the outer portion of the tree and is higher-than-average in strength than the rest of the wood fibre in logs, and represents material that is not usable in the LVL process. Presently, PSL is made of Douglas fir, Western hemlock, Southern pine and Yellow-poplar.

After a waterproof structural adhesive, typically phenol-formaldehyde mixed with wax, is applied, the strands are fed into a continuous press to form a mat. The continuous pressing operation allows for greater densification of the wood than achieved in pressing LVL. The adhesive is cured using microwaves that cure the billet first from the inside. The pressed billets with cross-section typically 280 × 480 mm^2 are ripped into narrower members. The billets can have the maximum length of 20 m (figure 3.3.6).

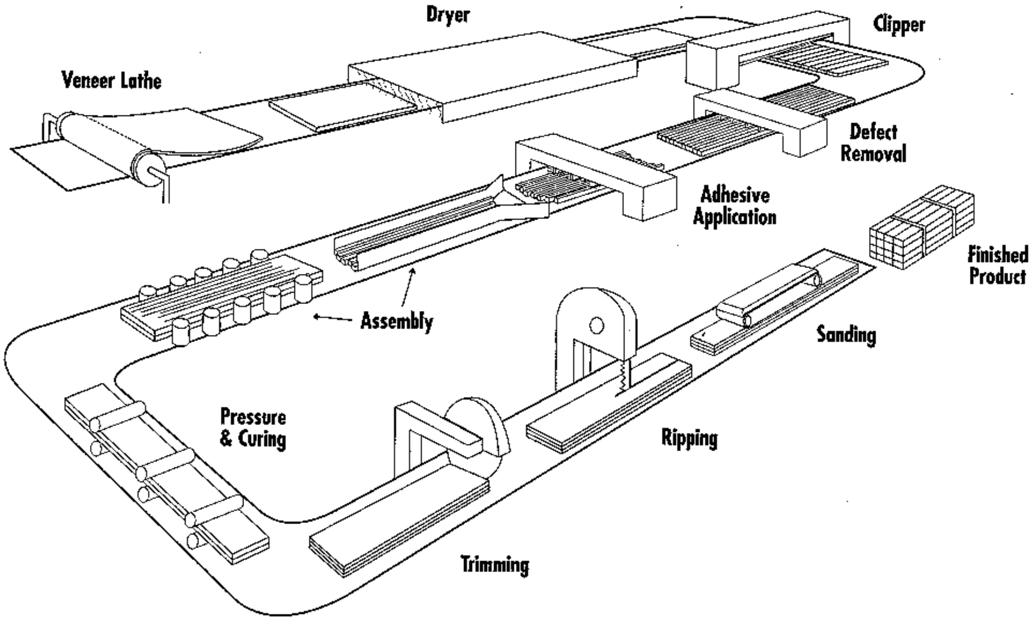

Figure 3.3.6: Schematic picture of PSL production (Nelson 1997)

PSL holds the advantages of LVL, with the exception of layering veneer strands by grades. Strength is enhanced by homogenising the structure and by increasing the amount of compress of the material. Large cross-section of billet minimises the need of secondary gluing in applications.

As same as LVL, the PSL technology is limited to peelable logs. PSL is heavier than same size sawn timber or glulam and its adhesive is more abrasive to saw teeth and drills. Like LVL, PSL production lines are capital-intensive (Nelson 1997). PSL needs even fourfold investment than LVL.

At the time only one company produces PSL in the world and it has protected the technology with strong patents. In the near future it is not expected that the PSL production would grow remarkably.

Applications of PSL are columns, short span lintels in prefabricated homes, top and bottom plates in multistory buildings and in open web trusses where members are stressed axially.

3.3.3 Laminated Strand Lumber (LSL)

In North America two factories produce Laminated Strand Lumber. It is marked as TimberStrand® LSL in North America and IntrallamTM LSL in Europe (figure 3.3.7).

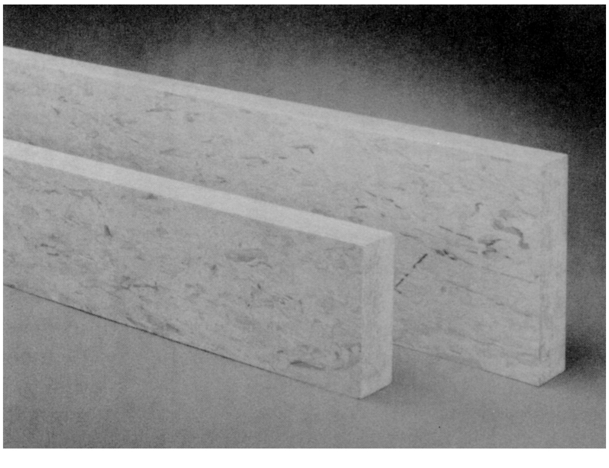

Figure 3.3.7: Laminated Strand Lumber (LSL) (Nelson 1997)

LSL is a kind of extension of oriented strand board (OSB) technology in which the whole log, excluding bark, is processed through the rotating knives of a stranding machine. In the case of LSL, however, about 300 mm strands are significantly longer than the 70 - 150 mm long strands used for OSB, but their thickness is about the same: 0,7 - 1,2 mm. The larger length is the key of LSL's longitudinal strength and for orienting the strands during mat formation so that strands will be essentially parallel to the finished product's length. Undesirable strands are taken away beforehand and used as fuel for the production process. Two features unique to LSL technology are the use of a polymeric-diphenylmethane-diisocyanate adhesive that is sprayed onto the strands as they tumble inside a rotating drum, and curing of the adhesive in a stationary steam injection press. 2,5 m wide billets up to 140 mm thick and 14,5 m long have been made with this technology (figure 3.3.8).

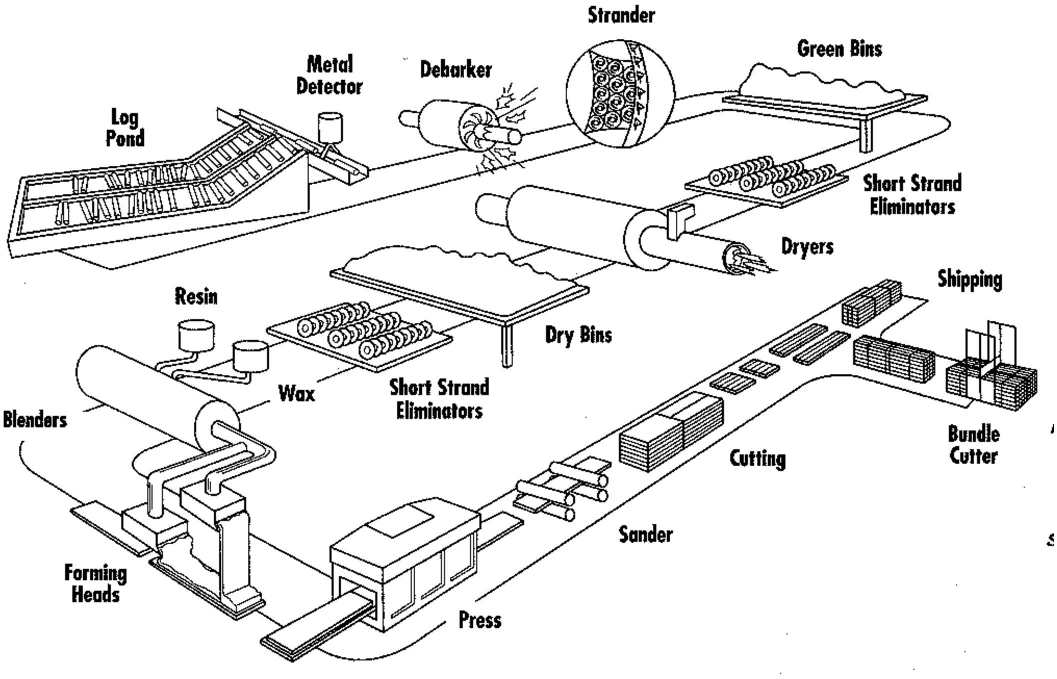

Figure 3.3.8: Schematic picture of LSL production (Nelson 1997)

The raw material of LSL is not limited to peelable logs of preferred species. Small and crooked logs of many even underutilized fast-growing species are acceptable. LSL demonstrates excellent fastener-holding capacity and mechanical connector performance. Dimensional stability of LSL, particularly thickness swelling, is not as good as that of LVL and PSL. As with all SCL products, there are significant investment requirements for LSL production lines (Nelson 1997). LSL investment requirements are about double compared to LVL's investment requirements.

3.3.4 Research Needs

The production volume of LVL will increase remarkably due to development of new engineered products and substitutions of old ones. Especially the need of high-quality and high-tech products and solutions is increasing. In addition to that products must be environmentally friendly.

The conventional production of thick (75 - 89 mm) LVL is less efficient due to long hot-pressing time. Preheating or more reactive glues might increase productivity if the other processes in production line can follow the change. Glues used for thick panels should be suitable for the longer assembly time and often also for the longer hot-pressing time.

Although PF-glue costs low price and has good performance especially in long-term loading and in humid and wet conditions there are demands to use other glues. The colourless glues are required in some applications. Alkaline phenol adhesives may cause corrosion in mechanical joints and blue stain in veneers. Polyurethane adhesive producers have also expressed their interest in the development of PU adhesives for LVL production.

Different glue spreading methods have different sensitivity to the production conditions, which should be better evaluated. Spray spreading needs less adhesive, but it provides smaller margin of open time. Strip spreading needs more adhesive, but it provides larger margins for open time.

More knowledge is needed on the effects of raw material parameters (wood species and quality) and process parameters (glue-type, pressing time, panel thickness) on end use properties of LVL. It improves reliability of production of different grades and optimisation of a raw material usage. Gluing of different wood species should be possible and easy. Suitable grading and quality control methods are necessary.

LSL is used in structural and non-structural applications. In the production strand orientation can be changed so that a beam (strand in longitudinal direction) or a panel grade (more random orientation) can be manufactured. Like in OSB the decreasing raw material quality will lead to more ineffective material usage, which is compensated by lower raw material costs. The aim to produce high quality products from low quality raw material has not fully succeeded.

For the economical production of LSL the availability and applicability of different wood species, small dimension wood, waste wood and by-products obtained from sawmills for example should be studied. In addition to the knowledge on the effect of raw material parameters on the end use properties and glue consumption it is necessary to be able to predict strength properties based on the strand orientation more accurately.

Like in the case of all the other glued products environmental, heathens and waste treatment aspects will be pronounced in the future. Thus the development of life cycle analysis will be necessity.

European standardisation does not yet cover fully SCL products. Short- and long-term test methods should be developed to match end use conditions.

Thus the research needs are as follows:

- Finding optimal glues and gluing methods for different SCL products,
- New glues for SCL (colourless for example),
- Modelling properties of SCL based on raw material and production parameters,
- Efficient utilisation of different raw material sources (different wood species, under utilised wood),
- New more suitable short-term test and quality control methods (non-destructive evaluation for example),
- New long-term test methods,
- More accurate evaluation of long-term properties of SCL and
- Life cycle analysis of SCL products.

3.3.5 Standards

EN 301 “Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements”

EN 302-1 “Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of bond strength in longitudinal tensile shear”

EN 302-2 “Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination (Laboratory method)”

EN 302-3 “Adhesives for load-bearing timber structures - Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength”

EN 302-4 “Adhesives for load-bearing timber structures - Test methods - Part 4: Determination of the effects of wood shrinkage on the shear strength”

ASTM D5456-99a “Standard Specification for Evaluation of Structural Composite Lumber Products”

JAS Japanese Agricultural Standard for Structural Laminated Veneer Lumber 1993

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Intrallam LSL 1.5 E, Ü: TJM - Z-9.1-323 - FMPA. Type approval

Parallam PSL DF, Ü: TJM - Z-9.1-241 - FMPA. Type approval

Glossary of Terms

Curtain coater: glue spreading method

Continuous pressing: press producing continuos panel between rotating steel belts for example

EWP: engineered wood product

LSL: laminated strand lumber

LVL: laminated veneer lumber

MF: melamine formaldehyde

OSB: orientated stand board

PF: phenol-formaldehyde

PSL: parallel strand lumber

PU: polyurethane

SCL: structural composite lumber

Staging press: press producing continuous panel using stepwise pressing

Stationary press: conventional press for fixed size panels

UF: urea formaldehyde

4. Adhesive Joints

4.1 Stress Distribution and Strength Models

Per Johan Gustafsson

Strength analysis of an adhesive joint requires modelling of the bond line. Two sets of models are needed: For the calculation of the stresses some model or assumption regarding the stiffness properties of the bond line is needed. And for calculation of the joint strength is in addition some model or assumption regarding the strength, yield or fracture properties of the bond line needed.

In section 4.1.1, bond line modelling is discussed. Section 4.1.2 relates to joint modelling and calculation of the stress distribution. Modelling of strength and fracture properties is discussed in section 4.1.3. Chapter 4.1 is not a complete and general state-of-the-art report, but influenced by work carried out the division of Structural Mechanics, Lund University, during the last decade. An important field of modelling not discussed in the present writing is modelling for reliability analysis.

4.1.1 Modelling of a Bond Line - An Overview

a) Typical features of a bond line

The modelling of stiffness properties relate to modelling of stress versus deformation or strain. Such modelling, - if leaving material micro structure models out of this discussion -, can be made with the adhesive regarded as a bulk volume or with the adhesive regarded as bond line of small or zero thickness. The physical build up of a bond line commonly involve 5 or more separate parts with different properties: (1) a surface layer of the adherend material – (2) an interface or a thin layer where the adherend and the adhesive interact and might be mixed with each other and with surface dirt- (3) the adhesive – (4) the second interface - and (5) the second aherend surface layer. Due to difficulties both in testing and in modelling these parts are commonly not modelled separately but treated as a homogenous layer with properties corresponding to the integrated performance of the parts. This means that the properties, i.e. the integrated characteristic properties, have to be tested for each combination of adherend, adhesive and bond layer thickness. Characterisation only by the adhesive properties is relevant if the adhesive is weak and flexible as compared to the other parts of the bond line.

There are two characteristic features that make the difference between bond line modelling and modelling of materials and structural elements in general. One relates to geometry: the thickness of a bond line is very small as compared with the in-plane dimension of the bond line and as compared with characteristic dimensions of the adherends. The second relates to the above-mentioned heterogeneity: a bond line may in general, although being thin, have very different properties in different parts.

In modelling of details such as spew fillets is the adhesive itself acting as an adherend and the layer of interaction between the adhesive and the wood acting as a bond line. The approaches used for modelling of the adhesive is in such cases the same as for materials in general and not a bond line modelling in the sense of being different from stress and cohesive strength analysis in general.

Since the thickness of a bond line is small as compared with the in-plane dimension of the layer, it is natural to distinguish out-of-plane stress, strain and deformation from the in plane stress, strain and deformation. This is illustrated in figure 4.1.1 where y-axis is orientated according to the normal of the bond layer. The out-of-plane components of stress (strain) are σy, τxy and τzy (εy, γxy and γzy) and the in plane components are σx, σz, and τxz (εx, εz and γxz)

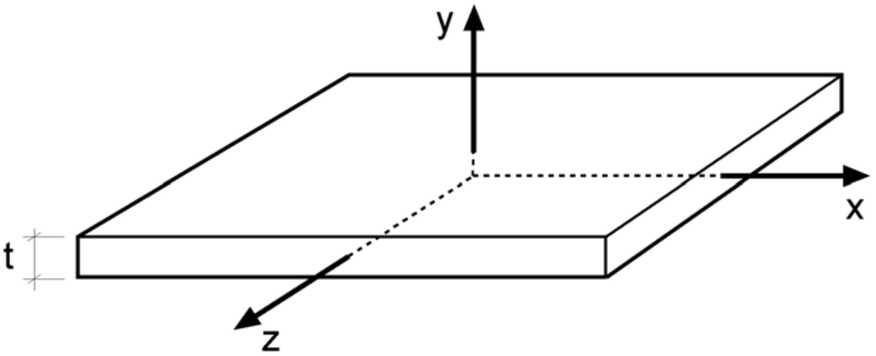


Figure 4.1.1: Bond line layer with thickness t.

The in-plane stresses and the out-of-plane strains of the bond line are because of the above mentioned bond line characteristic features defined by single values, taken as the average values:

$$\begin{bmatrix}\sigma_x\\ \sigma_z\\ \tau_{xz}\end{bmatrix}_{bondline} = \frac{1}{t}\int_{-t/2}^{t/2}\begin{bmatrix}\sigma_x\\ \sigma_z\\ \tau_{xz}\end{bmatrix} dy, \qquad 4.1\text{-}1$$

and

$$\begin{bmatrix}\varepsilon_y\\ \gamma_{yx}\\ \gamma_{yz}\end{bmatrix}_{bondline} = \frac{1}{t}\int_{-t/2}^{t/2}\begin{bmatrix}\varepsilon_y\\ \gamma_{yx}\\ \gamma_{yz}\end{bmatrix} dy = \frac{1}{t}\begin{bmatrix}\delta_y\\ \delta_{yx}\\ \delta_{yz}\end{bmatrix} \qquad 4.1\text{-}2$$

where t is the bond line thickness and [δy , δyx , δyz]T the relative displacements across the bond line. The out-of-plane stresses and the in-plane strains are for a plane bond line by the same reasons treated as constants with respect to y:

$$\begin{bmatrix}\sigma_y(y)\\ \tau_{yx}(y)\\ \tau_{yz}(y)\end{bmatrix}_{bondline} = \begin{bmatrix}\sigma_y\\ \tau_{yx}\\ \tau_{yz}\end{bmatrix}_{bondline}, \quad \begin{bmatrix}\varepsilon_x(y)\\ \varepsilon_z(y)\\ \gamma_{xz}(y)\end{bmatrix}_{bondline} = \begin{bmatrix}\varepsilon_x\\ \varepsilon_z\\ \gamma_{xz}\end{bmatrix}_{bondline} \qquad 4.1\text{-}3, 4.1\text{-}4$$

b) Stress analysis without consideration to constitutive properties of the bond line

In the simplest and most common method of modelling, both the bond line thickness and the in-plane stiffness are set equal to zero and the out-of-plane stiffness treated as being infinitely large, i.e. the out-of-plane deformations zero. This means that the out-of-plane bond line stresses can be determined from the conditions of equilibrium, for a bond line with no curvature giving

$$\begin{bmatrix}\sigma_y\\ \tau_{yx}\\ \tau_{yz}\end{bmatrix}_{bondline} = \begin{bmatrix}\sigma_y\\ \tau_{yx}\\ \tau_{yz}\end{bmatrix}_{adherend} \qquad 4.1\text{-}5$$

where [σ_y , τ_{yx} , τ_{yz}]adherendT are the stresses in the adherend at the location of the bond line as obtained in a stress analysis where the bond line is ignored. The in-plane state is commonly regarded as being of much less interest, but may in this kind of modelling be obtained in terms of the in-plane strains, the bond line in-plane strains according to the conditions of compatibility being equal to the strains in the adherend:

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_z\\ \gamma_{xz}\end{bmatrix}_{bondline} = \begin{bmatrix}\varepsilon_x\\ \varepsilon_z\\ \gamma_{xz}\end{bmatrix}_{adherend} \qquad 4.1\text{-}6$$

This simple kind of modelling gives accurate results if the bond line is thin and has strains in the same order of magnitude, or less, than the adherend material. For most wood joints this means that accurate out-of-plane stress results will be obtained as long as the adhesive is elastic and hasn't started to yield or fracture. If knowing the constitutive equation for the bond line material the in-plane stresses can be obtained from the in-plane strains and the out-of plane stresses as determined by equations 4.1-5 and 4.1-6.

c) Stress analysis with consideration to constitutive properties of the bond line

In the second common approach for bond line modelling is a constitutive equation for the out-of-plane stresses and the out-of-plane relative displacements across the bond line taken into account in the joint stress analysis. The influence on equilibrium from the in-plane stresses is neglected and so is the possible effect of the in-plane strains on the out-of plane stresses. The bond line thickness is set equal to zero or to some value close to the true bond line thickness. The bond line thickness does, if not being zero or very small, affect the equilibrium, but not the constitutive modelling. For 3D analysis:

$$\begin{bmatrix} \sigma_y \\ \tau_{yx} \\ \tau_{yz} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix} \begin{bmatrix} \delta_y \\ \delta_{yx} \\ \delta_{yz} \end{bmatrix} \qquad 4.1\text{-}7$$

where the stiffness parameters D_{ij} are constants in the case of a linear bond line performance. Equation 4.1-7 must for a general non-linear performance be given as an incremental relation and the stiffness parameters taken as functions of the deformation history.

The coupling parameters in equation 4.1-7 are often set to zero in order to simplify analytical stress analysis, for 2D states of stress or deformation giving

$$\begin{bmatrix} \sigma_y \\ \tau_{yx} \end{bmatrix} = \begin{bmatrix} D_{11} & 0 \\ 0 & D_{22} \end{bmatrix} \begin{bmatrix} \delta_y \\ \delta_{yx} \end{bmatrix} \qquad 4.1\text{-}8$$

This model is further simplified in shear lag analysis, where the bond line opening deformation δ_y is made equal to zero, assuming that the influence of those deformations on the normal and shear stress distributions is negligible. The shear stiffness parameter D_{22} is often expressed as (G/t), where G is an effective shear modulus of the bond line material and t is the bond line thickness. Thus, in shear lag analysis

$$\tau_{yx} = (G/t)\,\delta_{yx} \qquad 4.1\text{-}9$$

The in-plane strains and the out-of-plane stress components not involved in the bond line constitutive modelling can be obtained from equations 4.1-5 and 4.1-6, respectively. If having sufficient knowledge about the constitutive properties of the bond line material it is possible to determine also the in-plane stresses.

d) Concluding remarks

In the above first referred to simple kind of modelling the assumptions are such that the bond line properties don't enter into the stress analysis. Instead the bond line stresses and strains are obtained afterwards. In the second kind of modelling the constitutive properties are commonly represented by distributed springs or by a continuum medium assigned appropriate stiffness properties in accordance with equations 4.1-7, 4.1-8 or 4.1-9. Carrying out the stress analysis numerically by the finite element method the distribution of the bond line deformation or stress distribution is moreover approximated according to element mesh and element shape function. Future development in the area of basic approaches for bond line modelling may gain from the development in the area modelling of localised fracture regions in iso- or orthotropic homogeneous materials during the last decades by use of various kind of so-called smeared or discrete models.

4.1.2 Joint Stress Distribution Modelling

a) Small interest in wood bond line and joint stress distribution modelling

The literature on mechanics of adhesive joints is comprehensive, including textbooks (i.a. (Abel, et al, 1991), (Adams and Wake, 1984), (Kinloch, 1987), ASTM(1978), (Arnason et al, 1991), (Mays, Hutchinson, 1992), (Karlsson,1994), (Lees, 1984)), international journals (i.a. International Journal of Adhesion and Adhesives, and Journal of Adhesion Science and Technology), conference proceedings (i.a. (Verchery and Cardon, 1987), (Mital et al, 2001)), internet homepages (for the European Thematic DOGMA Network: http://www.vtt.fi/val/val3/projects/dogma/joining/-joiningindex.htm) and a large number of PhD-thesis's, research reports and papers, including literature on finger joints (Nielsen, 1991) and comprehensive reports on glued-in rods (Deng, 1997), (Johansson, et al., 2001). It appears, however, that only a small fraction of this research is on stress analysis of wooden joints. The low interest in stress analysis of glued wooden joints is, as an example, illustrated by the fact that neither the word "stress" nor "strength" are included in the index of a leading text book on gluing of wood (Raknes, Schmidt, 1988), written for use in wood industry as a comprehensive handbook on gluing of wood. There may be several reasons for the small interest in stress analysis. One major reason may be the timber engineering tradition of taking fracture in the wood as a good and sufficient bond line design parameter. Another major reason may be that linear elastic analysis suggests that the bond line properties commonly have very little affect on the service load stress distribution in the glued joint. These two factors put together may seem to result in the disputable conclusion that bond line modelling is of no interest neither with respect to constitutive modelling of stiffness properties nor with respect to modelling of strength properties.

There are classical analytical solutions for the distribution of shear and normal stresses in overlap adhesive joints, i.a. Volkersen (1938) and Goland and Reissner (1944). These solutions are obtained for linear elastic properties of the adherend as well as the bond line, using bond line modelling according to equations 4.1-8 and 4.1-9, respectively. Such modelling is relevant when adherend-adhesive combinations are such as steel-epoxy, where the bond line deformations are significant and therefor decisive of for the bond line stress distribution. The adhesive used in wood joints are commonly thin and, in the elastic range, not very compliant as compared to the stiffness of wood. This suggests that elastic bond line stress analysis of glued wood joints in many cases, perhaps most cases, with a good accuracy can be carried according the simplest kind of modelling, i.e. according to equations 4.1-5 and 4.1-6. This implies that the most important thing is a good modelling of the wood, taking into account features like anisotropic properties, influence of moisture, creep, possible changes of material stiffness orientation at the bond line, heterogeneity, etc. Although the modelling of the wood probably is of the prime concern in service load stress analysis of glued wooden joints, it is outside the present scope and shall therefor not be further discussed.

b) Analytical shear lag modelling

Shear lag models are very useful in relation to joint strength analysis, as in contrast to service load analysis, also for bond lines with a high elastic shear modulus, as has been found by fracture mechanics analysis (Gustafsson, 1987). The representative bond line stiffness parameters used in such fracture analysis are orders of magnitude less than the initial elastic stiffness and determined from the condition of correct representation of the total work required for bond line fracture. Another example where the classical shear lag analysis is relevant is in the case of joining by a flexible glue or a sealant where the purpose may be tightening rather than carrying of load or prevention deformation. Good methods for analysis of stress and deformation are of course valuable also when the purpose of the joining is tightening.

The basic assumption in lap joint stress distribution analysis by the so-called Volkersen model are linear elastic performance of adherends and the adhesive, the bond line modelled as a shear lag layer with properties according to equation 4.1-9 and the adherends modelled as two bars (two beams that by constraints are prevented from bending and from shear deformation). These assumption leads to an ordinary homogeneous second order differential equation

$$\tau'' - \omega^2 \tau = 0 \qquad 4.1\text{-}10$$

where

$$\omega^2 = \frac{G}{t_1 E_1 t}\left[1 + \frac{t_1 E_1}{t_2 E_2}\right] \qquad 4.1\text{-}11$$

ti and Ei , i = 1,2 are thickness and E-modulus, respectively of the adherends. The general solution for the shear stress distribution is

$$\tau = A_1 \cosh(\omega x) + A_2 \sinh(\omega x) \qquad 4.1\text{-}12$$

where x is the co-ordinate along the joint. If a distributed load is acting along the joint, e.g. reflecting the influence of differential shrinkage of the adherends, then a loading term has to be added to the right hand side of equation 4.1-10 and a particular solution to the homogeneous solution, equation 4.1-12. Before determination of the constants A_1 and A_2, due to geometrical compatibilty and equation 4.1-9:

$$\frac{N_2}{t_2 E_2} - \frac{N_1}{t_2 E_1} = \tau' \frac{bt}{G} \qquad 4.1\text{-}13$$

where b is the joint width and N_2 and N_1 are the cross section normal forces at section x. Substitution of equation 4.1-12 into 4.1-13 results in a set of two linear equations from which A_1 and A_2 can be obtained for arbritrary end-loading conditions:

$$\begin{bmatrix} 0 & 1 \\ \sinh(\omega L) & \cosh(\omega L) \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = \frac{G}{bt\omega} \begin{bmatrix} N_2(0)/(t_2 E_2) - N_1(0)/(t_1 E_1) \\ N_2(L)/(t_2 E_2) - N_1(L)/(t_1 E_1) \end{bmatrix} \qquad 4.1\text{-}14$$

where $N_2(0)$ is the load applied to adherend 2 at the end x = 0 and so on. For pure tensile loading of joint, i.a. for $N_1(0) = N_2(L) = P$ and $N_2(0) = N_1(L) = 0$, is found

$$\tau = \frac{PG}{t\omega b t_1 E_1}\left\{\frac{(\cosh(\omega L) + t_1 E_1/(t_2 E_2))}{\sinh(\omega L)}\cosh(\omega x) - \sinh(\omega x)\right\} \qquad 4.1\text{-}15$$

The performance of the Volkersen theory is illustrated by application to stress analysis of the CEN-prEN 302 lap joint test specimen, shown as a part of figure 4.1.5. For this centric loaded specimen is $t_1 = t_2 = 5$ mm, b = 20 mm and L = 10 mm. In figure 4.1.2 two shear stress distributions are shown. Both are obtained for P = 1.870 N, $E_1 = E_2 = 13.000$ MPa and t = 0,1 mm. The strongly non-uniform distribution was obtained with G = 1.500 MPa and the other with G = 5,1 MPa. The first value is an approximate estimation of the elastic shear stiffness of an adhesive like resorcinol/phenol. This value is about the same or higher than the shear stiffness of wood, indicating that application of the Volkersen theory is indeed very questionable since the shear deformation of the wood, being many times thicker, is ignored, at the same time as the small shear in the bond line is considered and even governing the shear stress distribution. The other curve, showing an almost uniform shear stress distribution, is valid for G = 5,1 MPa, obtained by fracture energy equivalence from reasonable examples of bond line shear strength, 10 MPa, and fracture energy, 980 J/m^2. The particular load, P = 1.870 N, is the joint failure load according to a non-linear finite element analysis.

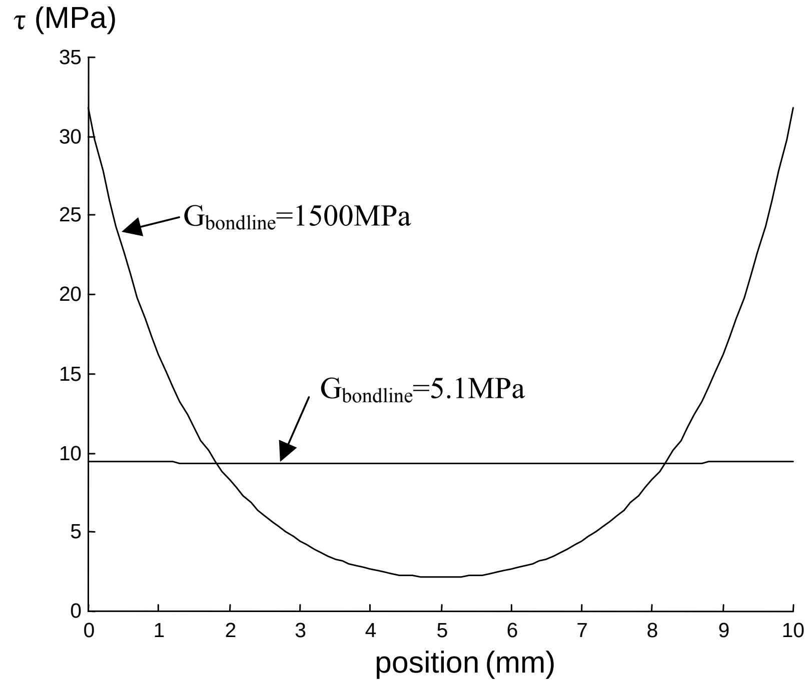


Figure 4.1.2: Volkersen theory predictions of shear stress distribution.

Second order differential equations similar to equation 4.1-10 can be derived for overlaping plates loaded in shear and tubular joints loaded in tension or by a torque. Consideration to shear deformation in the adherends leads to a forth order differential equation and if also taking into account bending and normal deformation of the bond line 6th and 8th order equations can be derived. The complexity in the solving the high order equations, in particular the determination of the integration constants, makes, however, the more advanced analytical analysis of fairly limited interest as compared to numerical calculations by the finite element method. The analytical solutions are in general limited to linear elastic performance although various kind of solutions have for been presented also for other constitutive relations, including a bilinear stress-deformation curve (Ottosen and Olsson, 1988), ideal plastic performance with a limit strain (Gustafsson, 1987) and elasto-plastic performance (Hart-Smith, 1973).

c) Modelling by use of the finite element method

Advanced stress distribution analyses of adhesive wood joints available at the present were carried by finite element analysis, modelling the bond line by non-linear elastic 2D coupled equations

$$\begin{bmatrix} \dot{\sigma}_y \\ \dot{\tau}_{yx} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} \dot{\delta}_y \\ \dot{\delta}_{yx} \end{bmatrix} \qquad 4.1\text{-}16$$

so that stress components could be related to the total deformations:

$$\begin{cases} \sigma_y = f_1(\delta_y, \delta_{yx}) \\ \tau_{yx} = f_2(\delta_y, \delta_{yx}) \end{cases} \qquad 4.1\text{-}17$$

The state of stress is by equation 4.1-16 defined by the current state of deformation and thus not path dependent. The work needed to reach any given state of deformation is on the other hand path dependent. The functions f_1 and f_2 can by principle be assigned any shape and include the complete stress response, including the fracture softening down to zero stress. Simple shapes being bi-linear for $\delta_{yx} = 0$ and $\delta_y = 0$, respectively are shown in figure 4.1.3. In this figure is the y-direction indicated by n and shear by s. Similar but less crude shape functions f_1 and f_2 are illustrated in figure 4.1.4 with respect to the normal stress versus normal deformation at zero shear deformation and with respect to shear stress versus shear deformation at zero normal deformation. The particular curves defined in this figure represents three-linear approximations of test results obtained by Wernersson (1994) for a resorcinol/phenol-spruce bond line. Finite element analysis according to equation 4.1-16 have been presented by (Wernersson, 1994), (Serrano,1997) and (Serrano, 2000) for wood-to-wood joints and steel-to-wood joints.

In figure 4.1.5 stress distributions as obtained by a model of the type illustrated in figure 4.1.3 and for pure normal and shear defined in figure 4.1.4 are shown for the above discussed CEN specimen for the ultimate elastic stage, P = 1.120 N, and for ultimate stage before failure at P = 1.870 N. A big difference between the results of the finite element analysis and the analytical results in figure 4.1.2 and between the elastic and the ultimate stress distributions can be noted. In figure 4.1.6 and 4.1.7 are the shear test specimen of ASTM D-905 and the calculated shear and normal stress at the elastic and ultimate stages shown. In this calculation the same material data input as for the CEN-specimen was used.

A further example relates to analysis of a single finger in a finger joint, figure 4.1.8 and 4.1.9. In figure 4.1.10 is a 2D finite element model of a complete finger joint and the stress distributions along the outermost finger shown in figure 4.1.11 for material data obtained for gluing by a resorcinol adhesive, in figure 4.1.12 for gluing by a PUR and in figure 4.1.13 for gluing by a PVAc.

It is believed that the state-of-the-art with respect to stress distribution calculations for glued wooden joints is represented by non-linear elastic bond line modelling according to equation 4.1-16 together with finite element analysis where the wood is modelled as a 2D or 3D (Serrano, 2000) orthotropic linear elastic material. The calculations presented in this reference were carried out by a so-called smeared implementation of the model and also extended to a 3D modelling taking into account both of the out-of-plane bond line shear deformations.

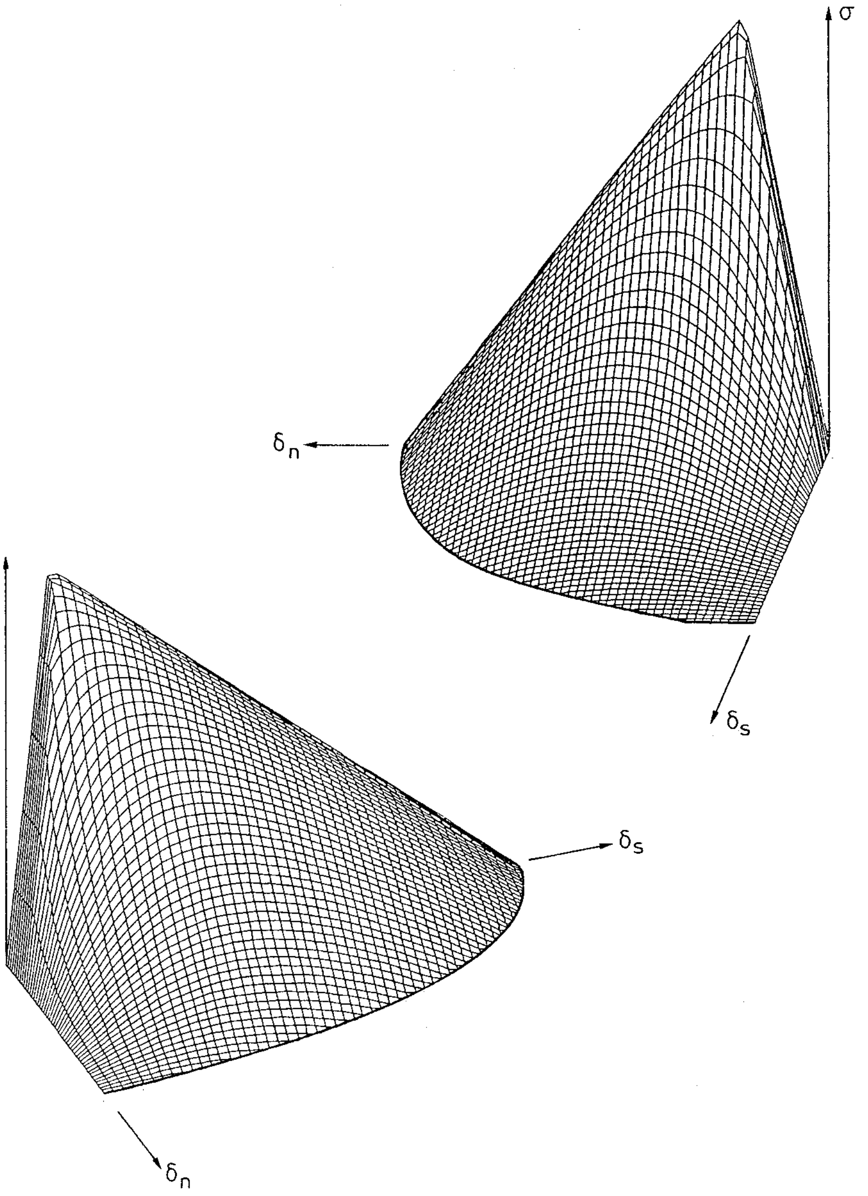


Figure 4.1.3: Bond line constitutive model.

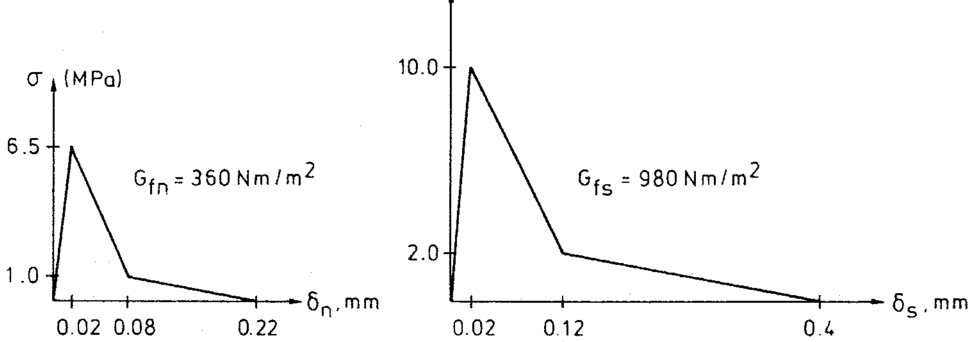


Figure 4.1.4: Bond line model represented by three-linear curves in pure normal and shear states of deformation.

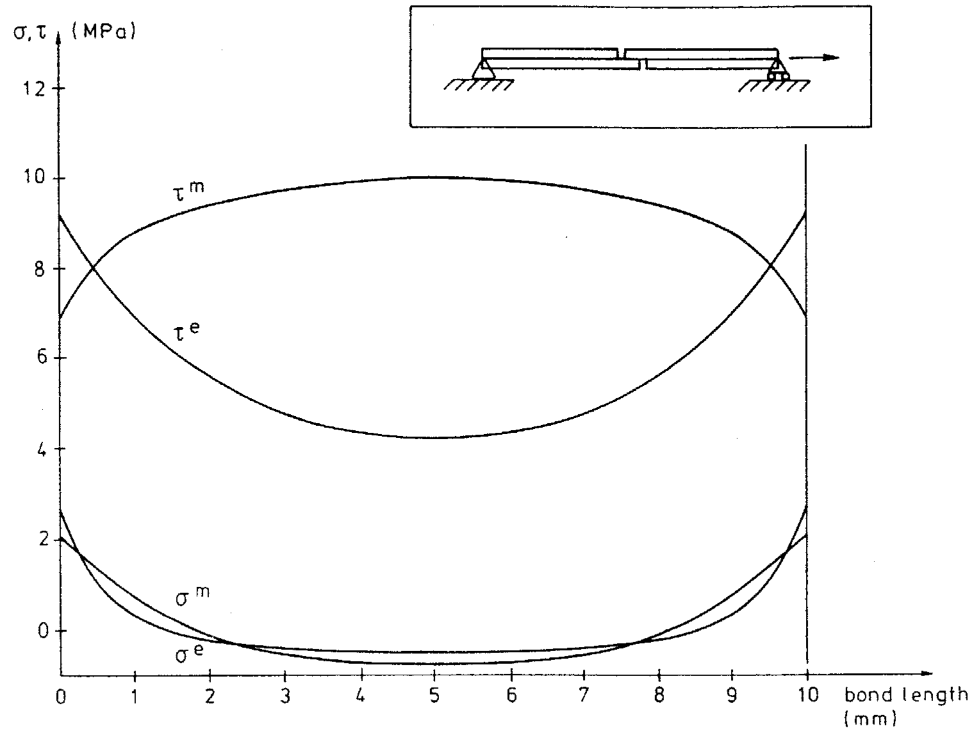


Figure 4.1.5: Normal and shear stress distribution in the CEN-prEN302 specimen at load 1.120 N (elastic) and 1.870 N (ultimate).

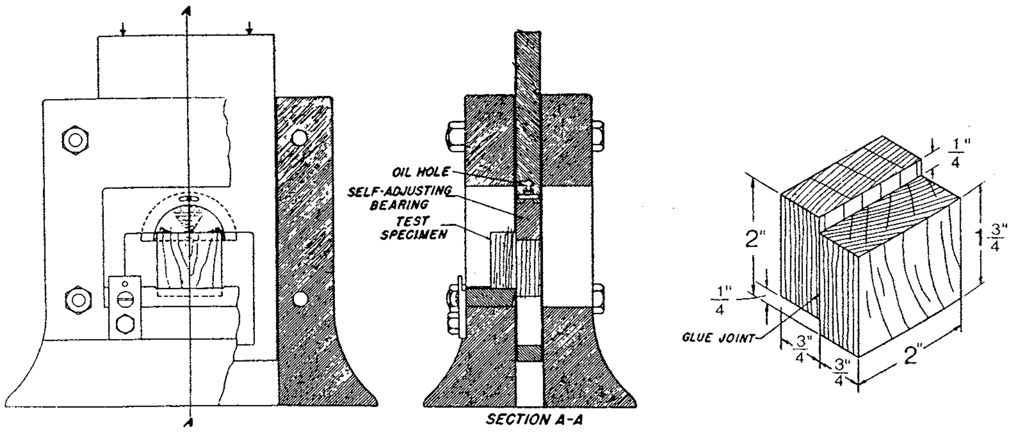


Figure 4.1.6: ASTM D-905 shear test configuration.

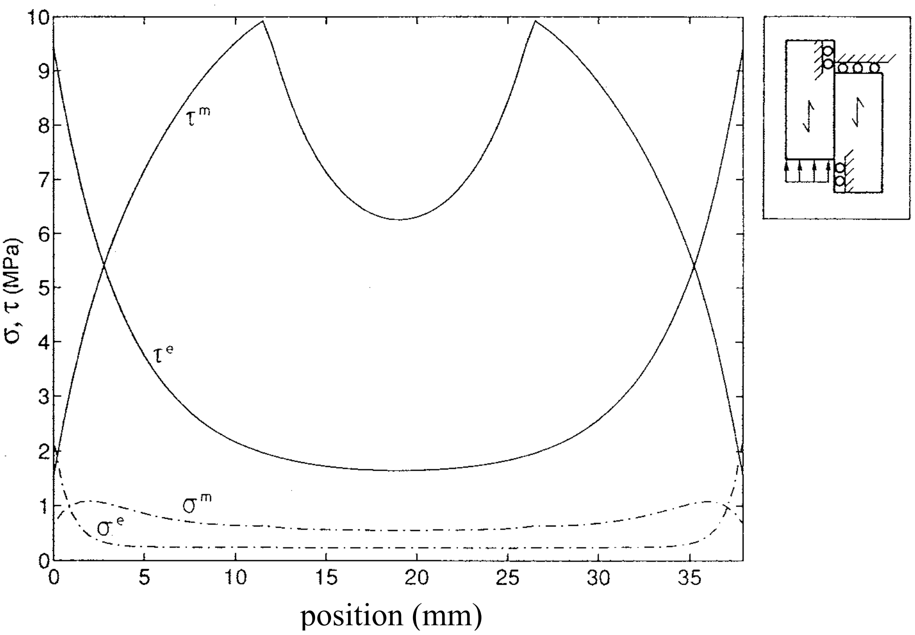


Figure 4.1.7: Stress distributions along the bond line of the ASTM D-905 shear test configuration.

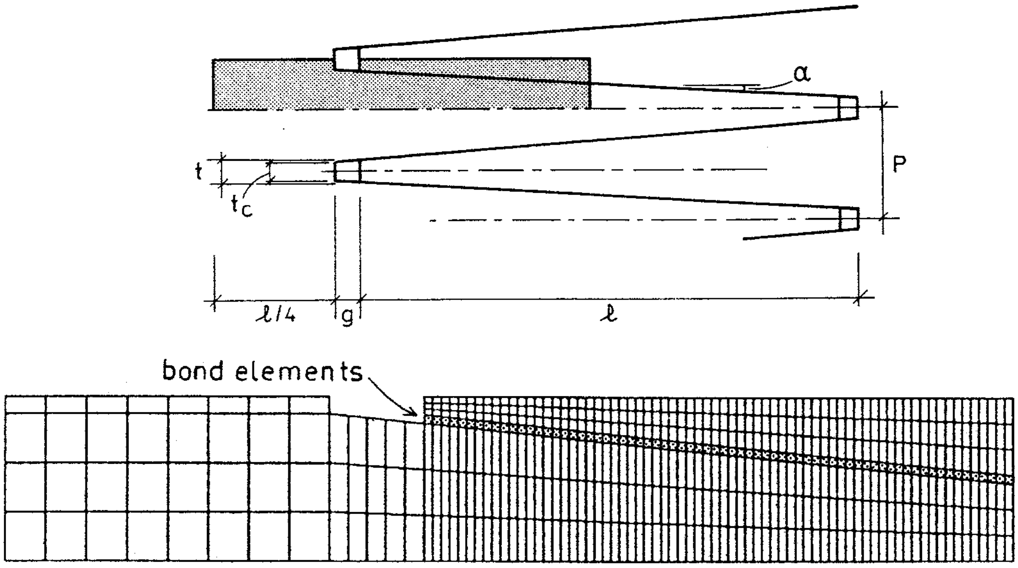


Figure 4.1.8: Finite element model of polar-symmetric half of a finger in a finger joint.

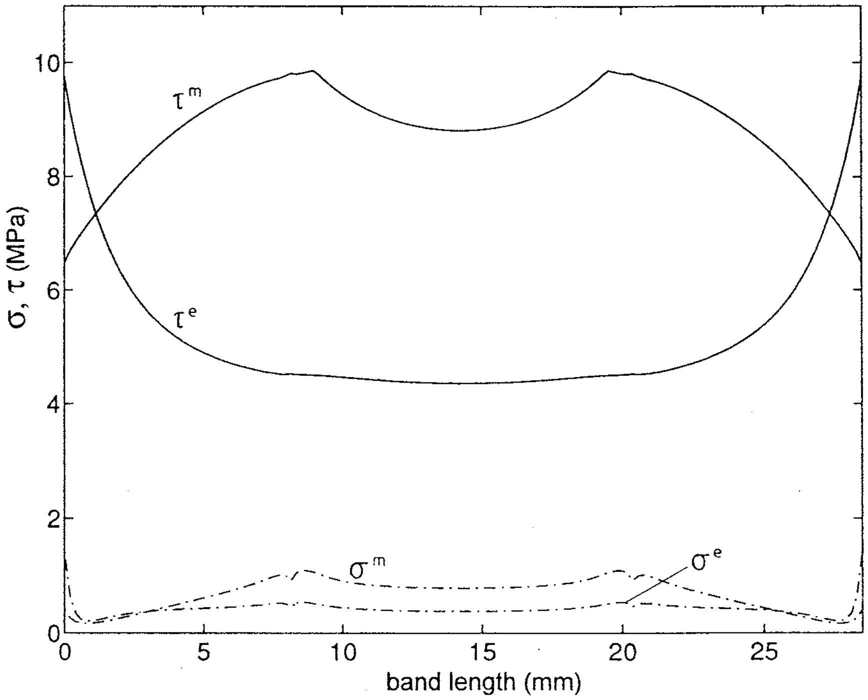


Figure 4.1.9: Stress distribution along bond as calculated by the FE-model in figure 4.1.10. Finger geometry is I30, i.e. l = 30 mm, p = 6,2 mm, tc = 0,6 mm and g = 1,5 mm.

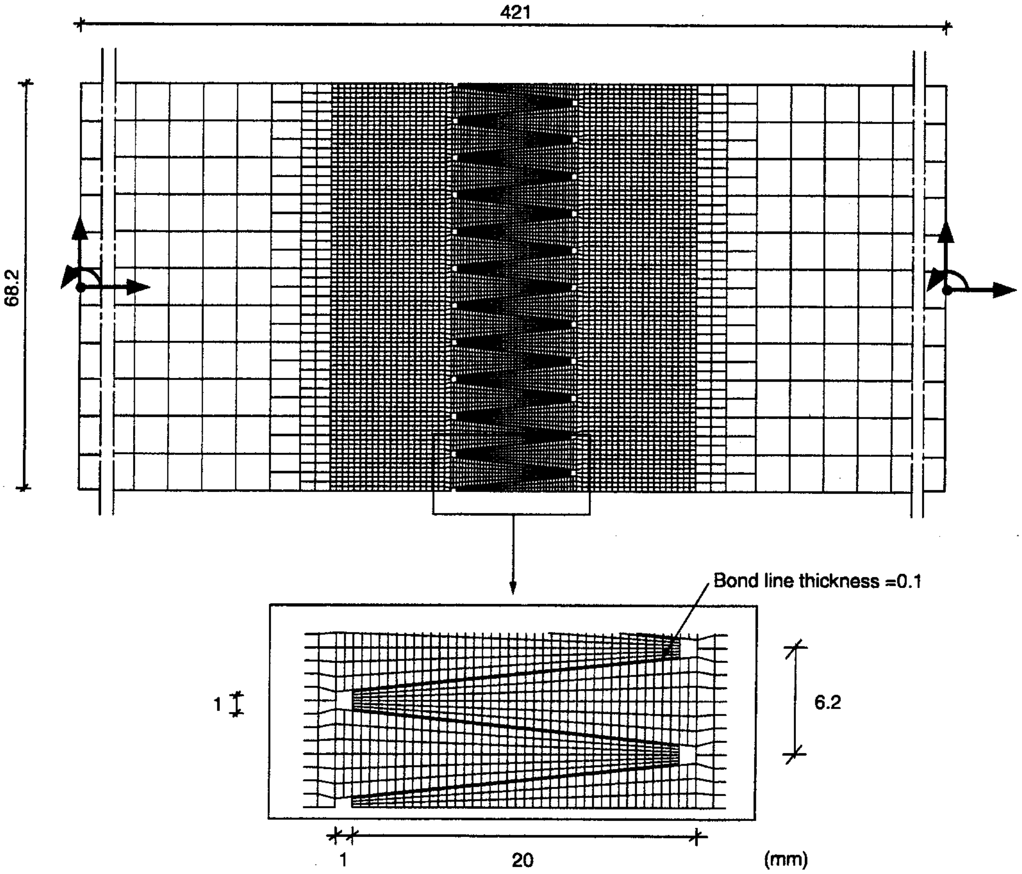
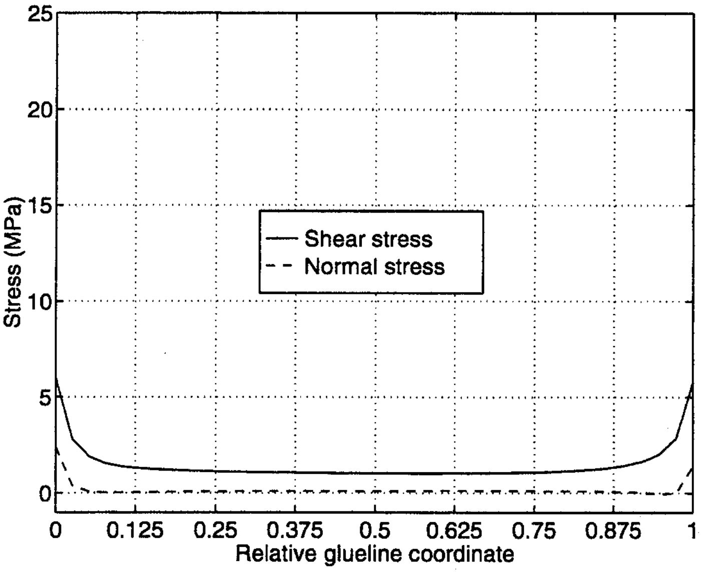
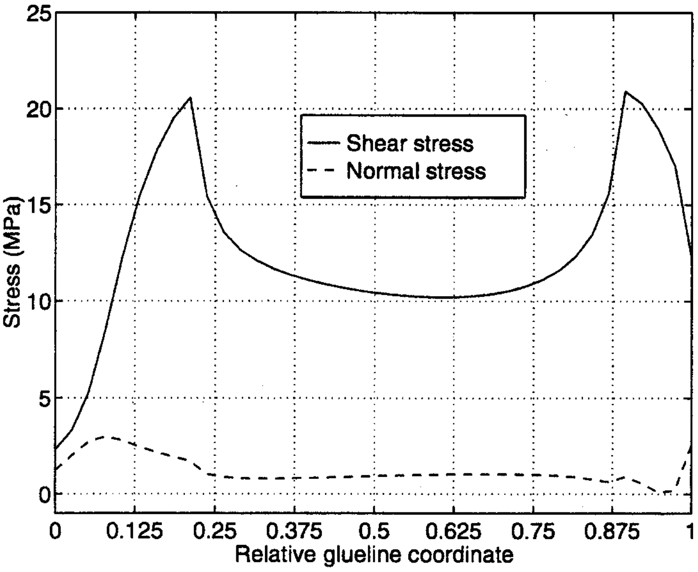
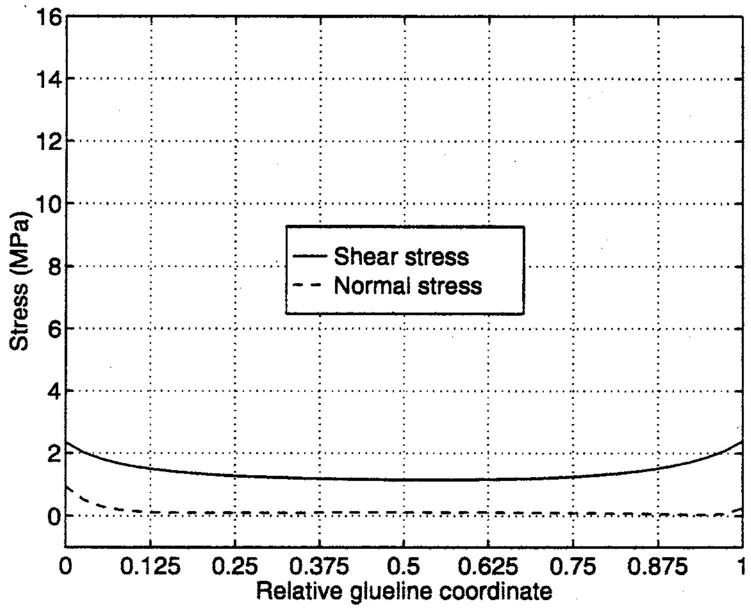


Figure 4.1.10: Finite element model of a finger joint.

Figure 4.1.11: Elastic and ultimate stress distribution in outer finger in finger joint shown in figure 4.1.10 and glued with a resorcinol adhesive.







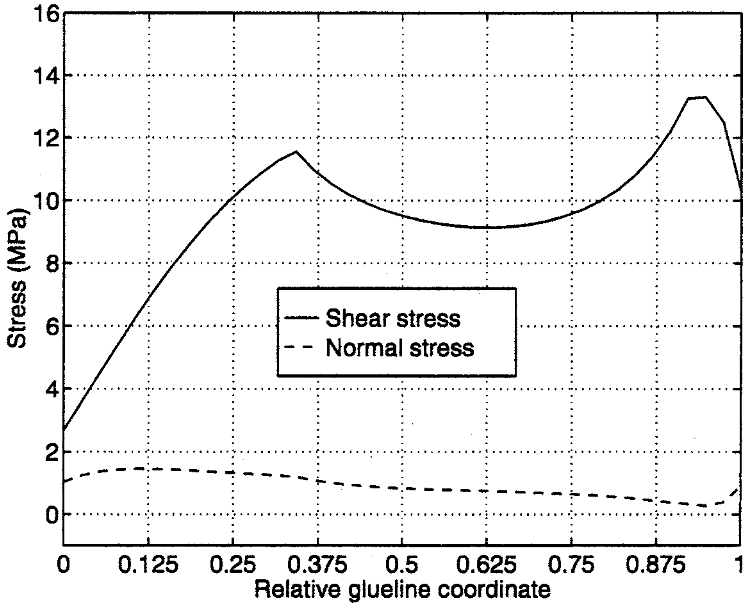
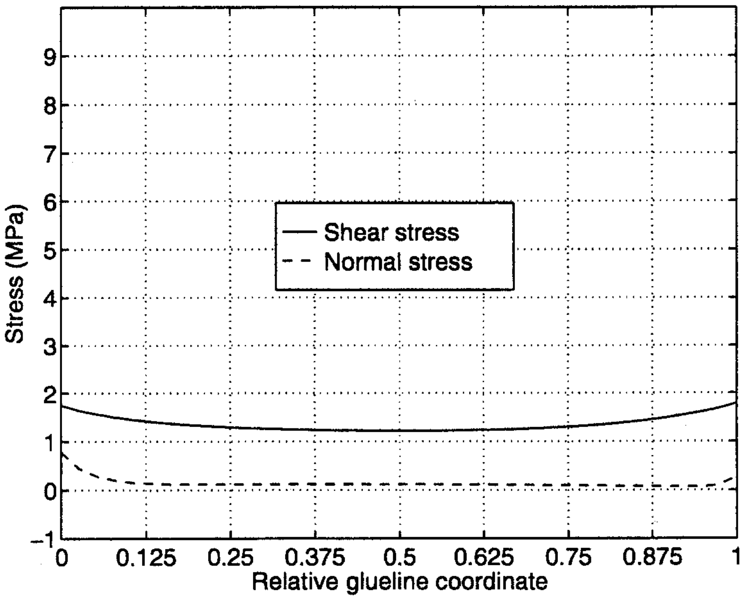


Figure 4.1.12: Elastic and ultimate stress distribution in outer finger in finger joint shown in figure 4.1.10 and glued with polyurethane adhesive.



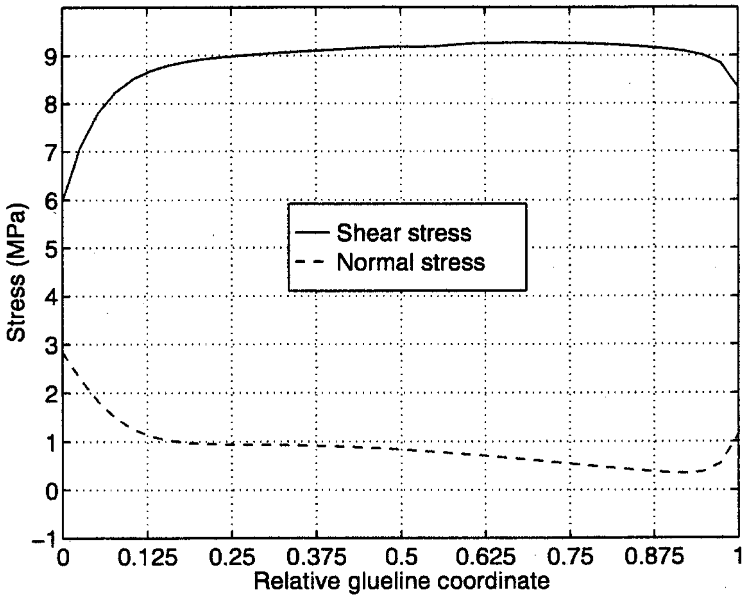


Figure 4.1.13: Elastic and ultimate stress distribution in outer finger in finger joint shown in figure 4.1.10 and glued with a PVAc adhesive

4.1.3 Joint Strength Analysis

The strength of joints can be studied by tests, by semi-empical equations or by rational theoretical analysis. Here only theoretical methods shall be discussed. For theoretical analysis the properties of the wood and the bond line must be defined in terms of some model or assumption with respect to constitutive properties and also with respect to failure criterion unless fracture modelling is a part of the constitutive model. The non-linear elastic bond line model of the kind represented by figure

4.1.3 includes definition of limit deformations and the gradually decreasing stress as the deformation increases. This makes it possible to obtain the joint strength as the peak load found during non-linear analysis for increasing joint deformation. In such case there is no need for a separate failure criterion. In other cases, in particular including the common case of linear elastic stress analysis a failure criterion is needed.

Failure criteria applied to bond lines include criteria in terms of

- The state of stress in a point
- The state of strain or deformation in a point
- The stress intensity factor at a stress singularity
- The J-integral at a stress singularity
- The energy release rate during crack propagation

Within these groups various criteria have been proposed for application to bond lines or to adhesives regarded as a bulk material. An example of a stress-based criterion (Raghava, Cadell and Yeh, 1975) proposed for polymeric adhesives is

$$\sigma_R = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2+2(R_c-R_T)(\sigma_1+\sigma_2+\sigma_3)} \qquad 4.1\text{-}18$$

where σ_i are the principal stresses and σ_R , R_c and R_T are material parameters. A stress criterion applied wood joints is:

$$\tau_f = \tau_{yx} \qquad 4.1\text{-}19$$

where τ_f is the bond line shear strength. For wooden joints the bond line is often such that failure takes place in the wood along the bond line. Because of this, criteria as for wood have been used for bond lines. Thus the Hankinson formula

$$\tau_f = \frac{f_0 f_{90}}{f_0 \sin^2\alpha + f_{90}\cos^2\alpha} \qquad 4.1\text{-}20$$

was used in (Glos and Horstman, 1989) for prediction of the shear strength for bond line shear stress at an angel in between longitudinal shear and rolling shear. The equation was used as apart of a semi-empirical formula and the shear stress was defined as the average shear stress for the entire bond area.

A deformation based yield criterion (Wernersson, 1994) applied to bond lines in wood is:

$$\left(\frac{\delta_y}{\delta_{yf}}\right)^m + \left(\frac{\delta_{yx}}{\delta_{yxf}}\right)^n = 1{,}0 \qquad 4.1\text{-}21$$

Where m, n, δ_{yf} δ_{yxf} are material parameters.

Application of elastic fracture mechanics stress intensity analysis to strength analysis of joint was presented in (Leicester, 1973) and (Walsh, 1974). The stress singularities at the end of a butt joint and at the end of an overlap joint were analysed. Although stress intensity analysis of glued wooden joints are mentioned also in more recent papers (Bryant, Hunt, Shi and Ferguson, 1998) it appears that application of stress intensity analysis has not gained much interest in recent years.

Strength analysis according to the crack propagation energy balance equation of Griffith

$$\frac{dW}{b\,da} = G_c \qquad 4.1\text{-}22$$

gives for pure tension and pure shear, i.e. for fracture mode 1, 2 and 3, the same result as the stress intensity analysis. dW is energy release or the decrease of potential energy during an extension of the fracture area by bda and G_c is the critical energy release, which is regarded as an material property parameter for the mode of fracture under consideration. It is not known whether equation

4.1-21 has been applied to the strength analysis of glued wooden joints. The J-integral approach for analysis of the strength at a linear elastic stress singularity is basically the same as 4.1-21 and that approach has in a recent paper been applied to the performance of the bond at the tip of a finger in a finger joint (Bui and Milner, 1998).

A quasi-non-linear fracture mechanics strength analysis method was presented in (Gustafsson, 1987). Here the linear elastic stress analysis and the stress based strength of equation 4.1-18 were used, the difference from conventional analysis being that the elastic stiffness of the bond line was assigned a value such that the energy dissipation predicted by the elastic-brittle analysis equals the fracture energy G_f of the bond line:

$$G_f = \frac{1}{2}\tau_f \delta_f = \frac{t\tau_f^2}{2G} \qquad 4.1\text{-}23$$

giving the effective or energy-equivalent value of the bond line shear stiffness as

$$G = t\tau_f^2 / (2G_f) \qquad 4.1\text{-}24$$

The shear stress versus shear slip properties correspond to this shear stiffness is shown as curve I in figure 4.1.14. The result of application to single lap joint strength prediction is shown in figure 4.1.14. For long and slender joints, having a strong stress concentration at the ends of the joint, the results obtained coincide with those of linear elastic fracture mechanics, equation 4.1-22, and for short joints with stiff adherends, resulting in constant stress along the bond line, the same result as by the assumption ideal plastic performance of the bond line is obtained. Figure 4.1.14 also shows the strength predictions as obtained by other assumptions regarding the shape of the bond line shear stress deformation curve. A method for analytical stress analysis at the assumption of bi-linear shapes of the stress-slip curve is presented in (Ottosen, Olsson, 1988).

Figures 4.1.15 - 4.1.19 illustrates by application to a heel lap joint pretty much state-of-the-art for rational glued wood joint strength analysis. The test results are from (Glos and Horstman, 1989) and the analysis from (Gustafsson and Serrano, 1998). The results obtained by the finite element method are valid for a material model of the kind represented by equations 4.1-17 and figures 4.1.3 and 4.1.4, and quantified by figure 4.1.16. The results denoted 1D-theory are obtained by equation 4.1-19, with $\tau_f = 3{,}85$ MPa, having made the stress analysis by equation 4.1-15 with G according to equation 4.1-24, with $G_f = 800$ J/m². It can be noted that the bond line thickness t does not affect the strength analysis.

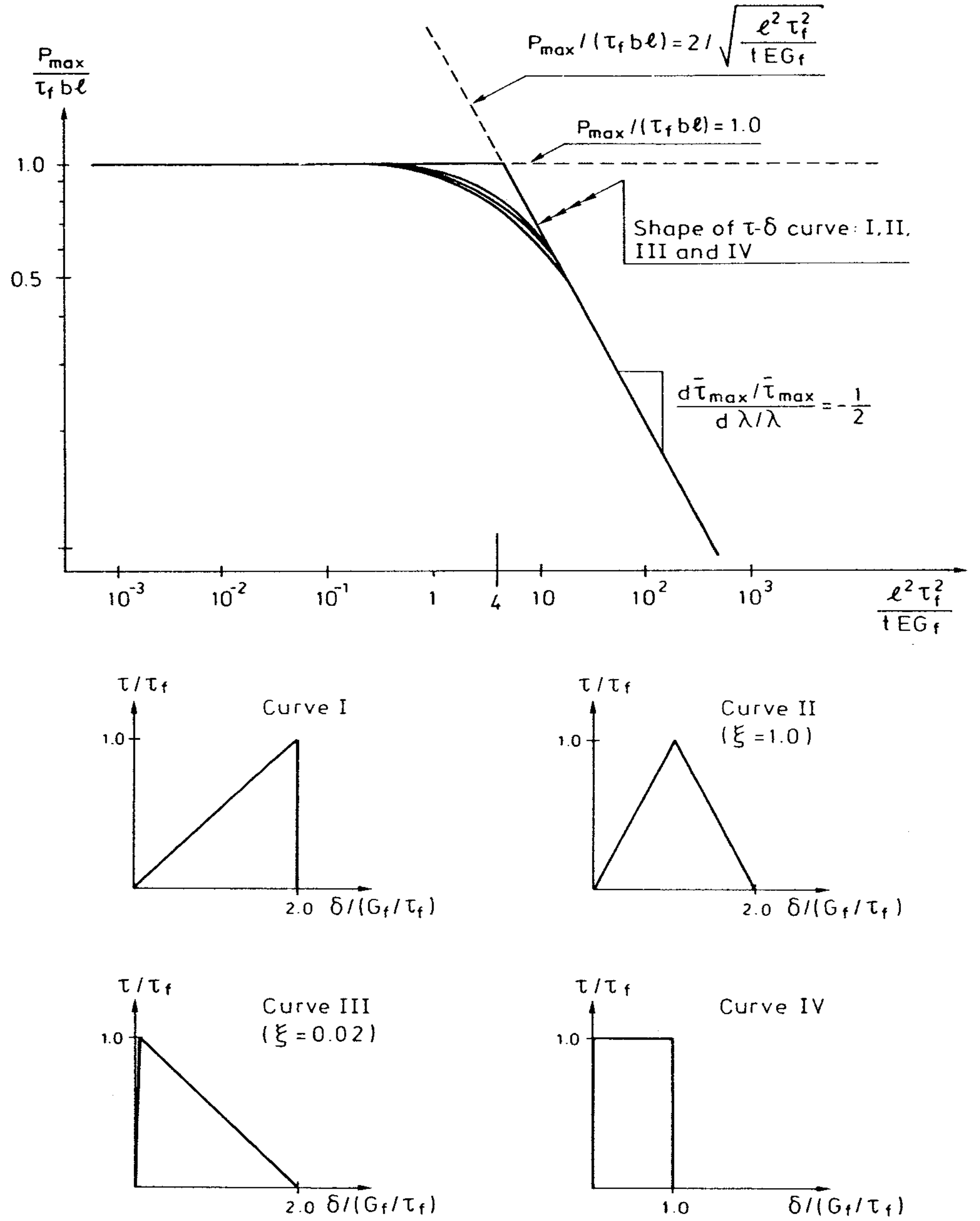


Figure 4.1.14: Upper: Predicted strength of single lap joint. *Note:* in this figure t is the adherend thickness, not the bond line thickness. The bond length and width is l and b, respectively. Lower: Shear stress deformation properties of bond line

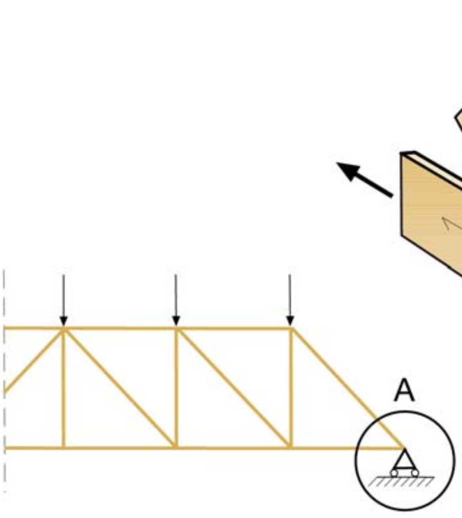


Figure 4.1.15: Part of a truss and a glued truss heal joint.

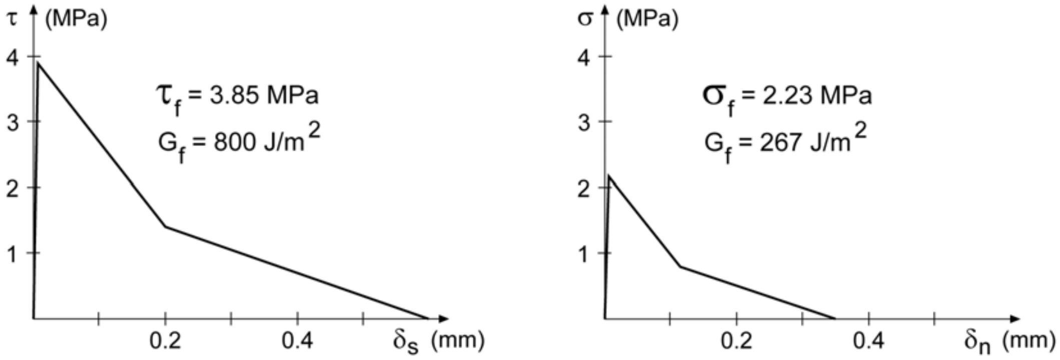


Figure 4.1.16: Bond line properties at pure shear at pure tension.

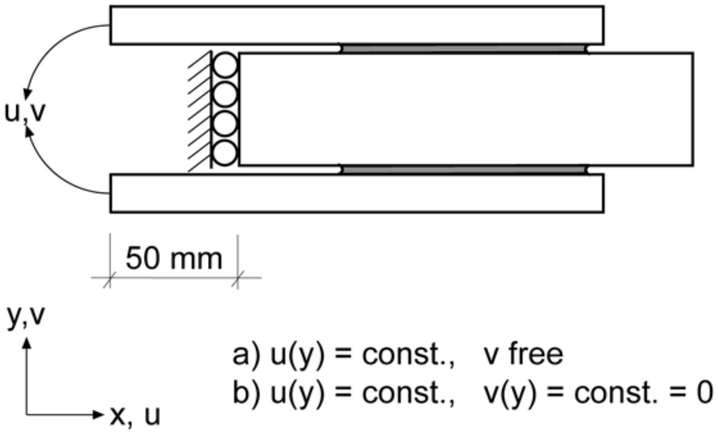


Figure 4.1.17: Details of boundary conditions studied at finite element analysis.

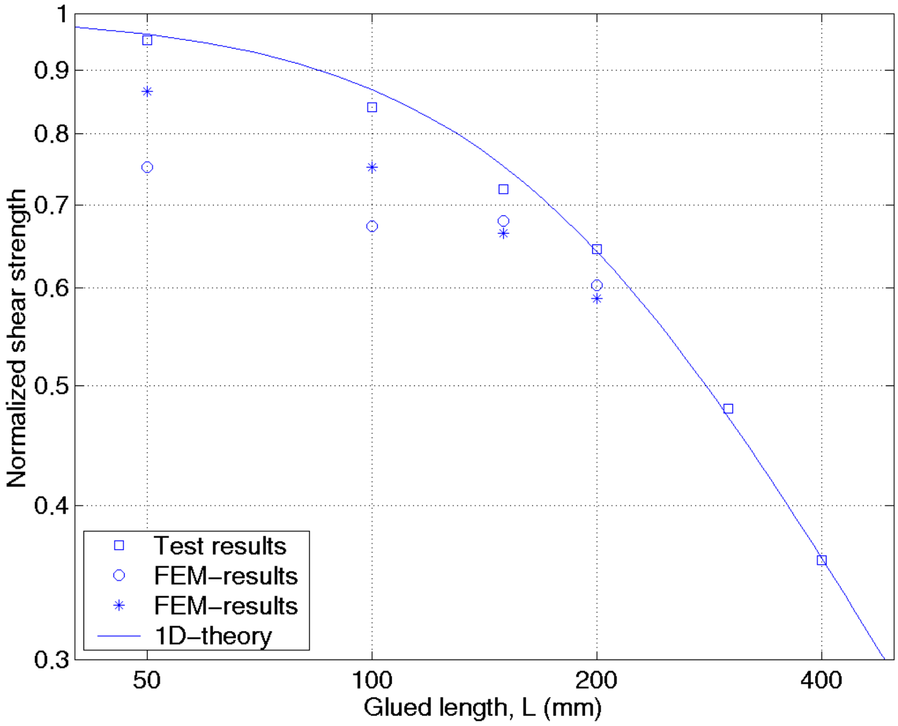


Figure 4.1.18: Normalised joint strength, Pf/(2bl), versus length of glued area. The FE-results are for boundary conditions a and b as shown in figure 4.1.17.

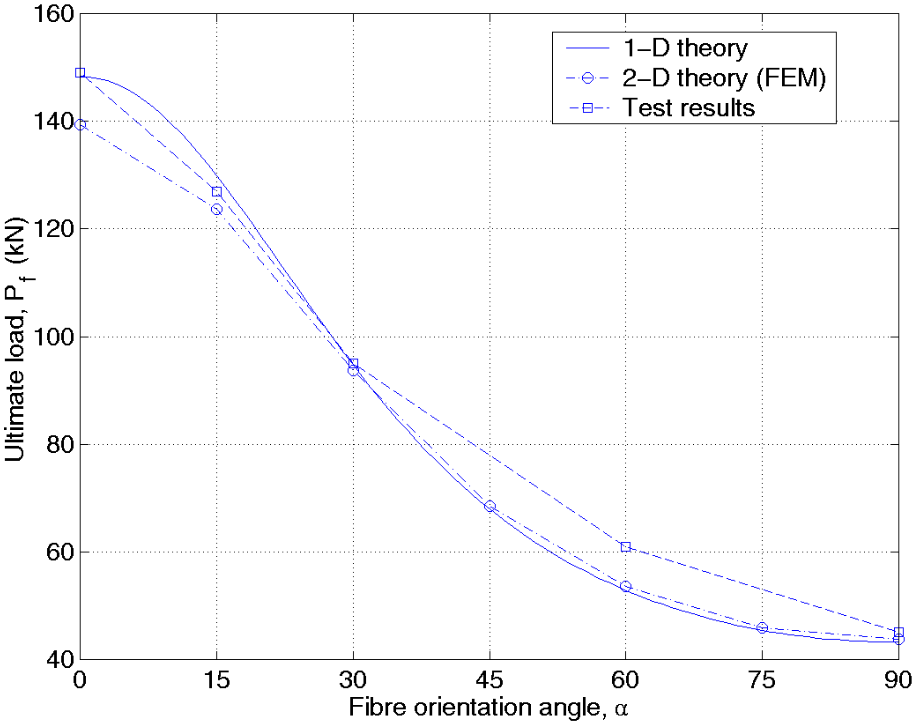


Figure 4.1.19: Joint strength versus fibre orientation angle, corresponding to the truss heel joint angle.

4.1.4 Research Needs

The goal is accurate and rational strength and deformation analysis of glued wooden joints. For this good modelling of the adherend, i.e. the wood, and good modelling of the bond line are needed.

- Research on constitutive modelling of wood, taking into account annual ring and fibre orientations, development of eigen-stresses due to moisture effects, time dependent stress redistribution, etc should be pursued and completed in view of application to joint analysis. This research is needed for accurate calculation of the stresses that act on the bond.
- The adhesives used are often strong and stiff, making the strength and fracture properties of the wood decisive. Accordingly, better knowledge about the strength and fracture properties of wood would improve the possibilities for accurate joint strength analysis. This relates in particular to the modelling of strength and fracture mechanics properties at fracture perpendicular to grain.
- The present state-of-the-art for glued wooden joints bond line modelling is essentially non-linear elastic fracture modelling. This means that influence of rate and duration the load, influence of unloading-reloading and of stress path is not taken into account. Obviously there is a need for methods for modelling of viscosity and plasticity and/or damage. Moreover, in almost all of contemporary wood bond line models only one or two of the six stress and strain or deformation components are considered. There is accordingly a good potential for more advanced and accurate bond line modelling.
- The bond properties are not constant from one unit bond area to the next, and neither from one joint to the next. Efforts should be made to include these non-deterministic features into rational modelling since they are of importance for size effects and at reliability analysis.
- In some cases knowledge and modelling of the strength and fracture properties of the bond line are sufficient, while in other cases the bond line deformations are significant and give a stress redistribution that has to be considered. Research should be conducted in order to find out then modelling without consideration to bond line deformation is sufficient. In the same way it should be found out when the quasi-non-linear kind of linear elastic fracture modelling is sufficient.
- Loading of a bond line is not only due to the external useful loads, but also due to structural constraints and climatic variations. The bond line stresses due to moisture and temperature gradients and variations may be very large. This kind of internal loading should be investigated and it might very well be found relevant to consider this loading in strength design calculations.

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4.2 Glued-In Rods

Charlotte Bengtsson

Glued-in rods have been used during a number of years in several of the European countries, which are active in timber engineering. They are economically, architecturally and industrially attractive means of transferring forces within a structure and of providing local reinforcement to critical zones of timber members. They also provide an important technology for the repair and upgrading of historically important timber structures, which exist throughout Europe. Not withstanding their importance, internationally accepted design rules for glued-in rods do not exist. This section presents the main findings within the EU-project “Glued-in rods for timber structures” (GIROD). The project started in February 1998 and ended in March 2001. The description of the project is based on summaries written by the different partners in the project: Swedish National Testing and Research Institute (SP, coordinator), University of Lund (Sweden), TRADA Technology Ltd (UK), University of Karlsruhe (Germany) and FMPA in Stuttgart (Germany). Additionally, glulam- and adhesive producers from Sweden and Germany participated in the project. The main structure of the project is given below:

Within the GIROD-project the work ha been focused on rods glued-in with three different adhesive types: two-component epoxy (EP), two-component polyurethane (PUR) and phenol-resorcinol-formaldehyde (PRF). Mainly steel rods were used within the project but also some fiber reinforced plastic rods (FRP) were tested.

The description of the GIROD-project given here is based on the project structure given below.

4.2.1 Development of a Calculation Model

4.2.1.1. Proposal of an Engineering Formula

This work was performed by the University of Lund, Sweden. The objective was to establish a calculation model for the basic pull-out strength, that can be used as a basis for establishing design rules for glued-in rods and for creating a better understanding of the mechanical behaviour of glued-in rods. The work was organised in four parts:

1. Theoretical work on models for stress and strength analysis
2. Bond line tests of mechanical properties
3. Full scale joint test for calibration and verification
4. Verification of model and design equation proposal

The main aim was to propose a strength design method which fulfilled the following requirements:

- The method should be both general and simple, preferably just one or a few explicit equations.
- The equations should have a rational theoretical and physical basis.
- The method should give reasonably accurate strength predictions, on the average, and in general give predictions on the safe side.

The combined Volkersen-Fracture mechanics theory was used as a basis. The pull-out strength according this theory is determined by the geometry of the joint and by two bond line and material property parameters. It is proposed that these two parameters are determined by testing the pull-out strength of two sets of full-scale joints with different geometry (length and/or diameter) and loaded in “pull-compression”. Given the two material parameters, the equation for the “pull-compression” loading is used also for “pull-pull”. This gives a single and simple design equation, which according to theory gives “exact” predictions for the pull-compression loading and predictions on the safe side for pull-pull loading. For definition of the two loading modes see Figure 1a.

The above proposal is intended for adhesives that produce a tight contact to the rod. For adhesives with no bond to the rod and significant shrinkage (i.e. the PRF tested) no equation that fulfils the above basic goals has yet been found. For such adhesives it is proposed that testing is made as for the common adhesives, but no design equation is proposed, only a design rule saying that the load bearing capacity of joints with greater or equal rod diameter, greater or equal length, and greater or equal wood density may be assigned the same load bearing capacity as the tested joint.

For the loading case pull-compression:

$$\frac{P_f}{\pi d l} = \tau_f \frac{\tanh \varpi}{\varpi} \quad \text{where} \quad \varpi = \sqrt{\frac{l_{geo}}{l_m}} \qquad 4.2\text{-}1$$

where l_{geo} is a length parameter defined by the geometry of the joint and the rod to wood ratio for modulus of elasticity:

$$l_{geo} = \frac{\pi\, d l^2}{2} \left(\frac{1}{A_r} + \frac{E_r / E_w}{A_w} \right) \qquad 4.2\text{-}2$$

and l_m is a material property length parameter, which can be expressed as:

$$l_m = \frac{E_r G_f}{\tau_f^2} \qquad 4.2\text{-}3$$

The ratio E_r/E_w can be estimated in an approximate manner. The two parameters to be determined from tests are then τ_f and l_m. (It is thus no necessary to separate l_m into E_r, G_f and τ_f, although this in general is simple since E_r in general is known).

For a square shaped cross section with a centric location of the rod A_w is taken as a^2, where a is the side length of the square. For other geometry $A_w = a^2$, where $a/2$ is the shortest distance from the center of the rod to an edge of the cross section. This shortest edge distance, $a/2$, may not be less than a distance determined in the project described in section 4.2.2, presumably $4d_r$. $P_f/(\pi dl)$ for arbitrary inclination, α, of the rod relative to grain may be determined by interpolation between the results for rods along the grain and perpendicular to the grain according to the Hankinson equation. The two material parameters must be determined for both rod to grain orientations.

Table 4.2.1: Test results for determination of material property parameters τ_f and l_m

Adhesive	d	l	a	l_{geo}	Failure load, P_f	$P_f/(\pi d\ l)$	τ_f	l_m	G_f [(1)] Nmm/mm^2
	mm	mm	mm	mm	kN	N/mm^2	N/mm^2	mm	
EPOXY	16	160	115	4070	62.61	7.79	10.5	3600	1.89
	16	320	115	16300	77.36	4.81			
PRF	16	160	115	4070	63.83	7.94	8.9	11000	4.15
	16	320	115	16300	98.43	6.12			
PUR	16	160	115	4070	58.98	7.33	9.7	3960	1.77
	16	320	115	16300	74.09	4.61			

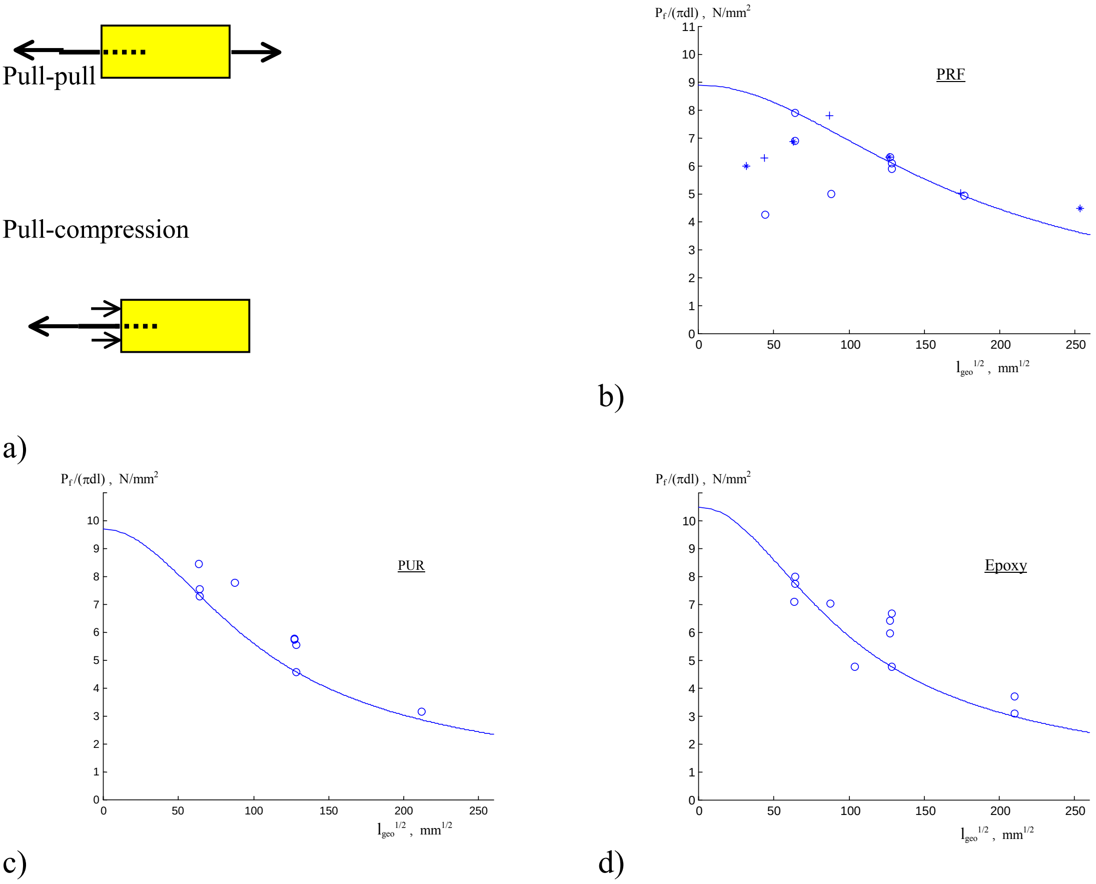
[(1)] G_f calculated from l_m with the assumption E_r=205000 N/mm^2.

Test results for the pull-out strength at pull-compression loading are presented by Johansson (1999). The parameters τ_f and l_m (and G_f) were determined from these test results for the three adhesives investigated by use of the method described above. This evaluation is indicated in Table 4.2.1. The tests refer to loading along the grain and the ratio E_r/E_w was therefore set equal to 18.

The material combinations for which the material parameters were determined have been tested for several other joints, with other geometry and other type of loading. In Figures 4.4.1 b-d the design equation compared with those other test results are shown. Each mark in the diagrams represents mean values obtained from series with 6-10 tests in each series. The diagrams include tests carried out at SP with pull-pull loading and pull-compression loading. The diagrams also include tests made at FMPA with pull-pull loading of joints of varying size and shape. Both the results of timber in strength class C35 and three series with timber in strength class C24 are included. For epoxy and

PUR, additionally, three previous series are included, see Aicher et al. (1999) and Gustafsson and Serrano (2001).

For the PRF the test results do not comply with the theoretical curve, but the diagram also shows a scattered picture, indicating that $P_f/(\pi dl)$ may hardly be described as a function of l_{geo}. The results found for PUR and epoxy are more appealing: the design equation gives reasonable predictions and the predictions are in most cases on the safe side.



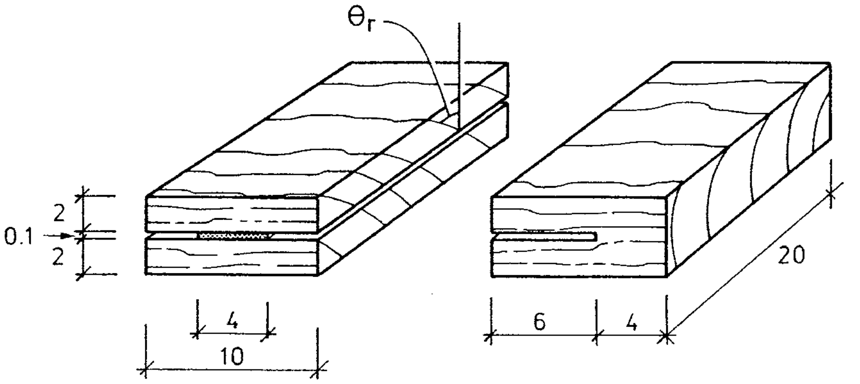


Figure 4.2.1: (a) Definition of loading modes. $P_f/(\pi dl)$, N/mm^2, versus square root of l_{geo}, $l_{geo}^{1/2}$, mm$^{1/2}$, for (Figures from Gustafsson and Serrano 2001.) – (b) PRF – (c) PUR – (d) EP

The different results found for the three adhesives are most probably related to the different ways in which the bondlines act. For PUR and epoxy there can be tensile stress (and very small deformation) in the critical region normal to the bond area. For the PRF there may be compressive stress (and significant deformation) normal to the bond area.

Above one single design proposal has been discussed. Possible modifications giving alternative, yet similar, proposals include:

- No consideration of grain to rod angle. Testing and all design made as for parallel orientation.
- No consideration of different loading conditions (pull-pull, pull-compression, pull perp. to beam). Testing and all design made as for pull-pull equation 4.2.1 replaced by the corresponding equation for pull-pull.

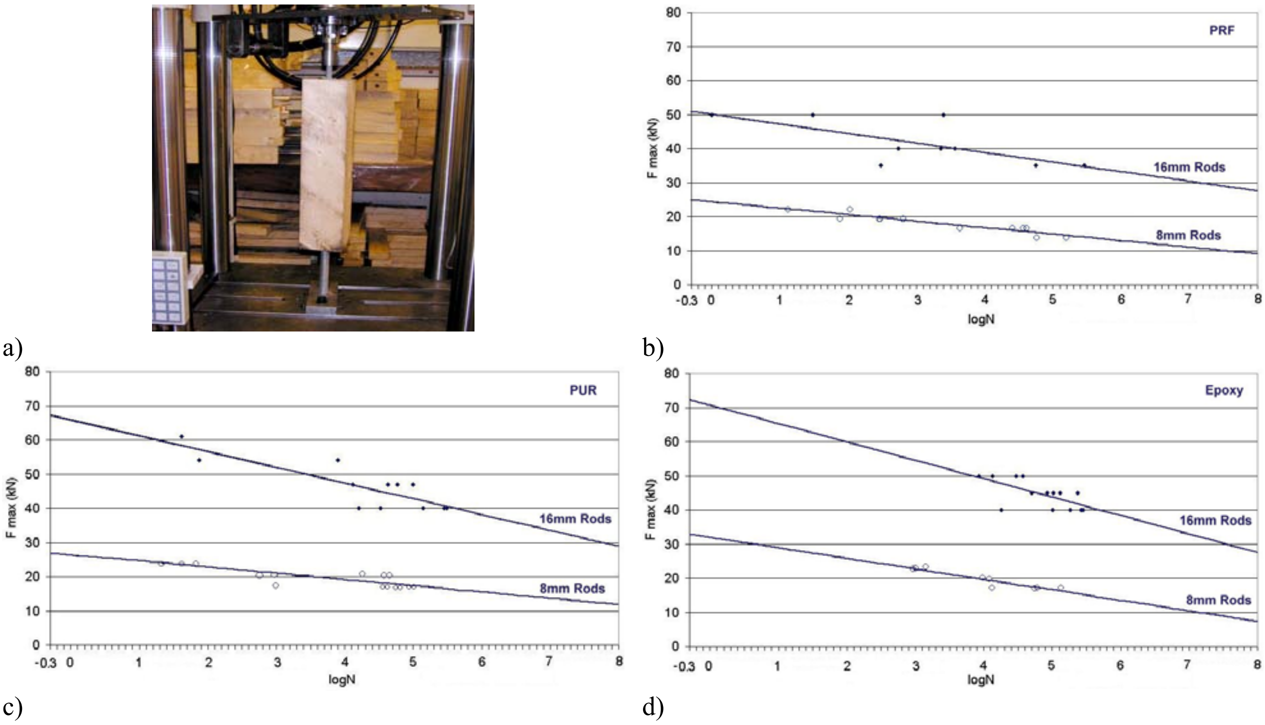
4.2.1.2. Effect of Fatigue

This work was performed by TRADA Technology Ltd, UK. In the future, glued-in rods will be common in timber bridges, where fatigue may be a significant issue. The objective was to give an indication of whether or not the fatigue behaviour of glued-in rods may limit their use in certain applications, for instance in bridges. Bonded-in steel rod specimens were exposed to low frequency (approximately 1 Hz) cyclic tension fatigue ($R = 0,1$) at fixed stress rates. The test configuration is shown in Figure 4.2.2a. Four distinct failure modes were observed through the tests: rod failure, failure in the adhesive (causing breakdown of the material in the bond-line itself), failure in the wood substrate and failure at the interface between timber and adhesive. The majority of the fatigue failure modes are relatively consistent with static test observations. From the results, it is apparent that fatigue does have the potential to cause damage in bonded-in rods, and that there is sufficient variation in failure modes to confirm that failure may be due to damage in any of the component materials (steel rod, adhesive or timber substrate) or breakdown of the timber to adhesive bond interface. The data obtained from the tests at $R = 0,1$ (i.e. maximum tensile load = 10 x minimum tensile load) is presented in the form of cycles to failure versus load in Figures 4.2.2b-d. It must be noted that observations and projected fatigue lives presented herein must be taken in the context of extrapolations based upon a limited data set, lacking confirmatory data at high numbers of load cycle ($>10^6$).

The work performed has demonstrated that fatigue performance is a significant factor in the performance of bonded-in rods and recommendations are made as to how further work, beyond the scope of GIROD, could improve understanding and design treatment of the fatigue behaviour of these types of connection. In relation to the stated objectives of the study, the experimental study has indicated that the fatigue behaviour of glued-in rods may limit their use in certain applications.

Some key conclusions that can be drawn from this limited experimental study are:

- The majority of fatigue failure modes were common to those observed in static test counterparts to the fatigue test specimens. Significant incidents of alternative failure modes were however also recorded, especially failures in the steel rods.
- It is apparent that different adhesive types behave in fundamentally different ways with respect to the fatigue performance and the eventual mode of failure at the fatigue ultimate limit state.
- Both the geometry of the test specimens and the adhesive type are important under the conditions of this test, but the general order of performance across the adhesive types was found to be consistent between specimen sets.
- The scope for further work to enhance the knowledge and design methods employed is very large.



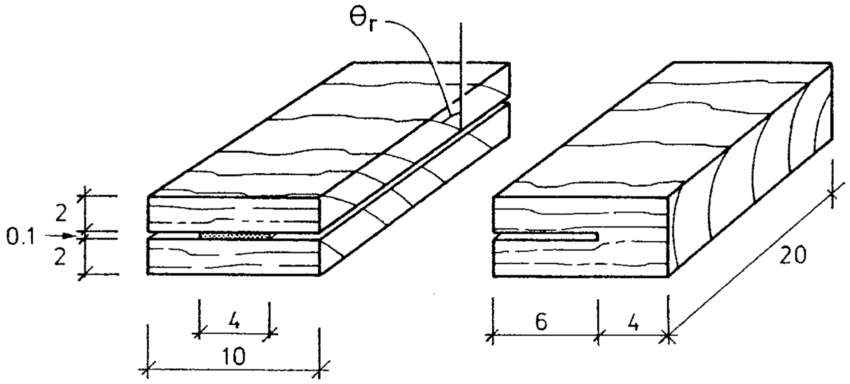


Figure 4.2.2: (a) Test configuration for fatigue tests – (b) Cycles to failure versus load for PRF-bonded specimens – (c) Cycles to failure versus load for PUR-bonded specimens – (d) Cycles to failure versus load for EP-bonded specimens - (Figures from Bainbridge and Mettem 2001)

A full description of failure mode-related fatigue performance basis of design would require further experimentation. To determine the full relationship with geometry and to verify the influence of R ratio and frequency upon the application of design methods based upon the observations drawn from the test set would be key to development of such development.

The results from this part of the work were presented thoroughly by Bainbridge et al. (2000) and Bainbridge and Mettem (2001).

4.2.1.3. Effect of Rod Spacing and Edge Distances

This work was performed by University of Karlsruhe, Germany. The objective of the work was to study and to quantify the effect of the spacing between rods and the distance to the timber edges on the axial and lateral load-carrying capacity. Tests were performed with rods glued-in parallel and perpendicular to the grain. The loading was axially as well as laterally. Furthermore, some theoretical investigations were carried out to describe the behaviour of glued-in rods depending on spacings and distances of rods.

Examples of results are: For rods glued-in parallel to the grain and loaded axially a rod-to-edge distance of 2,5 times the rod diameter and a spacing of 5 times the rod diameter is suggested. For rods glued-in perpendicular to the grain and loaded axially the load-carrying capacity decreased with increasing height of the beam or a descending ratio of the glued-in length to the height of the beam.

A part of this work was presented thoroughly by Blaß and Laskewitz (1999).

4.2.1.4. Effect of Varying Temperature and Moisture Conditions

This work was performed by FMPA in Stuttgart, Germany, University of Lund, Sweden and TRADA Technology Ltd, UK. Duration of load (DOL) tests on full-sized glued-in rod specimens were performed in different climates. An investigation concerning to what extent the axial strength of glued-in rods are affected by storage in constant and variable outdoor climates was also performed.

Storage in different variable sheltered outdoor climates without mechanical loading had very little effect on the residual strength in case of PRF. For PUR a strength loss of approximately 20% was obtained and for EP the residual strength increased with about 12%. Comparison was made to the residual strength after storage at 20°/65% RH. Storage of specimens at a constant elevated relative humidity of 85% delivered a drop in residual strength of 20% for PRF-bonded specimens.

Figure 4.2.3 summarises the DOL test results for full-sized glued-in rods carried out within the GIROD-project. The Madison curve is given as a reference curve. Also the time spans for load duration classes according to EC 5 are indicated in Figure 4.2.3. The EP-bonded specimens at 85% RH followed the Madison curve. At 50°C specially the PUR- but also the EP-bonded specimens displayed a strength drop with respect to time. This is mainly due to the thermo-mechanical properties of these adhesives.

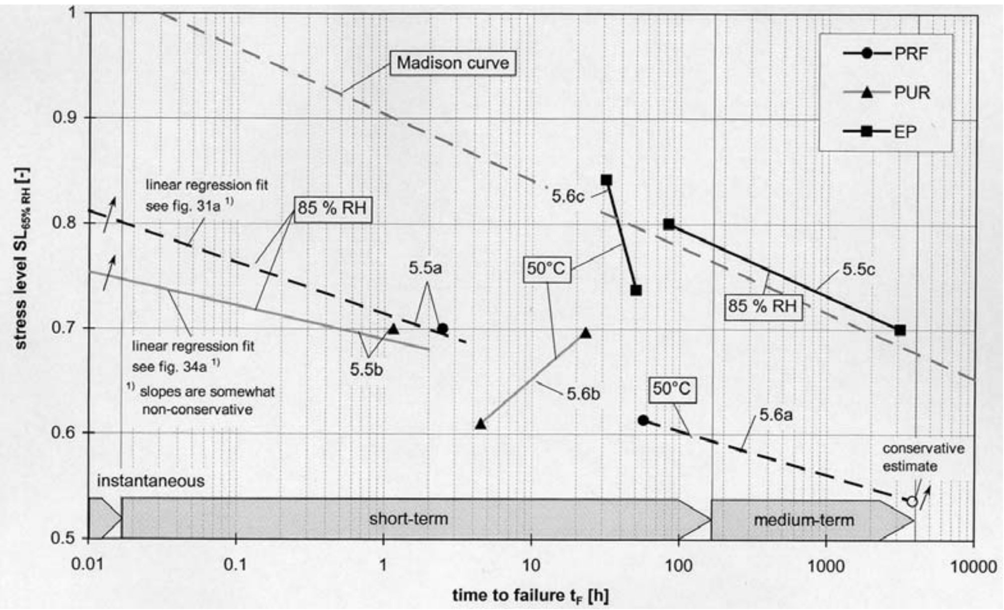


Figure 4.2.3: DOL behaviour of PRF-, PUR- and EP-bonded specimens with axially loaded glued-in threaded rods denoted by stress level (SL) versus time to failure (tf) in wet or warm climate conditions. All stress levels are related to results obtained in ramp loading at 20°C/65% RH. (Figure from Aicher 2001.)

An attempt was also made to derive k_{mod} values accounting for strength degradation with respect to load duration and service class. These results can be found in Aicher (2001).

4.2.1.5. Design Rules for Eurocode 5

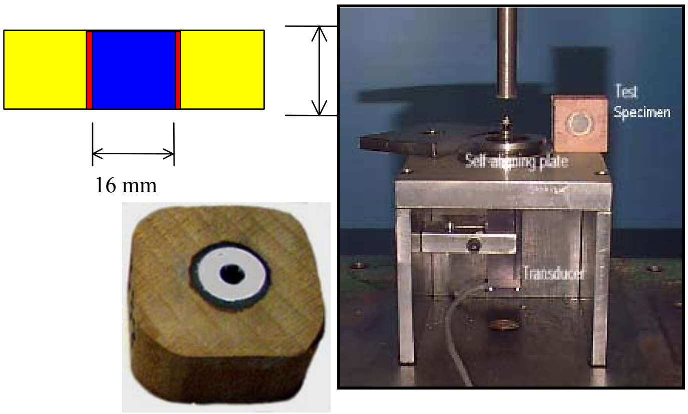
This work was performed by TRADA Technology Ltd, UK. The objective was to elaborate a proposal for design rules for glued-in rods based on the proposed calculation model, taking into account the information gained concerning influence of fatigue, rod spacing, time, temperature and moisture conditions.

The results of this part of the work are a guidance document style set of design rules drawn from the GIROD project and a condensed set of concise design rules more suited to consideration for incorporation in the body of EC5.

4.2.2 Development of Test Methods for Adhesives

This work was performed by SP Swedish National Testing and Research Institute, Sweden. The objective was to develop test methods to evaluate the durability and the creep-rupture properties of adhesives for glued-in rods.

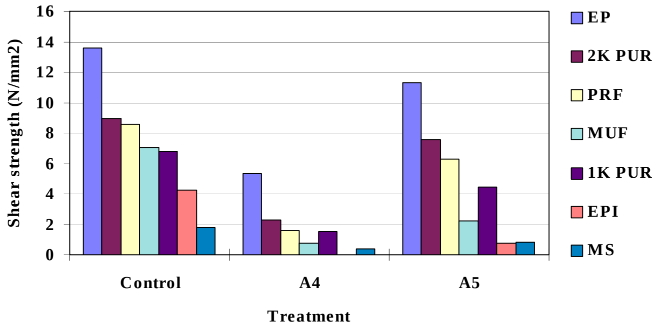
A possible test method for strength and durability of the adhesive for glued-in rods was developed. The suggested method consists of 40 x 40 x 20 mm beech blocks with glued-in 16 mm threaded rods which are tested in compression after different treatments (treatments A4 and A5 according to EN 302). The specimen and the test set-up are shown in figure 4.2.4.



a) b)

Figure 4.2.4 (a) The test specimen – (b) Test set-up for loading in compression – (Figures from Bengtsson and Johansson 2001.)

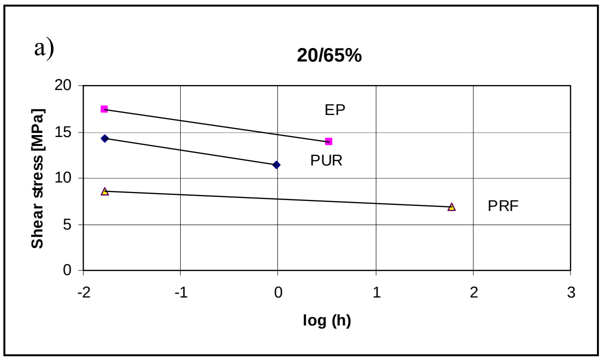
Figure 4.2.5: Shear strength (tested in compression). The shown values are average values of ten specimens in each group. (Figure from Bengtsson and Johansson 2001.)

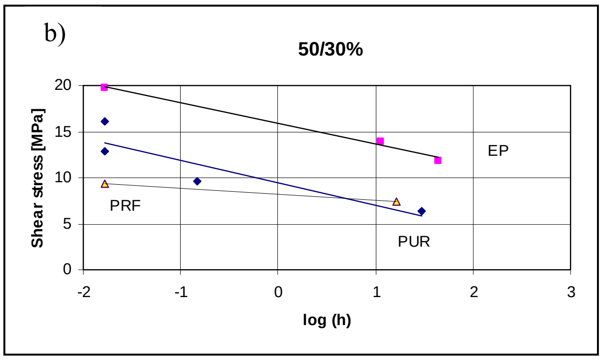


To the three adhesives mainly studied within the GIROD-project, EP, PUR and PRF, four other adhesives were added. These were: melamine-urea-formaldehyde (MUF), one component polyurethane (1K PUR), emulsion-polymer-isocyanate (EPI) and a modified silyl-epoxy (MS). In this way, the suggested test method was applied for a large spectrum of adhesives with differing mechanical and durability properties. For each treatment and adhesive ten specimens were tested, which gave a total amount of 210 specimens.

If present shear strength test results, obtained with the suggested method, are compared with the requirements according to EN 301 (classification of phenolic and aminoplastic adhesives for load bearing timber) only the EP-bonded connections pass. The shear strength values are shown in figure 4.2.5. However, comparison with the requirements according to EN 301 can be questionable as the suggested test specimens are very different from standard specimens prescribed in EN 301. As expected, cooking and testing in the wet state lead to very low shear strength of the glued connection. Bonding steel to wood puts extra strong requirements on the adhesive bond line as the wood swells while the steel rod is rigid.

Figure 4.2.6: Creep-rupture testing device. (Figure from Bengtsson and Johansson 2001.)





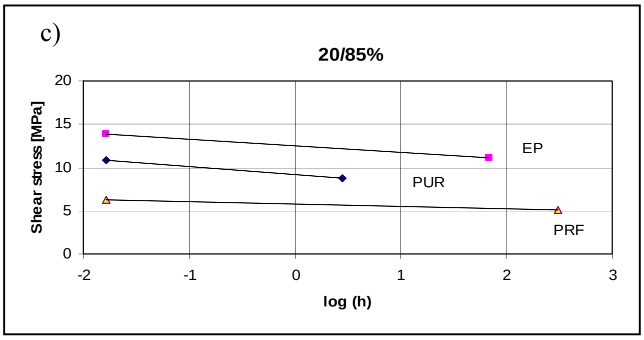


Figure 4.2.7: Shear stress versus median time (hours) to failure in logarithmic scale for the three tested adhesives (Figures from Bengtsson and Johansson 2001.) – (a) 20°C/65% relative humidity – (b) 20°C/85% relative humidity – (c) 50°C/30% relative humidity

A test method for creep-rupture testing of small glued-in rod specimens was also developed. The method is based on ASTM D 4680, see Figure 4.2.6. The specimens for this test method are of the same type as for the strength and durability tests. Three load levels, 40%, 60% and 80% of the ultimate load, in three climates, 20°C/65% RH, 20°C/85% RH and 50°C/30% are studied. The three adhesives tested are very different. It therefore seems preferable to focus the evaluation of the test results on the absolute shear stress capacity instead of a stress level. The shear stress capacities versus median time to failure (median of ten specimens) for the specimens tested at the time of writing in all three climates are shown in Figure 4.2.7.

In some cases comparison was made between the behaviour of small glued-in rod specimens and the behaviour of full-sized glued-in rod connections. These comparisons require further evaluation as the relationships are not simple.

Background for this part of the work can be found in Bengtsson and Johansson (2001).

4.2.3 Development of Production Control Test Methods

This work was performed by SP Swedish National Testing and Research Institute, Sweden. The objective of the work was to develop test methods which enable reliable and simple testing of glued-in rods for timber structures during production. The method/methods should be capable of revealing serious production errors, e.g. insufficient adhesive application, insufficient hardening, and other gluing errors. Two alternative test methods for full-sized glued-in rod connections have been studied: one destructive method and one proof-loading method.

Due to simplicity when testing it was decided to use a newly developed test method for testing glued-in rod connections. The method is a one-sided pull-out test (pull-compression). This method is suitable for production control. Four different proof-load levels, 50%, 65%, 80% and 90% of the short-term strength, were tested to try to find the maximum load that does not cause structural damage of the bond line. Specimens bonded with epoxy, on the average, reached higher pull-out loads after proof-loading until 80% and 90% than the specimens tested destructively. None of the tested groups of specimens displayed a decrease in pull-out strength after proof-loading to such high levels as 80% and 90%. The groups of specimens proof-loaded to 65% displayed a decreased pull-out strength. The reason for this behaviour was not explained within the present study.

Error detection was possible for coarse errors by proof-loading up to the 80% level. The induced errors in the present study were sometimes extreme errors. The selection of 80% as a suitable proof-load level is, however, still uncertain and must be further evaluated.

Generally, no relationship between the density of the wood surrounding the glued-in rod and the pull-out strength was found. This fact was also reported by others in the project and it needs to be further investigated.

The variation of the glue line thickness led to increasing pull-out loads for larger glue line thicknesses in case of EP and PUR, whereas for the PRF, which shrunk, the load-bearing capacity decreased.

As the destructive testing is done on specially produced test specimens, representative for a certain batch, the tests do not determine the reliability of the actual junction.

More details about this part of the work can be found in Bengtsson and Johansson (2000).

4.2.4 Conclusions

- A calculation model based on a combination of Volkersen theory and fracture mechanics gives good prediction of the pull-out strength for adhesives that bond to the rod such as PUR and EP. The pull-out strength is controlled by two material property parameters that can be easily determined in full-scaled pull-compression tests.
- Fatigue is a significant factor in the performance of glued-in rods and needs to be considered in applications like for instance bridges. Failure can occur in the rod, in the adhesive bond line, in the wood substrate and in the interface between wood and adhesive.
- The effect of rod spacing and edge distances have been clearly demonstrated and proposals to be used in design have been made.
- Storage without mechanical loading in variable outdoor climates had a strength reducing effect mainly on PUR-bonded rods. After storage in 85% RH the PRF-bonded rods were most affected.
- Glued-in rods have a DOL behaviour that can differ quite considerably from that of timber and other timber connections. In 85% RH the behaviour of EP-bonded rods behaved like the Madison curve while PRF and PUR had much shorter time to failure. At 50°C the PRF behaved in a better way than PUR and EP.
- It is questionable if the method developed for evaluation of the durability of adhesives for glued-in rods is suitable for the purpose. PRF, which is known to give very durable wood-to-wood bonding, obtains extremely low strength values after testing in wet conditions. It seems that the method punishes adhesives that do not bond to the rod.
- The creep-rupture test method developed for small specimens works well. The creep-rupture behaviour of small specimens compared to this behaviour for full-sized specimens will be further investigated.
- A simple production control test method based on proof-loading has been developed. It is able of detecting a number of serious production errors.

4.2.5 Acknowledgement

This research is sponsored by the European Commission (DG XII) through grant nr SMT 4-CT97-2199. SP also got a grant from NUTEK (Swedish National Board for Industrial and Technical Development). The financial support is gratefully acknowledged.

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4.3 Finger Joints

E. Aasheim

4.3.1 General

The finger jointing process consists of crosscutting, finger cutting, glue application, pressing and hardening. In general, the production equipment must be able to produce precise and even profiles.

This chapter deals mainly with finger jointing of structural timber, but finger joints are also used for other applications like interior and exterior trim, windows and doors, and sidings.

4.3.2 Geometry

The finger joint profile is characterised by the four parameters as shown in figure 4.3.1, the finger length, the pitch, the tip width and the tip gap. For shorter finger lengths (less than 15 mm) the gap is normally zero.

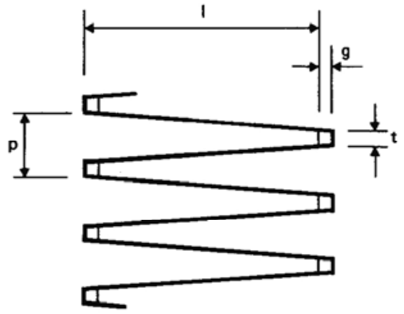

Figure 4.3.1: Finger joint geometry (l = finger length; p = pitch; t = tip width; g = gap)

The strength is increasing by decreasing tip width. In principle, the reduction of effective area is equal to the tip width multiplied by the number of fingertips. By choice of finger profile one should take into account that longer fingers allow larger tip widths, and are consequently less sensitive to cutting precision. The longer the fingers, the larger material loss. The longer the pitch, the larger the number of fingers and usually more expensive finger cutters.

The relative glue area (A) describes the glue surface in proportion to the cross section that shall be jointed. Simplified this may be expressed as:

$$A = 2 \times \frac{l}{p - t}$$

The cross section reduction (R) shows how much of the load bearing cross section that is reduced by the finger tips:

$$R(\%) = 100 \times t/p$$

Typical geometry:

l	p	t	R	A
10	3,8	0,6	15,8	6,3
15	3,8	0,5	13,2	9,1
20	6,2	1,0	16,1	7,7
30	6,2	0,6	10,7	9,7

For jointing of higher strength classes the parameters should preferably be:

- A: 9 – 10
- R less than 10%

4.3.3 Finger Cutting

By using blunt steel cutters the finger profiles will be rough and splintery. This is especially a problem when the moisture content in the timber is high. If one or more finger cutters must be grinded, it is important to grind the whole finger cutter set to secure that all the fingers have the same profile.

At lower moisture contents the timber is more brittle, and this can have a negative influence on the surface quality of the fingers.

A precise clamping system is also important for the cutting quality.

4.3.4 Finger Orientation

The fingers might be visible on the flat side or on the edge side of the jointed timber, see figure 4.3.2. Basically the two finger orientations should show the same strength, but experience shows that fingers visible on the flat side normally result in somewhat higher and less variable strength properties. One of the reasons for this is that fingers visible on the edge side result in fewer fingers and a high proportion of outermost fingers. The outermost fingers are sometimes a problem, adequate gluing is not always the case. If the thickness (shorter side) of the jointed pieces is small, fingers visible on the flat side are recommended.

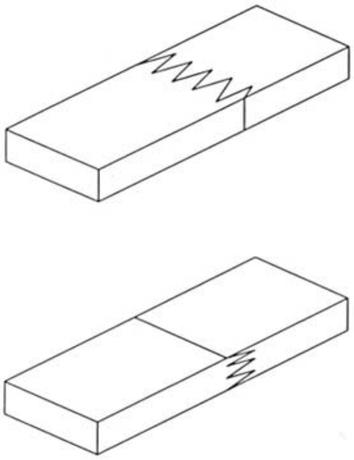

Figure 4.3.2: Finger orientation

4.3.5 Moisture Content

High moisture content might cause diluted glue, and this means reduced strength properties. The maximum moisture content is 23% for the most common glues, but normally the moisture content should be between 8% and 18%. Too low moisture content (below 8%) will result in reduced strength due to poor bonding between glue and wood.

4.3.6 Gluing

For finger jointing of structural timber the following glues are normally used in Europe:

- Phenol-resorcinol-formaldehyde (PRF)
- Melamine-urea-formaldehyde (MUF)
- Melamine-formaldehyde (MF)
- Polyurethane (PUR)

The majority of the glue systems consist of two components, and these must be mixed in the correct mixture ratio. When the glue and the hardener are mixed together, the chemical reaction starts. In the data sheet for the relevant glue important information like storage life, pot life, assembly time, glue amount, etc. is found.

After the finger cutting the glue is applied to the member ends. The application method shall ensure that all finger surfaces in the assembled joint are covered with glue. The glue should be applied to both member ends over a length of at least ¾ of the finger length.

4.3.7 Pressing

For structural finger jointing the following pressures are normally used:

Finger length (mm)	Pressure (N/mm²)
10	12
15	11
20	10
30	8
40	6
50	4

For example, if 10 mm fingers are used, the pressure should be 12 N/mm². With a cross section area of 100 mm × 200 mm, the press must have a capacity of 240 kN.

A finger joint shall normally have a gap after pressing. A control measurement of this gap is a simple way of controlling that correct pressure has been applied.

4.3.8 Hardening

The basic rule is that the glue and the wood shall have a temperature of minimum 20°C. To secure good durability of the joint, heat may be added by means of one of the following alternatives:

- Preheating of the member ends
- Hardening of the glue by high frequency (Hf) heater
- After hardening for 12 hours at 30°C

If Hf heating during pressing is used, the pressure must be reduced accordingly. The target wood temperature should be 60 – 90°C, normally close to the upper limit. Recommended pressures at 90°C are:

Picea abies	6 – 7 N/mm²
Pinus silvestris	7 – 9 N/mm²

This reduction of pressure is due to the reduced compression strength of the wood at these elevated temperatures.

4.3.9 Wood Quality Close to the Finger Joint

The joint will always represent a discontinuity of the wood fibre structure, and this leads to a reduction in strength compared to clear wood without knots. It is very important not to increase this reduction by limiting other strength reducing effects close to the joint. There shall be no knots, fissures or pronounced grain disturbance within the joint itself. Outside the joint the distance between a knot and the end of the crosscut shall be not less than ($l + 3 \times d$), where l is the finger length and d is the knot diameter, see figure 4.3.3.

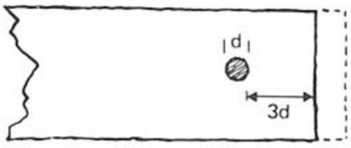

Figure 4.3.3: *Distance between knot and cross-cut*

When a crosscut is used to remove a knot from the joint, the crosscut shall ensure that all grain disturbances are cut away, see figure 4.3.4.

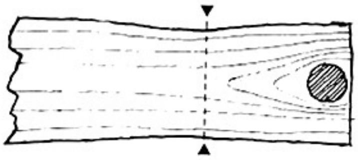

Figure 4.3.4: Removal of knot by crosscutting

There shall be no wane or edge damage affecting more than two corners within the finger length and within 75 mm of the root of the fingers. The area of the wane shall not exceed 1% of the cross section area.

Literature:

EN 301 Adhesives, phenolic and aminoplastic for load-bearing structures – Classification and performance requirements. European Committee for Standardization

EN 385 Finger jointed structural timber – Performance requirements and minimum production requirements. European Committee for Standardization

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4.4 Glued/Screwed Joints/Screw Glued Wooden Structures

Matti Kairi

4.4.1 Introduction

Glulam, finger-jointed products and different types of I-beams are traditional and widely used glued structural building components. In glued joints and screw glued wooden structures it is important to achieve sufficiently thin glue lines. Uniform adhesion and good quality of glue lines are often obtained by using high compression pressures (more than 0,6 MPa) during curing time. This means that heavy and expensive hydraulic pressing devices are needed in process. In contrast, pneumatic and vacuum techniques are cheaper, but lower pressures (0,05 - 0,4 MPa) can be obtained. Mechanical fasteners achieve the lowest and more uneven compression (0,01 – 0,2 MPa).

4.4.1.1. Applications of Screw Gluing Technique

Epoxy glue with nails has been used in constructions where it is not possible to obtain high compression pressure in uneven glue lines. However, it is reasonable to use non-gap-filling glue like polyurethane (PU) adhesive in order to make glue lines as thin as possible. By using screws with a higher compression pressure compared to nails and with an adequate surface smoothness and dimensionally stable material, like Laminated Veneer Lumber (LVL). Economically larger structural wooden components can be produced (figure 4.4.1).

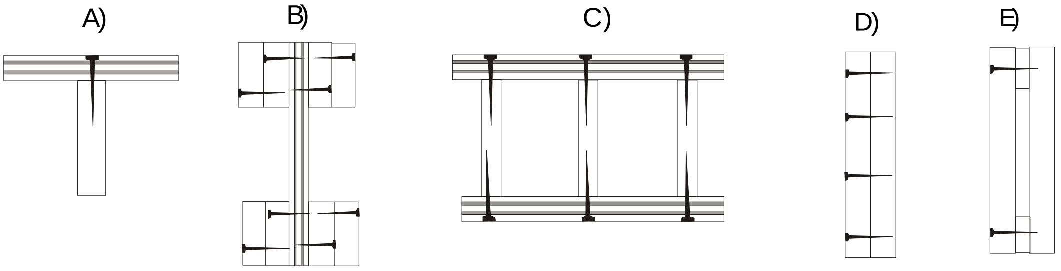

Figure 4.4.1: Examples of screw gluing technique on A) T-beam, B) I-beam, C) ribbed panel (stressed skin panel), D) flatwise glued double–beam and E) box-beam. The wood materials showed are LVL (Other structural composite timber can also be used).

Sibelius Hall in Lahti, Finland, is a pilot project in which structural PU gluing with screw pressing technique is used in LVL balcony elements (Figures 4.4.1c, 4.4.2 and 4.4.3), ceiling elements and wall structures. The balconies have span length of 8,1 m. Those elements utilise the full composite action of the ribs and skin panels. Thus, ribs provide shear resistance and skin panels provide moment resistance.

The top and bottom panels of the balcony element are made of optical grounded Kerto-Q LVL with thickness between 48,0 and 49,5 mm. The ribs, the square stiffeners at the ends and the triangle stiffeners between the ribs are made of 51 mm thick Kerto-S. Kerto-Q is LVL with 20% of the crosswise veneers, whereas Kerto-S is standard LVL. Grain direction of the stiffeners is parallel to span direction of the element. All wooden parts were sawn to desired sizes, optical grounded and the grooves were milled in the machining line of the fabricating hall.

Glued T-joints and triangle stiffeners were connected with Stadler IG 6 × 100 screws. These screws are standardised and the producer has a certificate of the uniform quality. Steel consoles at the ends were also fixed with screws.

Figure 4.4.2: Sibelius Hall, in Lahti, Finland, used PU gluing with screw pressing technique in balcony elements, wall structures and ceiling elements.

Figure 4.4.3: LVL stressed skin panels as balcony elements stored in the construction site.

Resorcinol-formaldehyde (RF) glue has been used in Expo-Dach 2000 in Hanover, Germany (Figures 4.4.4 and 4.4.5). Expo-Dach 2000 comprises 10 umbrella-like canopies. Each of the canopies covers an area 40 × 40 m², and contains three parts; tower, girder and network that were manufactured using structural assembly gluing.

The height of tower is 18 m. Four wooden columns in each tower (leg) were braced with triangulated box-beams made of glulam flanges and Kerto-Q webs. Kerto-Q board's thickness is 33 mm (Figure 4.4.1E). The components were connected with steel plates and dowels.

Four cantilever girders made of box-beams (Figure 4.4.1E) situate at the top of tower. Each girder consists of two box-beams, which are connected and braced with screw gluing to each other with Kerto-Q webs.

The network structure of the roof was manufactured with assembly gluing in the construction site. The network structure was made of sawn timber and Kerto-S-lamellas that were glued together (Figure 4.4.1D). The Kerto-S lamellas were settled to the most demanding parts of the roof structure, where the tension and compression loads are the most critical. The lamellas are full-length lamellas without finger joints.

Figure 4.4.4: The leg and large girders are assembled from two box-beams. The lenght of the girder is 18.6 m.

Figure 4.4.5: The assembly of the box-beams of girder. The flanges are made of glulam and two Kerto-Q boards thickness of 33 mm are screw glued both sides of flanges. The upper flange is straight and the lower one is curved

4.4.1.2. Structural Wood Adhesives

The most important wood adhesives for load bearing structures are phenol- (PF), urea- (UF), melamine-urea- (MUF) and resorcinol-formaldehyde (RF). Also casein glues belong to this family. These adhesives are standardised in EN 301 (Viitaniemi et al. 1997).

In addition, there are four types of adhesives that are considered as potential structural wood adhesives: epoxy adhesives, one- and two-component polyurethanes (PU) and emulsion polymer isocyanates (EPI). Within these four types there are brands for very different properties, but there is no short-term approval test to identify the suitable brands (Raknes, 1995).

One-component polyurethane glue, Collano's Purbond HB 110, has been accepted as structural adhesive by German authorities. The glue line is required to be kept under 0,3 mm thick, but no demands for the pressure are defined. The core problem is the pressure and in turn, how the PU glue line is kept under 0,3 mm thick. The conditions for the acceptable gluing are adequate shear strength and the thickness of glue line.

The study results (Kairi et al., 1999) have indicated that PU adhesives are not as brittle as the conventional structural wood adhesives, and by using them the local concentration of the stresses can be avoided. For example, the non-brittleness of glue and the handling stability are improved with the PU glued ribbed elements. PU glue works at least as well as RF glue in Kerto-LVL ribbed panels. The shear strength values of PU glue coincide with to the strength values of uniformly pressed specimens. Thus, screw-gluing technique is applicable. Even with low pressures, 0,03 – 0,1 MPa, it is possible to achieve a glue line thickness less than 0,3 mm, so long as glued surfaces are adequately smooth and straight.

In practice, it has been recommended that the glue lines of RF glues should be under 0,5 mm thick. During the manufacture of Expo-Dach 2000 it was studied how it is possible to produce demanding wooden structures with structural screw gluing instead of nail gluing.

4.4.2 Factors Affecting Strength and Quality of Bond Line

There are three main factors that affect the strength and quality of the bond line. First, the pressure needed for gluing depends on the quality of adhesive and the material to be glued. PU adhesives demand only about 0,01-0,1 MPa pressure (Housh, 1985) whereas PF and MUF adhesives demand about 1,4-2,0 MPa and RF adhesives about 0,6-0,8 MPa (Suomi–Lindberg, 1986). Too high pressure leads to a non-reliable glue line because it presses so much glue out of the bond line (Hoyle&Woeste, 1989). It may also crush the wood cells on the surfaces and cause thin glue line and inadequate penetration into the wood cells (Kiviluoto & Muilu, 1988). A low pressure, on the other hand, causes a decrease in shear strength. Too low pressure does not provide close contact between the surfaces and the bond line may remain partly poor (Suomi-Lindberg, 1986).

Secondly, the moisture content of wood influences both bond formation and its performance. The optimal moisture content of wood is 8-12% for most adhesives (Kilpeläinen, 1989).

Thirdly, the ability of screws to compress the surfaces close enough to form a good glue line depends strongly on the straightness and smoothness of the wood surfaces. Due to low pressures obtained by screws, surface roughness and straightness are very important in order to ensure the conditions for the good adhesion of the glue on the wooden surfaces. Therefore, the surfaces must be sanded before gluing to correct dimensions by tolerance of ± 0,5 mm for RF, and cleaned from dust, oil and dirt.

The gluing tolerances of PU glues are more restrict regarding too thick glue line than the tolerances of RF glue.

4.4.3 Pressing the Glue Line with Mechanical Fasteners

PU adhesives do not need as high compression pressure as conventional structural wood adhesives, such as PF and MUF. Therefore, pressing by mechanical fasteners is possible. However, with screw gluing the low and uneven gluing pressures are obtained.

In screw pressing the pressure distribution in the glue, the type, size and spacing of screws and the size and material properties of wood members affect line. The screw type Stadler IG 6 × 100 was found to be the most suitable for screw pressing in the tests of Sibelius Hall, in Lahti, Finland (Kairi et al., 1999). Pressing of the joints succeeds, when the glued surfaces are adequately smooth. The strength is adequate and thickness of a glue line is under the limit of 0,3 mm, when the glue spread is 250 g/m², screw spacing is less than or equal to 400 mm and the end distance is 100 – 150 mm.

In Expo-Dach 2000, the assembly gluing was carried out as screw gluing following the nail gluing method according to DIN 1052. In fact, in the revision of DIN 1052, it will be proposed that the nail gluing method be changed to screw gluing method. There is one screw for every 150 cm² area according to the standard. In this project more screws were used. The screw type used was certificated SPAX®-S screw. The gluing of wooden components was carried out with the gap-filling type glue Dyno S 204. The glue spread was distinctly over 500 g per m² to include extra spread.

The screws can be driven with electric drill to achieve the right compression pressure. Usually, the adequate pressure is achieved when the screw head penetrates just into the wood surface. The screw gluing technique is more statical than nail gluing because the compression pressure is produced like hydraulic pressure without any impact. In gluing it is important that the glue lines stay undisturbed during manufacture and curing.

The screw gluing technique is ideal for gluing in construction site because the screws can be driven out when necessary.

4.4.4 Test Methods

The effect of the uniform pressure on the thickness and strength of the PU glue line can be tested for example with T-joints in laboratory conditions (Figure 1A). Also, shear strength tests and creep tests can be done to test the joints (ASTM D143).

According to the test results (Kairi et al., 1999), it is possible, with low pressures (0,03 - 0,1 MPa), to achieve a PU glue line, which thickness is under 0,3 mm and shear strength is as good as those pressed at normal pressures (0,6 - 0,8 MPa). The important requirement for successful gluing is the adequately smooth surfaces.

In the case of Expo-Dach 2000, the delamination tests were carried out with the test specimens made according to DIN 1052.

4.4.5 Quality Control

The main objective of the quality control is to ensure continuous traceability from the beginning of manufacture to the complete glued component. The traceability is essential in the case of possible failure or confusion situation. Each manufactured or assembly glued component and structural part has to have a mark that details the manufacturer and manufacturing time.

The working and quality control instructions for industrial scale gluing are needed. The satisfactory result of gluing must be checked with quality control. Quality control record for each working phase can be designed according to the instructions of DIN 1052 Bescheinigung C. For example, the main parameters for acceptable gluing can be adequate shear strength and the thickness of the glue line (for PU glues < 0,3 mm and for RF glues < 0,5 mm).

Since PU glue has no gap-filling capacity, extra cautions have to be paid on the gluing process and on the surface quality of wood surfaces to obtain thin and uniform glue lines. Assembly gluing requires quality specifications and continuous quality control of dimensions is essential during the manufacturing.

4.4.6 Research Needed

The factors affecting the strength and quality of the glue line in screw-pressed elements need to be further studied. The applicability of screw pressing technique and the performance of PU joints over longer time period in load bearing structures need to be investigated with long-term tests.

In order to obtain satisfactory glue lines, the critical conditions and proper manufacturing methods affecting the PU glue line quality, thickness and strength should be figured out. The development of measuring methods for roughness and quality of wooden surfaces to be glued is a challenging task for further research.

In screw gluing, the design principle for the spacing of screws taking into account member sizes, orientations, thickness and surface quality has to be developed. For quality control and inspections reliable destructive and non-destructive test methods have to be standardised.

To ensure the manufacture of good quality screw glued wooden structures, the development and formation of training and registration system of qualified professional producers (glue joiners) of screw glued structures and components have to be established.

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4.5 Wood/Non-Wood

M.L.R. van der Linden

4.5.1 Introduction

The biggest difference in bonding metal, glass, and plastic compared to wood is simply that, with a few exceptions, the former materials are nonporous (Blomquist et al, 1983, pp 284). Wood bonding is often more than a surface phenomenon. Adhesives can penetrate well into the wood surface if time and pressure is appropriate. The resulting implications for bond durability are immense. On the other hand, wood substrates may vary considerably from tree to tree of the same species and even within a particular tree, depending on the season and the locations within the trunk or limb of a particular timber sample.

4.5.2 Gluing of Wood to Metal

Blomquist et al (1983, pp 36) mention that the interest in bonding metals to wood increased during World War II in aircraft fabrication. A new family of adhesives, based on combinations of various synthetic resins, was developed and utilized.

The preparation of most metal surfaces for bonding includes a combination of the same steps:

- Solvent cleaning (e.g. tri- or perchloroethylene) with liquid or vapor to remove organic contaminants (grease or oil) from the rolling process.
- Abrasive cleaning (usually sandblasting) to remove weak boundary layers of oxide, scale, etc.
- Chemical etching to remove residual oxide and to convert the surface to a stable oxide or other chemical structure
- Finally, priming the surface with a coating that adheres to the clean metal surface and bonds readily to the adhesive.
- Most frequently, the primers are adhesive solutions compatible with the intended adhesive. The primer usually is applied immediately after abrading or etching. Without priming, steel surfaces can be stored no longer than 4 hours, aluminium 6 days and stainless steel 30 days.
- (Blomquist et al added etching solutions, temperatures and time in a table).

Ranta Maunus et al (1994) used two types of epoxy and polyurethane adhesives for glued-in steel rods. They examined the strength of joints fabricated with the glued-in steel rods,as originally developed at the TSNIISK Institute in Moscow, Turkovsky 1989. They performed short- and long-term tests.

Inoue et al (1994) used urethane and epoxy to study the bond between glued-in steel rods and timber. They performed short-term tests and concluded that the bond was excellent for making a strong connection.

Ballerini et al used two-component epoxy glue, FIP 226R, for tests on glued-in steel rods. An unglued length of 3 times the diameter was left at the end of the timber element. Cyclic tests and a long-term pullout test of 18 months confirm the excellent potential for these types of joints.

The effectiveness of butt-joining solid timber beams with the aid of thin steel plates using pheno-resorcinol formaldehyde and epoxy types of adhesives was determined by Hugo and van Wyk (1977). Pinaster and p. radiata beams with dimensions 1000 mm × 100 mm × 25 mm were ripped in length in two equal parts. One part was used as a control beam and the other part as a matched experimental beam that was crosscut at midspan. These two parts were then joined with sandblasted steel plates 50 mm wide and 1,5 mm thick. The specimens were tested in 4-point short-term bending and showed to be as strong as the control beams. A design procedure was derived from these tests.

Kleinert et al (1987) tested the bond between timber and steel to be used in kitchen knives. The knives are subject to large changes in moisture content, resulting in loss of bond between the timber and steel. To overcome this problem different kinds of glues were tested, like epoxy, polyester and polyethylenvinylacetat. The glues Epilox R50-70 and Epasol EP 2 proved to be the most efficient ones. Even after a half-year of normal use they did not show any sign of failure.

Van Wyk (1979) examined the durability of steel reinforced end-joints in timber beams subjected to third-point loading during exposure to natural weathering conditions for 28 months.

4.5.3 Gluing of Wood to Concrete

Kornett (1980) performed shear and tensile tests on different combinations of materials, wood-concrete, steel-concrete, bonded by thermoplastic types of glue based on PETP, E-VA and PA. The concrete needs to be preheated to a temperature of 60-70°C. The short-term strength nevertheless is acceptable: failure mainly occurred outside the glueline.

Erler (1992) performed shear tests and bending tests on timber-polymerconcrete specimens. He used epoxy resin Epilox T 19 - 20 Leuna-Werke and polyester resin AS 2324 Chemische Werke Buna. These materials were mixed with sand and gravel to obtain polymerconcrete. Apart from short-term tests 8 bending specimens were tested during 1 year. All tests indicated that a full interaction between timber and concrete could be obtained and remained in time. A pilot project showed the effectiveness of the system, although long-term results were not available then.

Brunner and Gerber (1999) performed short-term and long-term bending tests on timber-concrete beams that were glued together with Sikadur-T35 LVP of SIKA AG, a two-component glue based on epoxy resin. The concrete was a self-compacting concrete (SCC) of SIKA AG of quality B40/30. The short-term tests indicated that full interaction between timber and concrete was obtained. The long-term tests only lasted 50 days and indicated that a major part of the time-dependent deformation was caused by shrinkage of the concrete.

4.5.4 Other Combinations

4.5.4.1. Gluing of Glass to Timber

In (Holz-Zentralblatt, Nr 89, page 1418) the company Ego mentions a glue (Conloc UV-665N) that is used to glue a glass surface to a timber window frame.

Schmid, Götz and Hoeckel et al (2000) describe a pilot-project with structural glazing, in which glass was glued to the bearing timber structure. The vertical elements turn out to be watertigth; the horizontal roof elements are still subject to research.

Natterer and Hamm (1998) tested four different types of adhesives to glue glass to timber. The composite elements were submitted to several climatic cycles. One glue resisted the stress test after these cycles and was used to manufacture the timber-glass composite. This composite was put to a 4-point bending test to study the efficiency.

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5. Products / Components

Simo Koponen

5.1 Introduction

This chapter mainly deals with the utilisation of gluing technology in construction industry and in joinery. At this moment in the building sector there is clear positive demand for wood products and components. Examples are the increase of building permissions of single and double family houses, the growing share of prefabricated houses and the increased research activity considering multi-storey timber frame houses. Workability, efficiency in raw wood material usage, good strength to weight ratio, rapid construction, modular prefabrication, easy transportation, emotional reasons (feel good, ecology, CO_2) and energy and time risk savings are promoting the growth of glued wooden building components.

The lack of ability to use new techniques may slow down this development trend. In most European countries there is no recent strong traditions of constructing houses with wood. However, the use of wood varies a lot among countries and even inside an individual country there are large differences.

Modern building industry will demand more predictable products and building system solutions. Wall, floor, roof and exterior systems consist of components and product bundles (Sandbers, 1999). Requirements for the raw material quality increase thus EWPs (Glulam, LVL, Plywood, OSB, LSL) are preferred instead of ordinary sawn lumber. The development of new gluing technologies will be important in industrial scale manufacturing of wood based components and systems (figure 5.1).

The need of increasing the productivity by automation is evident, but on the other hand there is a need for more flexible production methods.

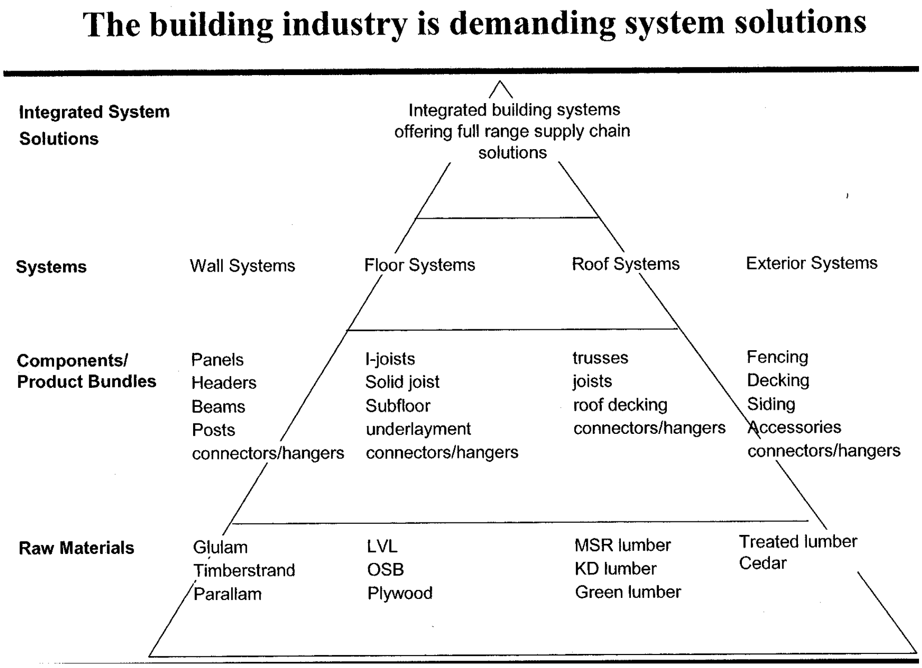

Figure 5.1: Building industries point of view (Sandbers, 1999)

5.2 Composite Beams and Columns

S.Koponen, M.Kairi, E.Aasheim, C.-J.Johansson

5.2.1 General

There is a wide variation in the type of composite beams and columns, in production methods and materials used. Both large and small companies (carpenters) produce these products. The distribution of the products varies from stock markets to custom-made products. The most common type of composite beam is I-joist.

5.2.2 Description of the Products

The first commercial I-joists appeared in 1968 in North America. During 80's and 90's I-joist industry has grown fast. It is anticipated that the current production of over 120 million linear meters of wood I-joists annually will rise to nearly 270 million linear meters by year 2005 (Nelson ,1997 and Forest Products Laboratory, 1999).

I-joist flanges may be single or laminated pieces of visually graded or machine stress rated sawn lumber or laminated veneer lumber (LVL). Sawn lumber is finger jointed to obtain adequate length and to minimise waste. Webs are predominately oriented strand board (OSB) or structural use plywood. Medium or high-density fibreboard is also used. Some companies produce beams with lattice-struts for open joist floor framing or formwork beams (Ménard, 1998) (figure 5.2.1).

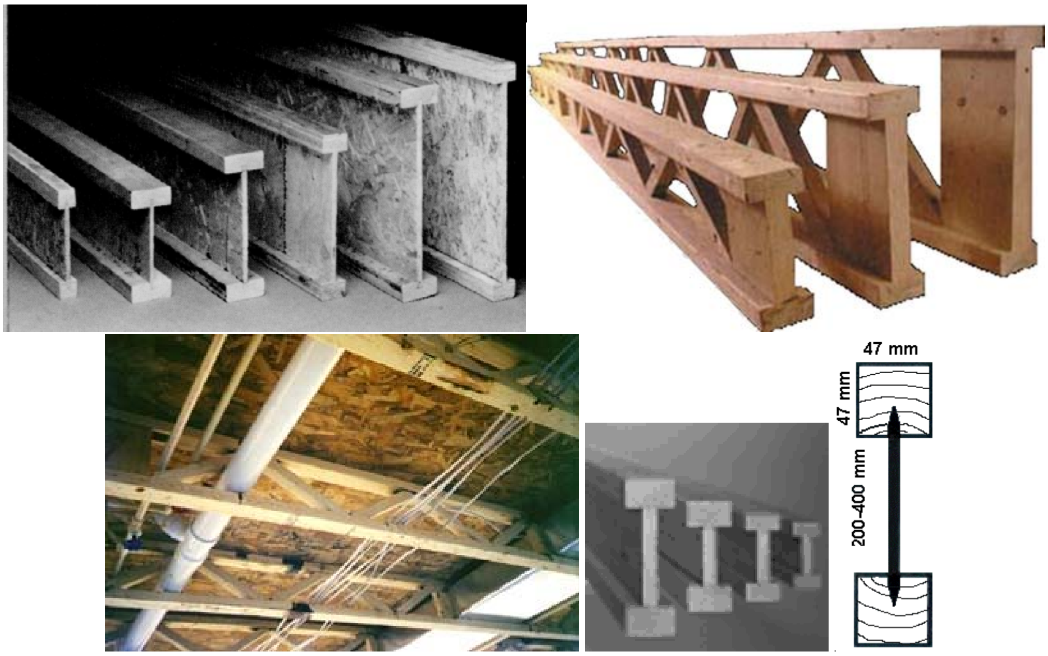

Figure 5.2.1: I-joists, open joists, solid wood I-beams and I-beam with fibreboard web

Kaufmann's Profilträger is I-beam for structural use made of solid lumber. The flanges are finger jointed and web is three-ply glued spruce lumber. Kaufmann and Doka produce also wooden I-beams for formwork systems.

The newly upcoming wood composite products are fibre reinforced timber structures (figure 5.2.2) and wood-plastic components (Bainbridge, 1998 and Greenland, 1998). In the first category wood properties are improved using glass or carbon fibres. Steel has also been used as reinforcing material. In the second category the properties of plastics are enhanced with wood fibres or wood is used as filler. The commercial use of these products has been relatively limited but the research has been active.

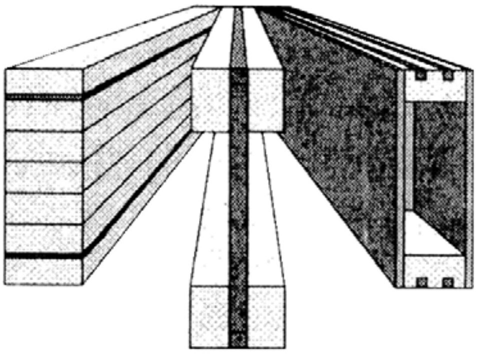

Figure 5.2.2: Conceptual fibre reinforced timber composite (FRTC) configurations (Bainbridge, 1998)

5.2.3 Use

Composite beams are used as main girders and joists in floor and roof structures in residential and industrial buildings. Wooden composites can also be used as columns and studs. Due to lightweight they are also suitable for renovation. In addition to permanent structural use, prefabricated timber beams are used in temporary construction works (formwork beams). Box beams and columns have also been applied especially for frame and arch structures of halls and domes. In North America commercial use and some pilot bridges have been constructed using fibre reinforced glulam beams.

The most of I-joist markets are located in the North America, where the I-joists are substituting sawn lumber due to increasing price and decreasing resource of large dimension lumber. I-joist producers provide dealers adequate technical data and support. The design of I-joists is based on span tables made by I-joist industry and associations (American wood council and APA). The simplified methods are given for determining allowable joist and rafter spans. Typical application ranges for different composite beams are presented in table 5.2.3.1.

Table 5.2.3.1: Typical spans for different types of timber beams

Product name	H [m]	L [m]
I-joist, lattice strut beam	0,3 - 0,5 (0,75)	4 - 12
Plywood-lumber beam	0,3 – 1,2	4 - 18
I-beam	0,6 – 0,8	10 - 26

5.2.4 Fabrication

Large-volume residential series of I-joists is usually fabricated in a fully automated continuous production line at speed of 115 meters per minute or more. Adhesive (EN 301, ASTM D2559, CSA 0112-M), typically phenol-resorcinol-formaldehyde is applied in the groove just before the flanges and webs enter into the assembly machine in which they are pressed together. Then I-joists pass through an oven to cure the adhesive. LVL is appropriate as a flange material due to dimensional stability and consistent strength.

In I-joists the joints between the flange and web are critical for member strength and are typically protected with patent by each manufacturer. Exterior rated phenol-formaldehyde and phenol-resorcinol are the adhesives used for the web to web and web to flange joints. The most patents considering I-joists deal with the manufacturing apparatus or the shapes of the glued grooved and tongued joints.

In a typical fabrication process, sawn lumber or LVL is ripped to the width of flanges, which, if required, are then end-to-end finger-jointed. A profile groove is routed into one side of each flange along its length, and the tongue is routed onto the edges and the ends of webs are cut to width in a prior operation.

At the other end of the production scale is the custom hand lay-up processes, which are more typically used for the heavier structures of commercial or industrial buildings. Plywood is typical web material. Flanges can be sawn lumber, glulam or SCL. Manufacturing and design instructions for I-beams and box-beams are given in Eurocode 5 and in handbooks of plywood manufactures or in Informazionsdienst Holz, for example. American Plywood Association (APA) gives instructions for the quality of contact surfaces and gluing. Substantially uniform pressure (1,2-1,8 MPa) can be applied by clamping or nailing (spacing 75-100 mm). The recommendations of APA advise also how the test samples shall be taken and how the beams shall be marked and identified.

5.2.5 Properties and Requirements

Currently the European standardisation work of wood composite beams is going on in CEN workgroup CEN/TC124/WG 03.04/05 – Light Composite Wood-based Beams and Columns. It deals with the adhesives used in composites, test methods, reinforcing materials, fixing of elements and treatments against fire and/or biological attack for example. The essential requirements for the composite beams and columns are: mechanical resistance and stability; safety in the case of fire; hygiene, health and environment; energy economy and heat retention (thermal bridge); aspects of durability, serviceability and identification.

The draft of pre-standard prEN 13377 (CEN/TC124/WG2/N310) concerning the prefabricated wood based formwork beams is under evaluation. In the draft, the requirements and test methods are given for panel web and lattice-strut beams.

In the United States, the International Conference of Building Officials (ICBO) has published a document titled Acceptance Criteria for Prefabricated Wood I-Joists, for evaluation of these products. The Council of American Building Officials (CABO) has issued product evaluations for I-joists. The recent ASTM Standard D5055, Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists, outlines procedures for establishing strength values and controlling the quality of prefabricated wood I-joists. In ASTM D5055 full-size I-joists loading test is presented.

Canadian Construction Materials Centre (CCMC) has issued product evaluations for many of the prefabricated wood I-joists marketed in Canada.

Prefabricated wood I-joists are proprietary products with engineering qualities depending on the materials and flange joints used and production process variables. Therefore designers and installers follow the design guidelines as well as the installation guidelines of the individual manufacturers.

Manufacturers provide testing based theoretical or combined bending stiffness, bending and shear capacity values. Wood I-joists are typically designed for a maximum live load deflection of L/360 for roofs and L/480 for floors. Since the last decade, users' requirements for the vibrations and acoustical performance have become stronger. The recommended deflection criteria for floors intend to ensure that the floor is stiff enough to keep vibration below acceptable limits. Acoustical properties can be improved by building system solutions for example.

Fire safety of wood-frame floor and roof assemblies of residential and commercial buildings is becoming more important. The most of the leading manufacturers have conducted fire tests and evaluations for common floor and roof assemblies to determine the fire performance of their wood I-joist products.

Because each manufacturer uses a different material resource and a different production process, custom production procedures must be established. Moreover, the quality of material purchased for the manufacture of wood I-joists varies therefore a quality assurance program that monitors daily production and independent third party quality audits conducted by an accredited certifying agency on a regular basis are necessary.

Before commercial production begins, each manufacturer's product must be extensively tested to determine the engineering properties. Products are manufactured in a plant approved for fabrication and supervised by a third party inspection agency. Once production is started, a random sample of product is frequently selected for testing to ensure the manufacturing materials and processes meet prescribed strength properties.

5.2.6 Advantages of Composite Structures

The most important properties of wood composite beams are lightweight and improved strength. The effect of defects is minimised and they have predictable strength. In I-beams 50% less wood is required than in ordinary sawn lumber. Enhanced dimensional stability reduces labour costs and provides timesavings (installation in half the time of conventional framing) at construction site. The amount of job site waste is minimised.

In the USA composites are used as a substitute for large dimension solid-sawn lumber. Raw materials can be obtained from small diameter, fast growth and less utilised trees (some hardwood for example). In Europe composite beams compete also with small dimension glulam.

In addition to cost effective manufacturing process and relatively low price, the acceptance on I-joists in the marketplace has been driven by the need for high-quality, dimensionally consistent and stable, lightweight framing members with reliable capacity, predictable performance and availability of required lengths.

I-joists usually eliminate the need for a collar beam or strut. The absence of conventional frame construction increases the proportion of useful space in a building. Thermal resistance (u-value) is about 15% better than that in a conventional timber-framed wall of similar dimensions. In the future the tightening of the energy consumption regulations will promote use of energy efficient solutions.

5.2.7 Research Needs

The use and markets of composite beams and columns will be divided into two categories. One structural application area of wood composites is an alternative to the traditional sawn lumber or to the other materials. Due to the competition among different solutions, the production volumes need to be increased and manufacturing and marketing shall be effective. Glues and gluing methods have to be suitable for fast manufacturing rates.

The other applications are cost effective solutions of customers' needs using technically advanced or complicated composite products. The production volumes are relatively small, but on the other hand, value added to the product is high and the production is carried out using flexible manufacturing methods in small or middle size factories. The glues have to have enough working life but short curing time and good adhesion and sometimes gap filling capacity. In some cases wood is reinforced with other materials. Reinforcement can locate in gluelines.

The development of reliable glues and gluing methods and glued components, which give also optimised solution for the end use requirements, is a challenge. Components belong to larger building system and will no longer be only substitutions for sawn timber but also give additional values like improvement in thermal or sound insulation.

Manufacturing of traditional I-joists is mostly based on a fast and cost effective production. The production and markets are already well developed in North America. LVL and OSB will be common flange and web materials. Production of I-joist will be continued in large volumes, and the products are sold on stocks. R&D of traditional I-joists will no longer focus on the I-joist itself but to the end users' and constructors' needs (improved fire, acoustic and vibration properties or solutions, faster erection of the building and jointing systems).

More prefabricated I-joist based components and system solutions will be developed. Some new solutions like lattice-strut beams and solid wood I-beams compete with the traditional I-joist markets and hold important share on special markets like formwork beams.

The European standardisation of structural composite beams and columns and standardisation of formwork beams are currently under development. The standardisation considers not only essential properties of products but also production inspections. Up to date, it is important to see applicability and potential risks of glued wood composites.

Especially constancy, long term strength and creep properties of glues and glued wood composites are important to be ensured. However, test methods are still under development and divergent methods have been used so far. In some cases current practise put new glue types off to come into markets. If the glue, gluing method and glued product are all based on a new technology, the time required to ensure long term performance might be a barrier.

The production varies from unique structures to continuous production. There is variation in the raw materials used. Therefore, it is difficult to give general detailed test plans to be used in production control. New test and inspection methods are needed which are more suitable for new products. Tests can include small size test samples cut from products, indirect test methods (non-destructive evaluation) and full size tests.

5.2.8 Standards

ASTM D5055 Standard specification for Establishing and Monitoring Structural Capasities of Prefabricated Wood I-Joists.

ASTM D5456-99a Standard Specification for Evaluation of Structural Composite Lumber Products

prEN 13377 Prefabricated Timber Formwork Beams - Requirements, Classification and Assessment

Eurocode 5 ENV 1995-1-1, Design of Timber Structures

CEN/TC124/WG 03.04/05 – Guideline for European Technical Approval of Light Composite Wood-based Beams and Columns for Load Bearing Componets in Building Structures

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STEP 1, Timber Engineering, 1995, Salland De Lange, Devevter

5.3 Stressed Skin Panels

Simo Koponen, MattiKairi, Carl-Johan Johansson

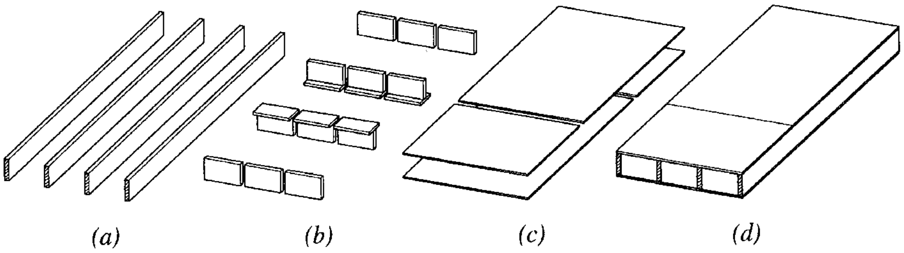
5.3.1 General

Properties, requirements and research needs concerning stressed skin panels are discussed. Also some other new competitive wood based solutions are presented.

5.3.2 Description of the Products

Traditional stressed skin panel consists of solid timber webs connected with wood panels forming the skins on one or both sides. The connection is made using mechanical fasteners. To prevent squeaking and to increase stiffness and sometimes strength webs and flanges are glued with elastic or rigid glue (figure 5.3.1).

Figure 5.3.1: Construction of a pre-fabricated stressed skin panel: a) webs, b) blocks and flange splices, c)



flanges and d) stressed skin panel (Step 1, 1995)

The production of pre-fabricated elements in factory conditions makes it possible to obtain better and established quality. Gluing conditions and methods are more constant, tasks and skills of workers are controllable (figure 5.3.2).

Constructional hollow core floor and roof components can be made also from solid wood like Lignatur (Switzerland) elements (figure 5.3.3). The height of the elements varies from 120 mm to 320 mm. The standard width is 200 mm and the length up to 16 m can be produced. The width of Lignatur surface elements varies between 400 mm and 1.000 mm.

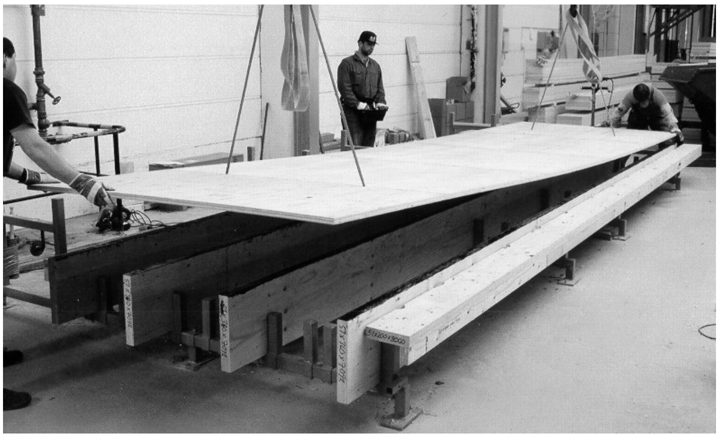


Figure 5.3.2: Assembly of pre-fabricated RF-glued stressed skin panel

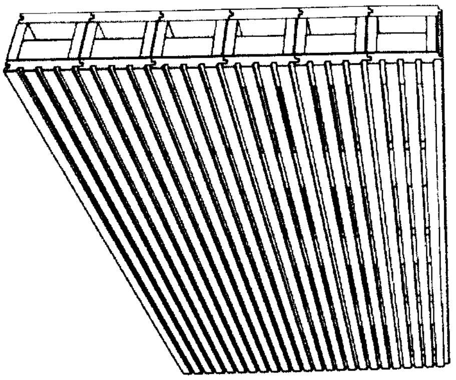


Figure 5.3.3: Lignatur hollow core elements (Blumer 1998)

The roof element of Colladello company (France) consists of solid wood top flange grain direction perpendicular to the span, thin glulam webs in diagonal orientation and finger jointed bottom flanges connecting two webs together (figure 5.3.4).

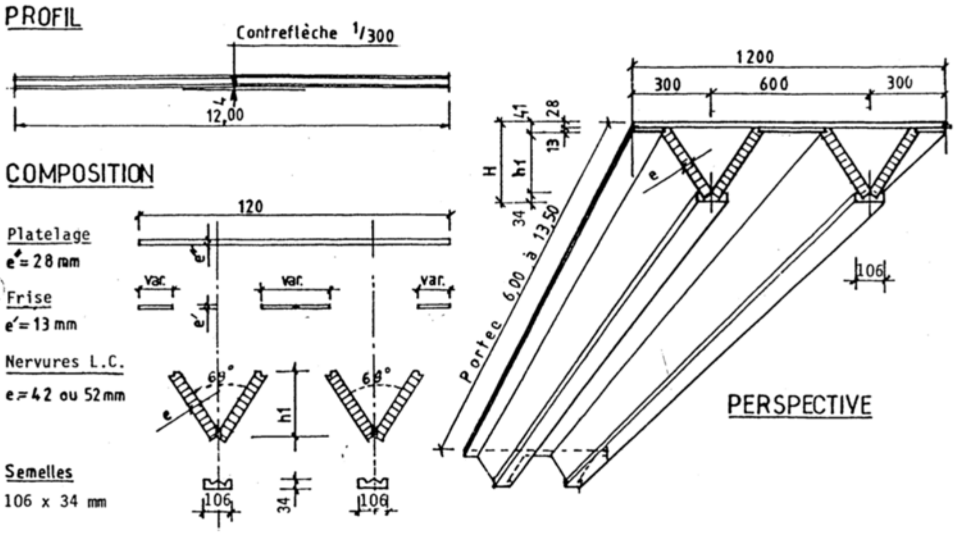


Figure 5.3.4: Construction of Colladello roof element

The structural sandwich panel (Structural insulating panel, SIP) consists of lightweight core laminated between two wooden panels. Core can be either polystyrene foams or polyurethane foams for example. If the panels are used for longer spans, joists are added on the edges of the sandwich panel (figure 5.3.5). Curved elements can also be manufactured.

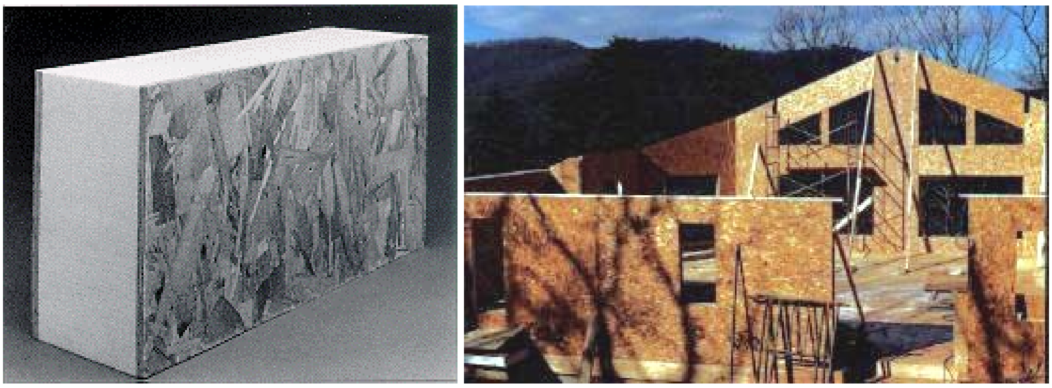


Figure 5.3.5: Wooden sandwich panels can be used for roofs and walls

The core of Masonite lightweight element (19 - 30 kg/m²) consists of Masonite I-beam joists and stringers (H = 150 - 400 mm). The thermal insulation is placed between Masonite I-beams (figure 5.3.6). The top face is construction plywood and the bottom face is smooth or perforated steel plate (t = 0,5 mm) with zinc-aluminium coating. The steel plate is fixed with polyurethane glue and nails and it acts as a structural reinforcement.

Figure 5.3.6: Fabrication and assembly of Masonite lightweight element

In addition to load carrying ability Masonite lightweight element gives solutions to thermal, acoustical, fire-technical, visual and moisture technical requirements.

5.3.3 Use

Stressed skin panels are used in floor and roof systems in residential, commercial and industrial buildings. Hollow core elements are used as floors, roofs and walls. Both are suitable for renovation. Sandwich panels are mostly used for roofs and walls in residential and smaller commercial buildings. Wooden sandwich elements are used in North America, Mexico, China and Japan. Also in Europe SIPs have been used (in the Netherlands for example).

5.3.4 Fabrication

Stressed skin panels can be manufactured either in the building site or they can be pre-fabricated. In the case of roofs of industrial buildings it is often profitable to complete the fabrication of the elements and make larger units on the ground level to save assembly time on roof level.

If gluing is used, adequate pressure and close contact between members can be obtained using clamping or nailing. It is economical to produce multi-span panels. However, the available lumber length determines the length of elements. In longer elements LVL webs or I-joists can be used to obtain adequate height and length. Glued scarf or finger joints can be adopted to joint skins. If butt joint is used skins should be backed with glued plywood splice plates.

Sandwich panels are pre-fabricated products with increasing production volume. Elements are fabricated by pressure-laminating OSB and polystyrene together with glue. If polyurethane foam is used as core, adhesion and gluing pressure can be based on the expansion and curing of the foam. APA has given instructions for the design and fabrication of plywood sandwich panels. APA also gives instructions for curved plywood panels.

Lignatur element is glued in high-frequency presses with melamine or urine-based glues. Various qualities of wood and different finishing can be used.

5.3.5 Properties and Requirements

In residential and commercial buildings stressed skin panel and sandwich panel elements have to fulfil simultaneously several functions. In addition to adequate strength and stiffness, vibration and acoustical properties have to be considered carefully in floor structures due to lightweight of the element. Elements have to also satisfy fire safety and thermal insulation regulations. Meanwhile, the other building physical aspects have to be taken into account (moisture, biological degradation, and air tightness). Pre-fabricated element finishing, painting and protective coating may be carried out in the factory. Assembly of the insulation, pipes and cables should be easy (knock out holes) or they might be integrated to the element as a building system already in the factory.

Especially in the industrial buildings fast erection of the building can be achieved using prefabricated elements. Glued elements are rigid, dimensionally stable and accurate during transportation and storage, and easier to assemble.

Eurocode 5 has given design instructions for stressed skin panels. The European standardisation work concerning prefabricated stressed skin panels and their acceptance methods is currently under preparation. APA has given gluing instructions, requirements for surface straightness and quality, gluing methods and assembly conditions.

Materials used in sandwich panels shall be compatible with the glue being used. Instead of OSB other structural wood or gypsum based panels or wood boards can be applied.

5.3.6 Advantages

Gluing between webs and flanges not only prevents squeaking of the floor but also increases stiffness and strength of the element. Reduction in weight and height of the elements is possible. Savings in assembly costs in building site and more usable space can be obtained.

For mechanically jointed stressed skin panels the connections between flanges, webs are not complete, and the semi-rigid behaviour of joints has to be taken into account. This makes the analysis of deflection and strength complicated. Due to a high creep of mechanical joints, the interaction has tendency to disappear and at the ends of panel the flanges and the webs act as separate members. With rigid glued joints full interaction between flanges and webs can be achieved and the design of structure is simple.

Rigid connections essentially improve the stiffness of the element. Thus the height of the element and material consumption can be reduced.

5.3.7 Research Needs

The performance and reliability of glued wooden structural elements depend on the wood materials quality, on glues used and their suitability to each other, on the type of structure and joint, on fabrication method and skills of designers and workers. Fabrication methods, transportation, erection and end use conditions should be compatible with the elements and glued joints.

The structure of the element should be such that it is easy and fast to be glued and the occurrence of gluing defects is minimal. The glue should have desired working time, but the curing should be fast enough to obtain economical turnaround time. The use of EWP as components of the elements probably reduces the risk of gluing defects.

While large and small companies fabricate glued elements, the variability of production methods and products is large. It is difficult to give detailed standardised test and inspection methods for the products and fabrication. Thus it is important that skills and experience of the designers and manufacturers are adequate. In the case of some structures it might be necessary to require acceptance of glued product manufacturers. It will also require experienced labour and supervisors to get defects free products. This is possible to ensure by introducing acceptance procedure of gluers and training arrangement.

Long term strength and creep of glues have often been questioned especially when new glue types are adopted. PF- and RF-glues are preferred, thus they have good weather resistance, stiff and constant molecular structure. However, due to the brittle behaviour they are sensitive to stress concentrations and impact loads, which can occur during fabrication, transportation or assembly of the elements. T-joints used in stressed skin panels are sensitive to transverse impacts on webs if thin wood members are used. Also shrinkage and swelling of wood might cause additional stresses.

Theoretical analysis and design methods of components, which take characteristics of glued joints into account, should be verified. In Eurocode 5 the glued joint is assumed to be rigid and mechanical fasteners do not take any loads. In U.S.A. superposition for adhesive and nails has been considered in standards when elastomeric construction adhesives are used between joists and sheathing. Both short term and long term behaviour should be studied.

It is important to develop new test methods for new products and glues. Current standardised test methods are developed for the old products. Often it is difficult or impossible to apply those methods to the new products.

The suitability of the wood surface for gluing should be easy to verify. There should be methods to inspect straightness, roughness and the other surface parameters before gluing is commenced.

Non-destructive and destructive inspection methods of glued components should be developed. In addition, criterions for the acceptability of the products should be determined. For example the thickness of the glueline is often taken as a criterion, but there are no instructions how to measure it.

5.3.8 Standards

Eurocode 5 ENV 1995-1-1, Design of Timber Structures

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STEP 1, Timber Engineering, 1995, Salland De Lange, Devevter

5.4 Wood Based Floor Coverings

Kai Kruse, Alfred Teischinger, Rico Emmler, Steffen Tobisch

5.4.1 Types and Definitions

As referred to the actual versions of European standards (EN 13329, prEN 13756) different types of wood based floor coverings exist which are listed in the following:

- Parquet: element with a top layer of minimum 2 mm prior to installation or assembly of the previous with a defined pattern.
- Multi-layer floor/parquet board: floor/parquet board of laminated construction with a single or edge-jointed and glued top layer.
- Veneer floor covering: similar to parquet with no minimum thickness for the top layer.
- Laminated floor covering: floor covering with a surface layer consisting of one or more thin material (usually paper), impregnated with aminoplastic, thermosetting resins (usually melamine). These sheets are either pressed as such (e.g. HPL) or bonded or pressed on a substrate (usually wood-based panels). The material is usually finished with a backing primarily used as balancing material.

5.4.2 Market Aspects

The European market of floor coverings is dominated by textiles like carpets (figure 5.4.1). In the last years wood based floor coverings increased market share significantly. This seemed to be mainly affected by reduced sales prices for wood based floors resulting in comparable price levels as textiles. At the same time end-users tend to buy products with natural and positive ecological aspects. Due to its natural resources and character as well as a marketing strategy which underlines ecological benefits when using wood products (LCA, carbon sink, etc.) especially wood based floorings (and wooden houses) became more popular. A wooden floor is beautiful and natural. It does not rap or harbour dust mites or moulds as fitted carpets do; therefore a wooden floor is safe for health.

Besides these aspects, wood industry developed wood based floorings as finished products. In combination with simple tools these 'systems' are being easy to installed by semi trained end-users (DIY).

Highest growing rate was recognised for Laminated Flooring (figure 5.4.2). Although it is produced for more than 30 years it became enormously popular when sales prices dropped down. In this context new technologies/developments (e.g. HDF (high density fibreboard), PCD tools) and the drastic expansion of production capacities are of special interest.

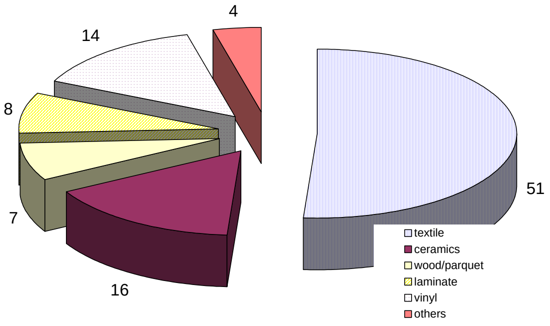

Figure 5.4.1: Market share (%) of floor covering in Europe (Perstorp 1997)

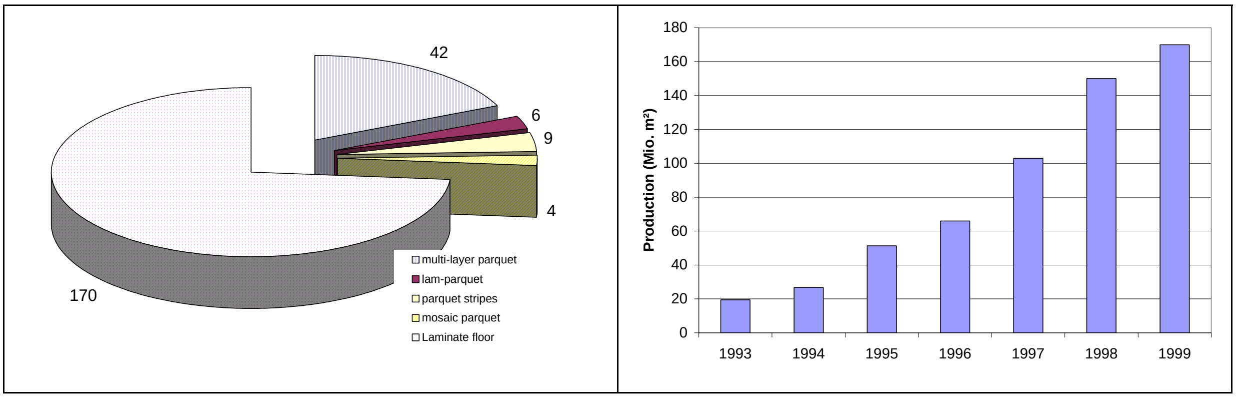

Figure 5.4.2: left: production (Mio. m²) of different wood floor coverings in Europe (FEP 1999)
right: production of Laminate Floor in Europe (EPLF 2000)

5.4.3 Parquet

Second biggest market share in Europe for wood floorings is for pre-finished laminated parquet.

The main reasons for the popularity of laminated parquet floors are:

- High dimensional stability because of crosswise glued layers of wood
- Use of different wood species and wood qualities in the various layers (expensive and high quality material in the face layer, low-price material in the bottom and core layers)
- Ready machined, lacquered and packed, factory pre-finished product
- Possibility to produce various patterns as plank, strip, parquet etc. and grade levels as exquisite, select, common etc. according to the specific grading rules
- Easy laying procedure at the building site

Using wood floor covering comprises lots of advantages as variety in design, using wood as a natural and sustainable resource and the environmental soundness of wood, but one has also to consider special features of wooden floors. When these special features are taken into account during production, installation and use, the wooden floor maintains its natural charm (Teischinger 1998). Pre-finished multi-layer laminated parquet as a glued product often is also recognised as “engineered wood flooring”.

5.4.3.1. Parquet Market in Europe

The solid wooden flooring market comprises several types of products such as conventional parquet strips, single layer lam-parquet, mosaic parquet, and parquet panels, prefinished parquet elements. All member states of the European Federation of the Parquet Industry (FEP) produced about 61 mio m² in 1999 (Anon., 2000a). Within this production the share is as follows:

prefinished multi-layer parquet	69%
single-layer lam-parquet	10%
parquet strips	14%
mosaic parquet	7%

The production share within the member states of the European Federation of the Parquet Industry (FEP) is as follows:

Sweden	23%
other Nordic countries (DK, NO, FIN)	17%
Germany	16,6%
France	12%
Italy	8,2
Spain	7,2%
Austria	7,1%
Switzerland	4,6%

Others..4,3%

The usage rates of wood species for the production of parquet were as follows: Oak 43,6%, beech 26,4%, tropical woods 10,1%, maple 7,8%, ash 4,0%, the rest is chestnut, maple, birch, pine, eucalyptus, cherry and others.

5.4.3.2. Structure and Standards

The whole area of “wood floor covering” is currently under standardization within the European Committee for Standardization (CEN) within CEN/TC 175 “Round and Sawn Timber”. As a basic standard prEN 13756 provides various definitions concerning wood floor coverings. Multi-layer parquets are seen there as laminated (layering by gluing) wood or wood based elements with a single or edge-jointed and glued top layer. A parquet has to have at least a top layer of minimum thickness of 2 mm prior to installation. A top layer with no minimum thickness for the top layer is therefore seen as a veneer floor covering. All elements may be “unfinished” or “finished”, where the latter means, that its face has been treated at the factory. Treatment is usually with lacquer, oil or wax. The element may need further treatment after installation.

For multi-layer flooring elements there are specific proposals and drafts as product standards such as pr EN 13489 wood flooring, product standard, multi-layer parquet and the proposal “wood veneer floor covering” (CEN/TC112/WG7, N 39E). These standards are the basis for the evaluation of conformity and the requirements for marking the products, which will be necessary according to the EU Construction Products Directive (CE-marking). In this case following performance characteristics are required for wood and parquet flooring: Reaction to fire, release of formaldehyde, breaking strength, slipperiness and thermal conductivity.

For the determination of special properties the following standard drafts are important:

prEN 1534 for testing the hardness of the top layer, prEN 1910 for testing the dimensional stability of floor elements, ENV 13696 and prEN 13442 various tests concerning abrasion, elasticity and the resistance to chemical agents.

Many innovations are made in the field of standardisation and test methods concerning the testing and qualifying the surface finish as summarised by Anon. 2000b. The problem of wear resistance of the surfaces (abrasion, scratching, impact, slippery and castor chair resistance) have to be specially considered here.

5.4.3.3. Production

Most laminated wood floor products are produced according to the scheme of a face (top) layer and a back (bottom) layer with the grain running in the same direction and a centre (core or middle) layer turned 90° during assembly. Tongue and groove have an optimised shape for fitting together the elements (figure 5.4.3). The core layer as well as the back layer is mostly made of cheaper softwood species whereas the top layer is made of hardwoods like oak, beech, ash, maple etc. The glues used in the assembly are Urea-formaldehyde (UF), Melamine-Urea-formaldehyde (MUF) glues and PVAc-glues depending on the production process, wood species, element size etc. Sometimes wood based panels such as plywood is used as a basis layer and a solid wood lamella as top layer.

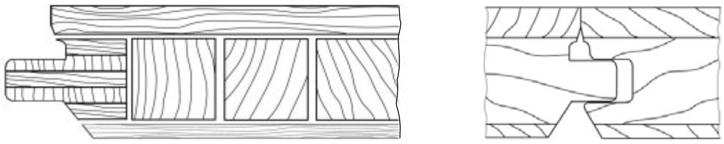

Figure 5.4.3: Typical shape of tongue and groove at a length side connection (right) and for the end connection (left). For better performance of the tongue and groove at the end side, a plywood strip may be glued in as part of the middle layer

The first stage in modern manufacturing process of laminated parquet is the production of planks or strips as top layers. The strips/blanks are graded into quality classes on the sorting conveyors after the machining line. The machined and graded strips are laid into cassettes of the same dimensions as the final parquet elements (blanks) and then the cassettes are lifted mechanically onto the lay-up station on the pressing line.

On another machining line dimension-cut solid wood boards are fed onto a line for manufacturing the strips used for the core layer mat. The strips are combined to a mat and are automatically tied together.

The core strip mats are driven through the glue spreaders before the lay-up and hot pressing. In some cases a double lay-up is done with the top layer (with double thickness) right in the middle of this package. In this case – after pressing - the double billets run through a band saw, which splits the billets into two parquet boards along the top layer (which is right in the middle at that time).

Pressing may be done by high-frequency heating or hot pressing. In the press, the top layer strips are first pressed together horizontally in four directions followed by the vertical pressing. The curing time depends on the glue system, the board thickness, type of heating etc. After pressing tongues and grooves are machined and the faces are getting prepared for surface finish by a sanding process. The side edges may get eased edges.

Many manufacturers apply multiple coats (three to seven coats) of touch urethane, UV cured finishes or oil or wax finishes. The finishes may have various levels of sheen, gloss, semi-gloss or satin (mat) finishes. Special finishes are acrylic impregnated finishes, which are not just on the surface but also within the floor. The scratch resistance of such a finish shall be up to 70% higher than on an urethane surface finish. Durability shall be excellent, however, this finish still has to be cared for regularly to achieve optimum beauty.

After surface finishing and a quality inspection the parquet elements are stacked into bundles and packed into shrink-wrappings of polyethen foils.

The main characterisation of the production process is: high accuracy in production, so that the pre-finished elements fit together properly when being installed. Accuracy in production of pre-finished parquet has to achieve an installation of the elements with a lipping of the elements of less than 0.2 mm according to the common standards. This includes a precise kiln drying of the wood before machining and an accurate M.C. of the ready-made parquet board but also packing in foils etc. to avoid moisture changes during storage and transportation. Depending on current national standards the accurate M.C. varies around 7±2%.

5.4.3.4. Installation

The installation methods for laminated/engineered wood floors include:

Floated: The elements are glued together by putting glue to the tongue and sticking together element by element to a floating plate. A urethane foam sheeting or a cardboard for smoothing the concrete slab and as a sound barrier may be laid between the sub floor and the wood floor.

Glued: Manufacturers recommend special adhesives to glue-down the wood floor to the concrete slab.

Nailed or stapled: The floor elements are nailed (according to a certain nailing schedule) to a wooden or wood based panel sub floor.

The top faces on parquet element itself as well as the installation may lead to typical patterns such as: random width strip flooring, strip-pattern flooring, brick-pattern flooring, “herringbone” parquet flooring etc.

Because of the increased number of concrete slab constructions the floating and gluing installations are becoming the most frequently used installation methods. An analysis of the development of the wood flooring in the last decades shows a strong relation between the growing production figures and the evolution of different adhesive systems (mastics) for installation. The main features of modern mastics are: elastomeric systems with high strength but reasonable elasticity to cope with the swelling and shrinkage of wood, good application characteristics, reasonable working time, excellent long term aging characteristics etc.

The most common adhesive systems are chlorinated mastics, polyvinyl acetate (PVA) systems, polyurethanes, epoxy systems, latex emulsions etc. Each system is different in price, application characteristics (water free systems do not load the parquet with additional water and induce a swelling and cupping of the elements), compatibility with a moisture barrier over concrete slabs, bonding strength, emissions during installation etc.

A new development is to form tongue and groove into a special shape so that one can click together the elements without putting a glue onto the groove.

5.4.3.5. Research Needs

One of the most interesting ideas is the development of a higher abrasion performance and hardness of the top layer besides the technology of the acrylic impregnation. This could be the CaLignum process, which is an isostatic pressing of wood under extremely high pressure (Schotte 2000). Compressed wood displays much greater resistance to scratching and a higher hardness. But there are still lots of questions like the dimensional stability under wet conditions to be solved before using it as a high resistance top layer for parquet use in high traffic areas like kitchens, foyers, offices, shops etc.

Modification of wood to reduce moisture absorption and swelling and shrinkage.

Development of larger pre-finished laying units, possibly with modified wood as top layers, for use in high traffic areas where a wetting of the floor cannot be avoided (coffee shops, restaurants, hotel foyers etc.).

Development of testing methods for better describing the wear resistance of the surfaces (especially abrasion resistance) as stated in (Anon. 2000b, Devantier 2000).

5.4.4 Laminated Floor

The term *Laminated Flooring* generally covers all multi-layer floorings with decorative paper finish. The following types of *Laminated Flooring* can be distinguished:

- HPL: high pressure laminate
- LPL: low pressure laminate
- DPL: direct pressure laminate
- CPL: continuous pressure laminate

For *Laminated Flooring* the three-layer construction is typical (figure 5.4.4) and consists of

1. Finish film: one or more layer of papers and/or films impregnated with resin. Usually two or three layers having the names: overlay, decor, underlay
2. Substrate: high density wood-based panel, usually fibreboard (or particleboard)
3. Backing: one or multi layer of paper impregnated with resin

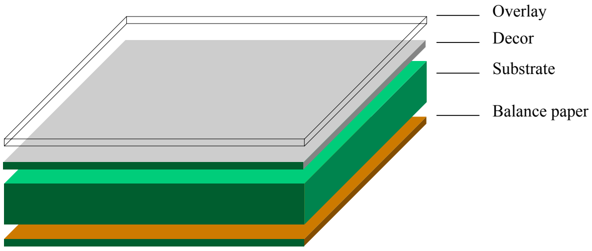

Figure 5.4.4: Typical components of Laminated Flooring (3-layer structure).

Major objectives of the different layers are:

- Protection against wear, moisture, impact ⇒ overlay, underlay
- Decoration ⇒ decor

- Installation ⇒ substrate
- Stabilisation of the element ⇒ backing

5.4.4.1. Production Processes

a) High Pressure Laminate (HPL)

High-pressure laminate (HPL) is one of the oldest laminates. HPL are composite products consist of up to 20 paper layers produced in sheets on single or multiple opening presses. Base materials are several resin-impregnated papers (webs) whereas the outer layers are melamine impregnated decor papers, and the core consists of phenolic resin impregnated unbleached kraft paper. These are folded up together and pressed at a specific pressure of 7 N/mm² in minimum and at a temperature of about 140°C. Thickness is between 0.4 and 1.6 mm. Press time show a wide range between 50 seconds and 90 minutes (including cooling of the laminate inside the press). Common dimensions are 1310 to 2150 mm in width and 1225 to 3650 mm in length. Surface design can be modified by using smooth, high gloss, embossed or structured plates.

b) Continuous pressure laminate (CPL)

Continuous Pressure Laminate (CPL) consists of up to 10 resin impregnated and, where indicated, printed paper sheets. The papers are pressed at continuous double belt presses with a specific pressure of 1.5 to 10 N/mm² at temperatures of 150 to 190°C. Production speed is about 17 m/min. Thickness is about 0.2 to 1.2 mm whereas the width is up to 2130 mm.

Both, HPL and CPL have to be bonded to the substrate by a suitable adhesive using a relatively low temperature and pressure.

c) Direct pressure laminate (DPL), low pressure laminate (LPL)

Direct Pressure Laminate (DPL) and Low Pressure Laminate (LPL) consist of resin-impregnated papers (e.g. overlay, decor, and underlay). They are pressed onto the substrate in batch or continuous presses. Simultaneously, the balance paper is pressed at the backside of the substrate. A specific pressure of 2 to 3 N/mm² is applied at a temperature of ca. 180°C. Press time range from 20 to 40 sec per cycle.

d) Paper impregnation

Impregnation processes of the different papers follow in general the same steps. For impregnation the paper is reeled of the roll and then passes to an impregnation bath (figure 5.4.5). Inside the bath the paper is brought into contact with the resin (MF, UF, PF). In some cases the paper is wetted previously for better resin penetration. First contact with the resin is on one side only to release contained air. This prevents entrapping of air inside the impregnated paper that would result in blisters and clouds of the final paper. After the first resin contact, the paper moves to so called sky-rolls for completion of resin saturation. Afterwards paper is completely immersed in the resin bath again. Subsequently the wet paper passes the dryer containing 3 – 5 drying zones at temperatures from 105 – 135°C (150°C for overlay). The dried paper is cooled and cut into sheets, sometimes reeled as well. Feed speed of the process varies between 15 to 80 m/s (150 m/s for PF).

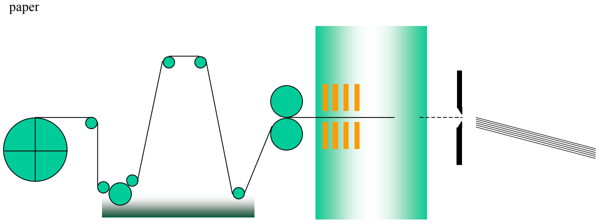

Figure 5.4.5: Impregnation process (Patt, Reinhard 1997)

Table 5.4.1: Characteristics of impregnated papers.

Paper	**Paper weight (g/m^2)**	**Resin type**	**Resin Load (%)**
Overlay	14 … 36 … 62	MF	200 – 280
Decor	70 – 100	MF, UF	100 – 125
Underlay	130 – 275	PF	
Balance paper	80 – 115	PF, MF, MUF	100 – 140

e) Production of substrate

Historically particleboard was used first as a substrate for laminate floorings. From the mid '90s High Density Fibreboards (HDF) became more and more common. Actually, it can be said that about 90% of the worldwide used substrates are HDF. For HPL and CPL particleboard still is widely used.

Depending on the intended area of application different suitable resin systems can be identified. Most of the substrates are produced by using UF, UFm, MUF, MDI or PF resin systems. For improving moisture resistance resin load have to be increased and/or higher content of additional components (e.g. melamine) are needed. Actually, lowest thickness swelling required is about 4%; lower quality boards have thickness swelling of 10% or 14%.

Formaldehyde emission is related to the resin system used. 0.1 ppm is the common maximum value, which is equal to E1-standard.

For meeting required properties during processing and application of laminated floorings high-density substrates are needed. HDF and particleboard often show mean densities of 850 to 950 kg/m³. Besides that, a distinct density profile over panel thickness is necessary. Maximum density in the surface layer should be of about 1,000 kg/m³ for low roughness and proper bonding of resinated papers in the short cycle press. Core layer density should be homogenous for stable and sharp-edged moulding of the narrow sides. Furthermore, minimum density in the core layer should be not less than 780 kg/m³ for sufficient bond strength during short cycle pressing.

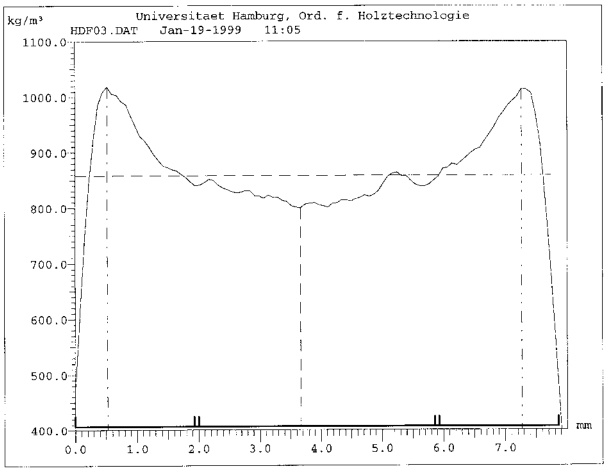

Figure 5.4.6: Density profile of un-sanded HDF substrate for laminated flooring.

Thickness of the substrate is of importance due to:

- Sufficient thickness to permit sharp-edged mouldings of the narrows (tongue and groove)
- Thickness as low as possible to serve in lieu of common floor coverings

5.4.4.2. Classifications, Quality Requirements and Test Procedures

Specification and classification of Laminated Flooring (DPL, CPL) are regulated in EN 13329. All Laminated Flooring shall fulfil basic general requirements whereas tighter tolerances can be required for special applications. General requirements cover tolerances regarding dimensions, light fastness, static intention and surface soundness of the individual elements. Classification of Laminated Flooring is basically linked to mechanical and moisture resistance, which is significantly related to the area of application (see table 5.4.2). Domestic and commercial areas are each differentiated into 3 levels of use (moderate, general, heavy). These 6 groups correspond with 5 abrasion rates of the Taber Abrasion Test, which are in combination with thickness swelling in most cases the decisive properties for classification.

Table 5.4.2: Classification requirements (EN 13329) for Laminated Flooring

Levels of use	Domestic			Commercial			Test method
	moderate	general	heavy	Moderate	general	Heavy	
Typical application	bedroom	Dining room, living room	Entrance area, private offices	Hotel room, conference room	Boutique, classroom	Public building, hallways	
Class	21	22	23	31	32	33	
Abrasion resistance	AC1	AC2	AC3		AC4	AC5	EN 13329
Impact resistance	IC1				IC2	IC3	EN 13329
Resistance to stain	4, gr. 1&2 3, gr.3	5, gr. 1&2 4, gr.3					EN 438
Resistance to cigarette	---	4					
Effect of furniture leg	---		No damage shall be visible, when tested with type 0 intendor				EN 424
Effect of castor chair	---		No change in appearance or damage shall be visible				EN 425
Thickness swelling	20%			18%			EN 13329

The common standard prEN 14041 for resilient, textile and laminate floor coverings with Health, safety and energy – saved requirements is published. The based tests methods for this requirement standard are in preparation (for instance prEN 13893).

For sufficient abrasive resistance specific overlays are used. So far most Laminated Flooring producers used overlays where the papers itself contain some amount of corundum (Al2O3) resulting in high abrasive resistance in the Taber Abrasion Test. Nowadays alternative procedures are applied where the overlay or decor paper is coated with resins containing corundum requiring different impregnation techniques.

Moisture resistance and especially thickness swelling are of great importance for product behaviour during utilisation where humidity and other moist situations (e.g. wet cleaning, mop up) affecting the substrate. The achieved moisture resistance mainly based on the used type and amount of adhesive for substrate production. Some process techniques and procedures can support improvements in moisture resistance (e.g. additives, resin distribution, hot stacking).

During utilisation of Laminated Flooring especially the connections of elements are sensitive to environmental effects (wear, moisture). For improving stability, the edges are sealed in many cases. For impregnation of the tongue-and-groove edges, polyurethane or paraffin are used which result in a delayed absorption of moisture (humidity, water exposure). Edge sealing is of great importance for elements being installed without glue (so called klick-systems). In case that the elements are glued together when installing, it is crucial to use an adequate glue for proper bonding.

In the last years, installation of Laminated Flooring without glue application became more and more popular. For this purpose a number of different metal profiles (clips) and tongue-and-groove systems (shapes) were developed. Several legal proceedings are ongoing due to questions of inventories and registered designs. Investigations have shown that are a lot of differences between the types of click systems referring thickness swelling, resistance to changing climates and long term stability.

5.4.4.3. Research Needs

Further improvements of moisture resistance (thickness swelling, (linear expansion))

Edge sealing (especially for glue-free systems)

Connections design

Liquid overlay (application, quality consistence)

Abrasive resistance (liquid overlay, lower paper weight)

Objective test methods to distinguish properties of click systems (Emmler 2001)

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prEN 1910 Wood and parquet flooring and wood panelling and cladding - determination of dimensional stability

EN 13329 Laminate floor coverings – specifications, requirements and test methods

prEN 13442 Wood and parquet flooring and wood panelling and cladding – Methods to determine the resistance to chemical agents.

prEN 13489 Wood flooring (including parquet), product standard, multi-layer parquet

ENV 13696 Wood and parquet floorings – Determination of the elasticity and resistance to wear

prEN 13893 Resilient, textile and laminate floor coverings –Parameters for the measurement of dynamic coefficient of friction on floor surfaces

prEN 14041 Resilient, textile and laminate floor coverings – Health, safety and energy-saving requirements

prEN 13756 Wood floor covering – Terminology

5.5 Joinery

Murt Redington

5.5.1 General

When moving from a discussion of the use of adhesives as a specific concept in areas such as the bond line or glued-in rods, to the use of adhesives in products, definitions have to become much more general. Thus, joinery itself needs to be defined in order to see how, where, why, how much… are adhesives used. Companies that consider themselves involved in joinery vary in their definitions. After interviewing a number of companies a basic definition can be given, but there are a number of important exceptions. Joinery may be considered as:

- Non-structural
- Non-moveable
- Visible objects
- Not subject to extreme weather conditions
- Made predominantly from wood and wood products
- That would traditionally have been constructed using joints.

A typical list of joinery examples, where the companies legitimately called themselves joinery companies, would include the following:

- doors, windows, stairs, architrave, skirting board, dado rail, shop fittings,
- office fittings, name plates, shop fronts, cupboards and shelving.

This typical list is confused by a number of exceptions. Although many companies specialise in just one particular product line, some are included while others are not. There is a hazy line between carpentry, joinery and furniture. Unwritten definitions carry considerable overlap. For instance, wooden flooring is considered by most as bordering on joinery but these same people have no problem in including stairs. On the other hand, kitchen unit manufacture is seen as such a specialisation within joinery that it generally is not considered as such. There are many historical and cultural reasons for this confusion.

To return to the definition above, it can be seen that the non-structural aspect is not strictly true. Loads are certainly transmitted, but the elements of joinery are not an integral part of the construction and can be removed from the structure. The fact that joinery elements can be removed is not the same as mobility in the sense that furniture is considered to be. The visibility criterion is important in that surface finish, appearance and aesthetics are considered to be essential features.

A number of joinery works were interviewed. It was difficult to get an idea of volumes of joinery and adhesives used. Joinery imparts a high degree of added value to wood and wood products and the companies preferred to think in terms of turnover. Thus the cost of adhesives is often not a factor in selection. The companies interviewed were SMEs in the annual turnover range of 5 - 10 million euros with one or two exceeding 25 million euros. They all fell broadly within the definition.

The biggest single issue in respect of the use of adhesives in joinery was in respect of “callback”. Callback is where the company has to repair the item or object due to warranty considerations. It is a complex area as there are a number of aspects to it. Although many joinery components are mass produced there is always some element of assembly or fixing on site. The production use of adhesives then has to be considered in two quite different environments, i.e. a controlled factory environment and a quite unpredictable assembly site environment. The callback costs are extremely high in that there is an initial high fixed cost in responding to the problem, no matter how small it is, and the actual repair cost. It is in this context that a self acknowledged conservative industry sector is reluctant to embrace new adhesives and technologies unless there is demonstrable development.

5.5.2 Production

The types of wood used in joinery are generally in the higher quality range. As mentioned previously the value added as a result of joinery operations is quite high. It is not unusual to have solid wood used in preference to veneered sheet material unless there are large surface areas involved. The types of wood used then include many tropical species, temperate hardwoods as well as fibreboard both veneered and plain. The variety of different types of wood found in joinery establishments is quite large. General purpose or broad spectrum adhesives are more the norm in order to handle the variety.

The variety of adhesives used by the companies interviewed was quite small. There was a difference in the usage of adhesives between factory production and on site installation. Generally the factory was more conservative in that mass production and larger volumes introduced an inertia to change. The people installing the joinery components were more adventurous in their use of adhesives as their requirements were different.

The typical adhesives used in the factory were the traditional adhesives such as PVA based glues and the formaldehyde based glues. The general impression was that the glues used in the factories were quite satisfactory. Typically, there would be a general welcome for a shortening of cure time. However, there would have to be a guarantee that long term performance would not be affected.

The PVA based adhesives were considered as the interior adhesives. Some companies were experimenting with cross-linked PVA adhesives. However they pointed out that due to the nature of the industry, changing from one adhesive to another was quite an expensive process as not only did set up machinery costs but also personnel training costs have to be taken into account. UF and PF adhesives were the exterior adhesives of choice. No RF adhesives were used by the companies interviewed.

On the installation side there were some innovations. The personnel involved in installation were working under a different time frame and sometimes under difficult conditions. Anything that made life easier was considered. In this context adhesive use in joinery was but one area of exploration. Mechanical fasteners and clips strongly competed with adhesives. Apart from the traditional adhesives, installation personnel used cyanoacrylates and structural mastics.

However, all this leads to the fundamental idea of the use of adhesives in joinery. As the term suggests joinery is about joining bits of wood together. The traditional emphasis on joints has yielded to the use of fasteners and adhesives as greater efficiencies in production were required. The use of adhesives has to compete on its merits in the light of the important design and function criteria. Ease of use, load spreading and vibration resistance have to be balanced against duration of load, installation and manufacturing reliability. This is the context of "callback". At the moment, it seems that in joinery, adhesives play a minor role compared to aesthetic and expensive joints on the one hand and fast, safe mechanical fasteners on the other. In many instances, adhesives are used as extra insurance in mechanical strength or "just to stop the squeaks". The basic technique was referred to as "glue and screw".

5.5.3 Requirements

Assessing requirements is not always clear cut. One of the common themes was that of incremental improvement. The industry accepted general improvements but is wary of radical improvements. Features such as:

- Consistency from batch to batch (viscosity, tackiness, colour)
- Greater tolerance of temperature and humidity range
- A demonstrable acknowledgement of environmental friendliness
- Longer shelf life and pot life

are always welcome as there is a low associated risk. The radical improvement was generally left to the competitor.

The industry is happy with tried and trusted adhesives. They have confidence in them and will only substitute if the adhesive is the same but considerably cheaper. In this context adhesives are a victim of their own success.

5.5.4 Research Needs

From the general contentedness of the industry with the current adhesives, there do not seem to be may research **needs**, as such. However, some aspirations were mentioned. Two of the most common were:

1. The need for accelerated testing: Unambiguous long term performance characteristics of improved or alternative adhesives were needed to convince people to change.
2. Bridge the gap between mechanical fasteners and adhesives.
3. This could be achieved by combinations of fastener design incorporating adhesives, improved adhesive delivery systems or formulation of adhesives with additional mechanical keying features. A final query was for an adhesive that could be “unscrewed with a screwdriver”.

5.6 Gluing of Wood to Fibre Reinforced Plastics

M.L.R. van der Linden

Fibre reinforced plastics (FRP) are relatively new materials that have been used in various industrial applications. They are composed of a reinforcement material (glass, aramid or carbon fibres) surrounded and retained by a (thermoplastic or thermosetting) polymer matrix.

Advantages of FRP are their high strength and rigidity at low weight, and the fact they are non-metallic, corrosion resistant materials, making them very promising for the reinforcement of structural members. Their major disadvantage is their high price, although in the last 10 years, the cost of highly durable, high strength fibres, such as aramid and carbon have declined substantially.

The following fibres are commercially available (listed by increasing price):

- Glass fibres: the most frequently used, have moderate cost for very good mechanical properties. May be used in the form of pultruded profiles (FRP), fabrics (tissues), mats of cut fibres or continuous agglomerates;
- Aramid fibres (ex. Kevlar) originate from aromatic polyamides, created through a process of extrusion and drawing. Available in various forms, including sheets, fabrics, ropes and ribbons.
- Carbon fibres are mainly used in the form of pultruded profiles. This process enables the formation of a wide range of cross sectional profiles, either of solid, open or hollow shape.

5.6.1 FRP Pultruded Profiles Used for Local Reinforcement of Timber Members

There are many examples of structures strengthened with externally applied FRP reinforcing strips or pultruded profiles. Although most commonly used in reinforced or pre-stressed concrete, there is also a high potential and some experience in the reinforcement of timber:

- To strengthen and rehabilitate existing structures as a result of increasing loading or design requirements (to enhance the structural capacity – flexural strength and stiffness)
- To restore deteriorating or damaged structures
- To reduce variability of week timbers used for new construction, increasing strength, stiffness and ductility of low grade solid timber (Crews, et al, 1998).

Generally a small proportion of FRP (0,5 to 1,5%) is placed along the length of the beam, within the tensile zone, glued with epoxy or polyester glues, and less frequently polyurethane (more ductile) or acrylic products.

5.6.2 Reinforcement of Mechanical Joints

Joints are often the weakest part of the structure. FRP are used in the joint area to increase its strength by improving the tension perpendicular of timber in this location. Therefore, failure does not occur in the wood but it is determined by the strength and the quality of the mechanical fasteners. Ductility is also increased.

Materials used are normally fibreglass fabric (wrapped around the joint in directions of 45º and 90º with respect to the wood grain direction) and commercially available epoxy (Chen, et al, 1994).

For joints with dowels or bolts loaded perpendicular to grain, reinforcement can ensure full load-carrying capacity for very small end-distances. Test results also suggest that reinforced joints have a time to failure load relationship similar to that of non-reinforced joints (Larsen, 1994).

5.6.3 New Joints (Bonded In-Rods)

Pultruded GFRP dowels and plates have also been used to make connections for new building projects and renovation and repair work (to joint new to old timber, for instance, or to stitch delamination of fissure openings).

Glues used for these bonded-in rods or bonded-in plates include epoxy and polyester, acrylic (CIB-W18/32-7) and polyurethane glues.

5.6.4 Reinforcement of Glued Laminated Members

Glulam members have been reinforced perpendicular to the grain with glass fibre mats (possible also with parallel fibres, or chopped fibres 50mm long with random orientation) glued with polyester adhesives to the sides of the beams or sandwiched between two beam parts. This reinforcement is able to double the load carrying capacity and change the failure mode from tension perpendicular to bending.

Local reinforcement for tension perpendicular can be very effective for end-notched beams. A simple reinforcement near the notch may increase the load-carrying capacity by a factor of 3. Reinforcement is stable under severe moisture and temperature influences and also an efficient vapour barrier (Larsen, 1994).

GangaRao et al (1996) showed that the used of a primer /resin combination increases the effectiveness of the wrap over the wood core. Owing to the porous nature of wood, a low viscosity primer was used to fill the pores creating a better surface for bonding. Then also Sonti et al. (1996) applied first a low viscosity resorcinol formaldehyde (RF) resin as a primer, and then a higher viscosity epoxy was used for bonding the glass composite fabric to the glulam beam.

Bui et al (1996) proposes the use of glass fibre mats glued with epoxy resin to reinforce finger jointed laminates (40 to 60% tensile strength increase), since this strength often limits the use of Australian hardwoods for glulam.

Reinforced glulam beams are being used commercially, using GF or AF mats applied on the tension side of the beam for improved mechanical performance (example: FiRP® manufactured by several licensees in the US).

FiRPM panel is a uni-directional high strength FRP with pretensioned fibres that are aligned to the long axis of the panel. This is glued to the glulam laminates with glues such as phenol-resorcinols, melamines or urea-based adhesives, therefore not requiring changes in the production line (just going along with wood laminations).

According to Dagher et al (1998) FRP reinforcement of wood provides many advantages including reduced creep. Besides, as little as 1% Glass FRP tension reinforcement can increase the bending MOR of glulam beams by as much as 50%.

<u>Discussion:</u>

a) *Generic technical approval basis has been developed in some countries for new product, concerning: structural behaviour, durability, dimensional stability, performance in fire, practicability for use by industry and restrictions on use.*
b) *Follow up of in-situ reinforcements: in addition to visual evaluation of delamination, global vibration tests are often carried out to monitor possible stiffness degradation. Other methods?*
c) *Glue line shear under wet service conditions (timber variations are higher than of FRP). Cyclic delamination tests are essential to assess the ability of the glue line to withstand moisture content fluctuations and induced dimensional changes (Tingley and Cegelka, 1996)*
d) *Temperature effect and ageing of glues (and FRP) are particularly important on surface reinforcements. Suitable test methods should be established.*
e) *Shear performance between the reinforcement layers and the wood and between the reinforcement layers themselves should be further investigated and modelled.*
f) *Since many applications will be in service class 2 or 3, the saturated tensile strength, creep and tension-fatigue characteristics of the FRP should be evaluate.*

Wood Plastic Composites

So-called Wood-Plastics Composites (WPC) are a family of products covering a continuous range from almost 100% wood to 100% plastic. These can be formulated in two basic forms: composites with external reinforcement or integral reinforcement. The first type includes timber or timber based structural elements locally reinforced with FRP, as described above.

5.6.5 WPC with Integral Reinforcement

This covers a number of new ”homogeneous” products, mostly under development or experimental use. Motivations for producing these WPC seem to be their improved dimensional stability and higher natural durability without the need for preservative treatment, as compared to timber. Though the present production of WPC is low, this is expected to increase due to the significant number of companies investing in this area (Tichy, 1998).

Basic formulations have a plastic matrix material such as polyethylene, polypropylene, polyvinyl chloride, and many others; wood reinforcing elements are dispersed generally throughout ranging from in size from large stands to wood flour; in addition to wood reinforced and filler elements, carbon fibre, glass fibre and other additives have been used to improve structural integrity and performance of these composites.

Extruded members of these WPC may present suitable compression strength, durability, abrasion resistance and ductility, although their end-use so far implies relatively low stress applications. More demanding structural applications depend on future improvement of the actual WPCs.

Some commercially available materials include Trex® Composite Lumber, some manufacturers using the patented StrandexTM technology, and Fibrex® a product of Andersen company. All products have a major wood component (around 50% or higher).

Trex® design values in flexion are about 1/3 of lumber. However, by simply increasing the density (without reinforcing materials) by 20%, bending strength and stiffness can be doubled. Fibrex and Standex both have products with MOE ≥ 6,9 GPa. Other properties of the WPCs such as shear, compression strength and bearing strength are equivalent and in some cases better than solid wood. Fastener performance is also typically much better with the composites (Tichy, 1998).

Discussion

a) *Extensive need for investigation is identified in the area of WPC of the integral reinforcement type, in order to produce improved materials with suitable mechanical properties for structural applications. Temperature effects of WPCs are likely to be more important than in solid timber, as well as long-term performance and creep problems. A lot of research is necessary to characterise such key aspects.*
g) *Life cycle costs are also a negative aspect of these products. Research is needed concerning environment impact of production, use and disposal of WPC components.*
h) *Besides, there is a need for specific standards for the evaluation of WPC, since only some test methods developed for wood fibreboard and particleboard may be fairly applied to WPCs also. In the USA one such standard is being written.*

Blomquist et al (1983, pp 116) mention that adhesion to surfaces of plastics generally is believed to result from two mechanisms. As with wood, adsorption or physical attraction resulting from Van der Waal's forces and hydrogen bonding (when possible) are credited as being the major force between a plastic and an adhesive. In addition, some adhesives for plastics contain solvents that partly dissolve the plastic adherend, allowing molecular interdiffusion between adhesive and adherend molecules.

Although electrostatic forces have been proposed as accounting for adhesion between plastics, this concept is still questioned by many. Because plastics (other than foams) have little or no pore structure, mechanical interlocking is not a likely mechanism of adhesion.

Brand and Hamm (1998) describe the repair of wind tunnel fan blades that consisted of filling cracks with an adhesive and curing a hybrid carbon fibreglass fabric doubler to the high stress region of the blade. The paper discusses the technical issues of the repair, the problems that arose and the subsequent fatigue testing done at NASA-Ames.

Glass fibre reinforced holes in laminated timber beams were investigated by Hallström (1996). The polyester resin was used both as matrix and adhesive between the reinforcement and the wood. The adherence was initially poor and a comparison was made between different treatments of the wood.

Specimens with and without reinforcement and with or without rounded corners of the holes were tested in 4-point bending.

6. Emission

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6.1 Introduction

During more then 20 years, formaldehyde has been a hot item in panel industry. In the late seventies, customers found out that gases escaping from particleboards provoked headache and irritation of the mucous membrane. The fact that particleboard has been the first sub sector to be tackled had to do with extent of market share in the total panel market. Indeed, every board made with an aminoplastic resin emits formaldehyde such as some other frequently used products as wallpaper, textiles etc.

Since that time we learned a lot about the emission mechanisms of boards and about the mutual influence several formaldehyde sources can have on each other.

6.2 Overview on Emittable Substances

6.2.1 Formaldehyde

Formaldehyde is one of the main components in aminoplastic and phenoplastic resins. The amount of formaldehyde in the resin and amount of emittable formaldehyde depends on the formulation of the resin (molar ratio) and the condensation process. Phenolic resins usually show very small emissions due to the C-C-bonding between formaldehyde and the phenolic ring. In order to decrease the formaldehyde emission from aminoplastic resins, the molar ratio of these resins has been decreased dramatically within the last two decades (Dunky 1994, 1995). In addition to that many resin formulators have change the condensation from a traditional three step (Horn 1978) to complex multi-step processes in order to guarantee an optimal performance of the resin even at this low formaldehyde contents.

Questions and topics of R&D:

a) *Development of fortified aminoplastic ”E-Zero” glues resins in industrial scale.*
b) *Development of low emission mixed or copolymerised adhesives (PF-PMDI, UF-PMDI, MUPF, UF-PF) in industrial scale.*

6.2.2 Phenol

Residual unreacted phenol can be present in phenolic resins and emit during the production of wood based panels as well as from the produced boards, however to a very small extent.

Even years ago, the general positive trend towards reduction of all types of environmental burdens led responsible phenolic resin manufactures to minimize the levels of free phenol and substituted phenols in phenolic resins. As a result of these developments, resoles with a level of monomeric phenol below 0,2% can presently be produced.

Questions and topics of R&D:

a) *See 6.2.1 b*
b) *Introduction of ”environmentally friendly” resins by reduction of monomers.*

6.2.3 Isocyanates

Organic diisocyanates are extensively used in the manufacture of polyurethane (PUR) products for indoor application. One of the most important monomeric compounds is 4,4´-diphenylmethane-diisocyanate (MDI) as a component of foam, coating and adhesive. In some types of wood based products polymeric MDI (PMDI) is used as binder. There exists a possible emission during the production of PMDI-bonded boards, partly under decomposition to the amines. Emission of PMDI-covered dust and aerosols during production has to be of concern. To solve this problem special working conditions were introduced. Emission of 4,4′-diphenylemethane-diisocyanate from produced boards has only been proofed directly (0-1 days) after production. No emission of MDI was detectable after this period (Fischer and Böhm, 1994)

Questions and topics of R&D:

a) Development of easy to handle MDI/PMDI emissions tests. Improvement of the sampling, identification and quantification procedure.
b) Development of emissions tests for other isocyanates than MDI.
c) Improvement of the production of MDI/PMDI to avoid high impurity contents

6.2.4 Wood Components

6.2.4.1. Free Acids (Formic Acid, Acetic Acid)

Due to the high temperatures during the production of wood based panels a hydrolysis of ester groups in the cellulose can take place with following emission of formic and acetic acid (Roffael 1989 a+b, Poblete and Roffael 1985 a+b,). This process especially can occur at highly alkaline conditions with phenolic bonded boards. Determination of the emission can be performed with similar test methods as for the subsequent formaldehyde emission (Roffael et al. 1990, 1991).

Questions and topics of R&D:

a) Development of phenolic adhesive resins in which alterations in the reactivity allow lower curing temperatures (Gardziella 1999).
b) Development of fast curing low alkaline phenolic resins in industrial scale.

6.2.4.2. Terpens

The most frequent terpens in indoor air are: α-pinene, β-pinene, Δ3-carene, α-terpinene and limonene. α-Pinene is a component of wood and therefore can be found in all furnished rooms. The amount of terpens is dependent on the used type of wood.

Questions and topics of R&D:

a) Contribution of terpens to overall VOC emission?

6.2.4.3. Other Volatile Organic Compounds (VOC's)

Volatile organic compounds (VOC's) are emitted into indoor air from a number of sources. VOCs usually are residual solvents, monomers from plastic materials and other chemicals that can even emitted by wood, but also residual methanol from the adhesive resin, which might emit from wood based panels and furniture. VOC's are classified by their boiling temperature (50-100°C to 250-260°C).

Most found compounds are aliphatic and aromatic hydrocarbons, terpens (section 6.2.4.2), chlorinated hydrocarbons, esters, aldehydes (without formaldehyde) and ketones (Seifert 1999, Brown 1999).

Questions and topics of R&D:

a) Use/Production of high quality formaldehyde with low methanol content.
b) Use/Production of adhesives with low monomer and solvent content. Reduction of auxiliaries in the adhesive formulation.

6.3 Test Methods for the Determination of Various Compounds in the Air

6.3.1 Sampling

For water-soluble chemicals usually a stream of air is passed through an aqueous solution, which absorbs the various substances like formaldehyde from the air stream. These substances are determined in the solution. A gas sampling equipment with gas volume counter is e.g. described by Menzel et al. 1981.

VOCs are sampled in various impingers (filled with water or other absorption liquids), so-called ”Summa Canister” for total VOCs (Broline 1999, Broline et al. 1995, Carlson et al. 1995, Peek et al. 1997). Sampling of VOCs can also be done by using sampling tubes filled with various materials (Tenax, Tenax TA, Carbotrap). Identification and quantification is done after thermodesorption by GC/MS (Uhde 1999, Brown 1999).

Questions and topics of R&D:

a) *Correlation between VOCs from wood based products and the production process / purity of the raw materials.*

6.3.2 Chemical Analysis of the Various Emitted Substances

6.3.2.1. Formaldehyde (Iodometric, Photometric, Other Methods)

Determination of formaldehyde can be done using (Gollob and Wellons 1980, Roffael 1993):

- Photometric method: e.g. MBTH method (Sawicki et al. 1961), chromotropic acid method (Altshuller et al. 1962), acetyl acetone method (Nash 1953, Belmin 1963), p-rosanilin method (VDI 3484).
- Titrimetric method: e.g. acidimetric sulphite method (Walker 1953 a), iodometric method (Goldmann and Gagoda 1943), hydrogen peroxide method (Walker 1953), hydroxyl hydrochloride method (Roe and Mitchell 1951)
- fluorometric
- Gas chromatographic methods (Wölfel et al. 1985).

The low stability of dilute aqueous formaldehyde solutions must be considered (Way 1980).

Questions and topics of R&D:

a) *Sensitivity (analysis threshold) and specific detection of formaldehyde for the various methods?*

6.3.2.2. Phenol

Analysis is done e.g. via the p-nitroanilin method, as described in VDI 3485-1 (1988), with some proposals of modifications by Schneider and Deppe (1995) or GC-MS after extraction with acetone-methylene chloride (Tiedemann et al. 1994).

The direct analysis of phenol by HPLC in combination with UV and/or fluorescence detection enables a sensitive and specific determination (Schulz and Salthammer 1999). Air sampling is done in alkaline solution by the use of Muencke absorbers. This solution is directly analysed by HPLC after neutralization. Suitable wavelengths for UV detection are 254 nm and 280 nm. Different HPLC techniques using isocratic conditions or solvent gradients have been proposed (Kaschani, 1991; Engelsma et al., 1990). In aqueous solution phenol exhibits a broad fluorescence (Berlman, 1971), which enables a highly sensitive fluorimetric determination to be performed.

Questions and topics of R&D:

a) *Sensitivity (analysis threshold) and degree of specific response to phenol of the various methods?*

6.3.2.3. Isocyanates

The accurate determination of airborne diisocyanates is a sophisticated procedure due to the high reactivity and low indoor concentration levels, which are in the magnitude of ng/m³. On sampling, an immediate derivatisation to a stable compound is necessary. Tinnerberg et al. (1997) developed a sensitive technique using dibutylamine for derivatisation and LC-UV/LC-MS. The most sensitive HPLC-method has been described by Schmidtke and Seifert (1990). When using 1-(2-methoxyphenyl)-piperazine for derivatisation and a column switching method, a detection limit of 1 ng/m³ could be achieved by electrochemical -(ELCD)-monitoring. This method can be applied for measurements in workplace areas or indoor environments and is recommended by the German quality guideline RAL-UZ-76. However the method is very susceptive to troubles and therefore hardly suitable for routine analysis. The OSHA method n°. 47 (OSHA 1989) has been developed for workplace areas with concentrations = 1 µg/m³ and describes a derivatisation of MDI with 1-(2-pyridyl)-piperazine on a coated filter, using the combination HPLC/fluorescence for separation and detection, respectively. A modified method with a detection limit of 9 ng/m³ (MDI) can be used for the determination of airborne diisocyanates in living spaces (Schulz and Salthammer1998).

6.3.2.4. Free Acids

Determination is possible via ion chromatography or via titration with e.g. a diluted NaOH solution (Poblete and Roffael 1985).

6.3.2.5. VOCs

The qualitative and quantitative determination of the great number of individual chemical components is difficult and is done via several modern analytical methods like UV/fluorescence spectroscopy, GC/FID, GC/MS or HPLC. For more information s see section 6.3.1 above.

6.3.3 On Line Test Methods

FLEC: Field and Laboratory Emission Cell:

This method has been designed for VOC emission testing of material surfaces. The surface of the test specimen itself becomes the bottom part. The cell is portable with regard to controlled non-destructive field-testing of homogeneous materials. Technical details have been provided by Wolkoff et al. (1993, 1995, 1996). The dependence of the emission profile from the type of material or chamber properties like temperature, humidity, air exchange, loading factor (surface-to-volume ratio in m²/m³) and sinks has been subject of numerous investigations (Uhde et al. 1998).

6.4 Test Methods for the Emissions During the Production Process

6.4.1 Dryer

Substances under investigation are formaldehyde and various wood inherent chemicals like terpenes. Sampling and analysis is done as described above.

6.4.2 Hot Press

Substances under investigation are formaldehyde and various wood inherent chemicals. During the hot press process various substances can emit from the hardening or already hardened resin and from the wood component. Sampling is done using ”enclosed caul plate and gas collection systems” (Carlson et al. 1994, 1995, Petersen et al. 1972, Wolcott et al. 1996).

6.5 Test Methods for the Subsequent Emission

Several principles of classification of the great number of test methods exist:

(i) Measurable emission vs. emittable potential

The first type of methods determine the really emitted amount of formaldehyde, e.g. as concentration of formaldehyde in a certain vessel or climate chamber. The other methods look at the emittable (free) formaldehyde without considering whether the amount really will emit or not or in which time this emission would occur.

(ii) Field measurements vs. laboratory test methods

The duration of the tests is the decisive parameter: on the one side the steady state equilibrium needs several days for adjustment; on the other side quick laboratory methods are necessary to check the daily production of wood based panels.

6.5.1 Climate Chamber (prEN 717-1)

A dynamic steady state is attained at a certain temperature and humidity and at a constant ventilation rate that is different from zero. Emitted formaldehyde is taken away from the test room at a constant rate. So the observable chamber concentration depends on three different processes:

During the hot press process various substances can emit from the hardening or already hardened resin and from the wood component. Sampling is done using ”enclosed caul plate and gas collection systems” (Carlson et al. 1994, 1995, Petersen et al. 1972, Wolcott et al. 1996).

- Formaldehyde is emitted by the board to the surrounding air.
- Some formaldehyde is readsorbed by the board.
- The chamber is supplied with pure air.

It is easily to understand that the steady state concentration under dynamic conditions will be lower than under static conditions. The higher the ventilation rate the lower the equilibrium concentration. A mathematical model thereof has been established by Fujii et al. (1973), Hoetjer and Koerts (1978) and Berge et al. (1980).

Chamber methods try to reproduce living conditions. This conditions are (by convention): 23°C, 45% humidity, ventilation rate of 1/hour and loading factor of 1 m^2 board surface / m^3 of chamber volume (including some special rules for open edges), air speed 0,3 m/sec (to prevent building up of a border layer with higher formaldehyde concentration on the surface of the boards, which might hinder the formaldehyde emission and lead to too low numbers). Additionally the formaldehyde emission is strongly depends on the humidity, since hydrolysis is the most important reaction leading to a release of formaldehyde, at least for UF-resins. In average such an steady state concentration needs more or less 10 days or even longer to be reached. This makes the test not very suitable for quality control in industry. However, to give a reliable prediction of the behaviour of the panel in real circumstances, it seems to be the only way.

Also smaller versions of chambers (e.g. the 1 m^3-chamber) are operating under the same conditions. Results of this method were said to be exactly the same as the results from the big chamber. Finally the chamber methods, the big chamber as well as all other chambers operating under the same conditions, have been accepted commonly as reference method and are described in EN 717-1.

Some advantages of the 1 m^3 chamber compared to a big chamber are:

- only 0,5 m^2 of panel is needed
- the volume is smaller, less loss of space, less consumption of energy
- filtering and cleaning of the air is less complicated due to the fact that only 1000 l/h is needed.

Disadvantages of the 1 m^3 chamber against a big chamber are the fact that no possibility to test whole furniture can be tested.

Comparison of results from big chambers at different research institutes is still problematic. These problems could have to do with the fact that prEN 717-1 only describes the basic operation parameters to which a chamber has to satisfy. Most of the institutes however built their own version of the chamber. The physical rules of the working of the chamber turned out to be more complicated than one could initially believe.

Questions and topics of R&D:

a) *How to reduce the necessary test duration to achieve the steady state concentration in the climate chamber, e.g. using some mathematical models in order to predict the steady state concentration already after short time (few days)?*
b) *How to achieve better conformity of results of different big chambers?*

6.5.2 Laboratory Test Methods for the Subsequent Formaldehyde Emission

Out of the innumerable test methods reported in the literature in the last two decades, only a small number is acknowledged commonly. The main advantage of these so-called derived test methods is the short duration of the tests compared to the climate chamber tests, which enables the daily production check.

a) Content of emittable (free) formaldehyde: perforator value (EN 120)

The emission rate is proportional to the content of free formaldehyde in the board. This correlation between formaldehyde content and emission rate, however, can only be found for boards that are more or less homogeneous like particleboards and MDF, but not like plywood. Eventually the perforator method was found to be the best compromise to measure the formaldehyde content of particleboards, fibreboard and OSB as production control.

b) Test methods describing the emission of formaldehyde:

The second way of measuring formaldehyde is to measure the emission directly, e.g. as concentration in a certain volume of air surrounding the board.

- Static test methods:
  Due to the formaldehyde emission an equilibrium concentration (static equilibrium) in the ”test chamber” is established, which can be measured; no air exchange.

  Formaldehyde is released from the tested board and enters the surrounding air at a certain rate; on the other hand the panel readsorbs the formaldehyde. At the start both rates are rather different and the emission rate is much higher than the absorption rate. After a certain period both rates tend to become equivalent and no more net transfer can be observed.

- Quasi-static test methods:
  The emitted formaldehyde is absorbed by suitable liquids, so there is no real equilibrium concentration possible; no air exchange.

  WKI flask method (EN 717-3): This method consists of bringing a small test piece in a temperature of 40°C and an atmosphere in equilibrium with water or a solution saturated with NaCl. Emitted formaldehyde is absorbed by the salt solution and the concentration in this solution can be measured.

- Dynamic test methods:
  A constant air change is given, which dilutes the emitted formaldehyde; the formaldehyde is sampled in gas wash bottles/absorption bottles and then analysed.

  Gas analysis method (EN 717-2): this is an accelerated dynamic emission method, usually used to test plywood and coated/finished boards.

  Today in Europe a special American accelerated test method, the *Dynamic Micro Chamber* (DMC, Christensen and Anderson 1989), is under investigation. This method seems promising due to the fact that the test duration as well as the conditioning period are very short. In comparison to the perforator test this method has various advantages:

(i) Instead of measuring a content of formaldehyde, the emission of formaldehyde is measured. In principle there is no argument against testing finished boards in the same way.

(ii) Per day tens of tests can be performed.

(iii) No toluene is used.

There is a good correlation with the 1 m³ chamber. Nevertheless more tests are needed, because, among other reasons, the regressions between DMC results and the test results of the standardized methods differ. Additionally the lowest detectable emission rates are still high compared to some requirements in Europe.

c) Correlations among the various laboratory test methods and the formaldehyde concentration in the climate chamber:

This is one of the crucial points not yet clarified completely. Depending on the structure of the board, various correlations will exist. It is doubtful that a uniform correlation will exist at all. On the other side it is necessary, that quick laboratory test methods are available, which can be used for daily production tests. The limits of the results achieved in these laboratory tests hence might be under permanent discussion. Various correlations have been described in the literature (Boehme 1993 a, Deppe 1988 c, Deppe and Jann 1990, Flentge 1989, Mansson and Roffael 1995, Meyer 1996 b).

Questions and topics of R&D:

a) Exact correlation between steady state concentration in a climate chamber and results from laboratory test methods like perforator
b) Lower detectable emission rates in the DMC-method

6.5.3 Special Test Methods for the Subsequent Emission of Other Substances

6.5.3.1. Phenol

See section 6.3.2.2.

6.5.3.2. Isocyanates

See section 6.3.2.3.

6.5.3.3. Free acids

Extraction at room temperature or higher temperatures with following chemical or titrimetric analysis. See also section 6.3.2.4.

6.5.3.4. VOC's

Climate chamber test with following analysis according to various methods (UV/fluorescence spectroscopy, GC/FID, GC/MS, HPLC and others), a procedure is also described in prEN 13 419, pt.1-3. See also section 6.3.1.

6.6 Emission During the Production Process

There exist some literature on emissions during the production process in laboratory scale, but nearly no actual and universally valid results from industrial production processes. Determinations at industrial production plants certainly are done regularly due to governmental regulations, but usually the results are not proprietary. Especially there is a lack of information concerning the influence of various production parameters (composition of the glue resin, press parameters and others) on the emissions in industrial scale.

Questions and topics of R&D:

a) Correlation between the production parameters and the emissions in industrial scale.

6.6.1 Emission During Wood Drying

The wood substance itself contains various volatile substances. Additionally, the high temperatures especially at the entrance of the dryer can cause some pyrolysis and/or hydrolysis of wood inherent chemicals. These are not yet analysed totally. Especially rather dry material entering the dryer can undergo such decomposition reactions. Known volatile substances are aldehydes and ketones, organic acids, alcohols and phenolic compounds.

6.6.1.1. Formaldehyde

Formaldehyde can emit from the wood substance during drying (Marutzky and Roffael 1977, Erle 1994, Ernst 1987, Ingram et al. 1994).

6.6.1.2. Free acids

See section 6.2.4.1 above.

6.6.1.3. VOC's

See section 6.8.5 below.

6.6.2 Emissions from a Fibre Dryer in the MDF-Production

6.6.2.1. Formaldehyde

Additional to the formaldehyde emission from the wood substance (fibres) itself, formaldehyde can emit from the resin applied to the fibres in the blow line before entering the dryer.

Questions and topics of R&D:

a) Reliable measurements of the formaldehyde emission from fibre dryers in the MDF-production.

6.6.2.2. VOC's

See section 6.8.5 below.

6.6.3 Emission from the Press Cycle

6.6.3.1. Formaldehyde

Formaldehyde is released from the glue resin and evaporated together with steam. Results from industrial scale productions usually are not available due to propriety belonging to the individual companies. Laboratory tests results have been reported by Carlson and al. (1995), Petersen and al. (1972) and Wolcott and al. (1996).

Questions and topics of R&D:

a) Which are the main influence parameters on the emission of formaldehyde during the press cycle? How to minimize the formaldehyde emission?

6.6.3.2. VOC's

See section 6.8.5 below.

Questions and topics of R&D:

a) *Which are the main influence parameters on the emission of VOCs during the press cycle? How to minimize the formaldehyde emission?*

6.7 Regulations Concerning Emissions

6.7.1 Regulations Concerning the Maximum Thresholds of Various Chemicals in the Air

Working place thresholds: various limits in different European countries: e.g. 0,5 ppm for formaldehyde in Germany and Austria.

Living room thresholds: recommendation of the German Federal Health Agency 1977 for formaldehyde: 0,1 ppm.

For total VOCs a concentration in air not higher than 300 $\mu g/m^3$ has been recommended (Jann 1997).

For 4,4′-MDI the maximum workplace concentration in Germany is 50 $\mu g/m^3$ (Deutsche Forschungsgemeinschaft).

Questions and topics of R&D:

a) *Are the 0,5 and 0,1 ppm thresholds, resp., low enough or should they be decreased?*

6.7.2 Regulations Concerning Emissions During the Production Process

The possible emissions during the production process are summarized in various national regulations like the so-called ”TA Luft” in Germany. The maximum emission of organic carbon is 20 mg/m^3 spent air (standard conditions) from the press and at the same time 120 g organic carbon per m^3 produced board; organic carbon here means the sum from all organic substances like formaldehyde, phenol and others.

6.7.3 Regulations Concerning the Subsequent Formaldehyde Emission

There is no uniform situation of regulation within Europe. Various EN-standards for wood based panels exist: limit are e.g. for:

Particleboard (EN 312): class 1: 8 mg perforator value
class 2: 30 mg perforator value

MDF (EN 622): class 1: 9 mg perforator value
class 2: 40 mg perforator value

OSB (EN 300): class 1: 8 mg perforator value
class 2: 30 mg perforator value

Special regulations within various countries, e.g. Germany and Austria, are part of these EN-standards. The German regulations (table 6.7.3.1) are the most stringent ones in Europe and are also accepted in several other countries, e.g. Austria as well as in any case of export to Germany.

Table 6.7.3.1: Actual regulations conc. the subsequent formaldehyde emission from wood based panels (Germany) according to the German Regulation of Prohibition of Chemicals (former Regulation of Hazardous Substances)

a) Maximum steady state concentration in a climate chamber: 0,1 ppm (prEN 717-1; 1995)	
b) Laboratory test methods (based on experimental correlation experiences):	
PB:	6,5 mg/100 g dry board as perforator value (EN 120; 1992)
MDF:	7,0 mg - ” -
PB and MDF:	Correction of PW to 6,5% board moisture content
Plywood:	2,5 mg / hr × m^2 in the gas analysis method GA (EN 717-2)

Questions and topics of R&D:

a) *Are the limits senseful and low enough?*

6.7.4 Regulations Concerning the Subsequent Emissions of VOCs and Other Substances

Indoor air guideline levels has been published for phenol and butylated hydroxytoluene (BHT) by Nielsen et al. (1998a) and for formic, acetic, propionic and butyric acid by Nielsen et al. (1998b).

For phenol the recommendation is a maximum steady state concentration of 14 $\mu g/m^3$ in a climate chamber test (Jann et al. 1997 and German eco label RAL UZ 76). The emission of 4,4´-MDI from wood based products should be not detectable by a detection limit of 0,1 $\mu g/m^3$ (RAL UZ 76). Nowadays the achievable detection limit (1,0 ng/m^3) is even lower (Schmidtke and Seifert 1990).

VOCs: there are not yet regulations in force, only a recommendation of not more than 300 $\mu g/m^3$ steady state concentration in living rooms (see section 6.7.1 above).

Questions and topics of R&D:

a) *Are the limits senseful and low enough?*

6.8 Influences on the Various Emissions of Wood Based Panels

6.8.1 Formaldehyde Emission During the Board Production

6.8.1.1. Glue Resin Composition

The lower the molar ratio of an aminoplastic resins, the lower is the formaldehyde emission during the press process (Petersen et al. 1972, Wolcott et al. 1996). Wolcott et al. (1996) could show, that the amount of the formaldehyde emission also depends on the type of bonding of the formaldehyde in the resin. If big parts of the formaldehyde in a resin are bonded in methylol groups, the emission is higher than in the case of methylene bridges.

Scavengers and catchers reduce the overall molar ratio of the aminoplastic glue resin mix and therefore the formaldehyde emission. It is not clear, if (i) a resin with a high molar ratio + addition of greater amounts of scavenger or (ii) a resin with a low molar ratio + addition of smaller amounts of scavenger will give a lower emission of formaldehyde, regarding the same overall molar ratio.

Questions and topics of R&D:

a) *How can the chemical cooking of the resin influence the formaldehyde emission?*
b) *How can the formaldehyde emission during the press process be minimized?*
c) *How can the effect of scavengers and catchers be optimised?*

6.8.1.2. Wood Furnish

The wood furnish also might influence the amount of formaldehyde emitted during the press process (see also section 6.8.2.3).

Questions and topics of R&D:

a) *Is there a distinct influence of the type of the wood furnish on the formaldehyde emission during the press cycle? Which could be the chemical reasons for such an effect?*

6.8.1.3. Production Process Parameters

- Moisture content of the glued particles or the dried fibres
  The moisture content of the glued particles has a distinct influence on the formaldehyde emission during the press cycle. Two reasons are responsible for this: (i) the additional water at a higher moisture content can increase the content of free formaldehyde, since the equilibrium will move to the left side (starting materials) and the hardening reaction is retarded; (ii) a greater amount of vapour is formed which increases the evaporation from the mat and the boards, including also a greater amount of formaldehyde.
- Press temperature
  The formaldehyde emission increases with the press temperature, as Carlson et al. (1994, 1995) could show for a phenolic resin and Wolcott et al. (1996) for an UF-resin.
- Press time
  The formaldehyde emission increases with the a longer press time, as Carlson et al. (1994, 1995) could show for a phenolic resin and Wolcott et al. (1996) for an UF-resin.
- Gluing factor
  The higher the gluing factor, the higher usually is the formaldehyde emission during the press cycle, however an upper limit seems to exist (Wolcott et al. 1996).

6.8.2 Subsequent Formaldehyde Emission

6.8.2.1. Glue Resin Composition

The molar ratio of the resin is one of the most significant influence parameters concerning the subsequent formaldehyde emission. The molar ratio had been decreased during the last two decades significantly in order to decrease the subsequent formaldehyde emission dramatically.

Resins for the production of particleboards and MDF with low formaldehyde emission (emission class E1) today have molar ratios of approx. 0,90 to 1,10; the resins are in case modified or fortified with different amounts of melamine

Adding scavengers and catchers decreases the overall molar ratio of the used resin mix. Scavengers and catchers, e.g. urea or similar compounds, contain NH- or NH_2-groups. The addition of scavengers to the resin mix usually is performed directly at the site of board production. Scavengers also can be added to the particles, or particles can undergo a pre-treatment, e.g. by spraying a scavenger solution onto the particles.

6.8.2.2. Hardeners

The NH_2-groups of the hardeners react with the free formaldehyde of the glue resin; higher amounts of ammonium-based hardeners can decrease subsequent formaldehyde emission, however hardeners usually cannot really replace scavengers or a low molar ratio of the resin itself.

6.8.2.3. Wood Furnish

Subsequent formaldehyde emission from pure wood usually is very low and can be neglected. The former problem of the influence of wood inherent chemicals on the iodometric perforator value does not longer exist, since the analysis now always uses the much more specific photometric method.

Measuring the emission from boards (e.g. plywood or veneered particleboards) the porosity of different wood species can influence the emission rate in a physical way.

6.8.2.4. Production Process Parameters

- Moisture content of the glued particles or the dried fibres:
- Higher moisture content gives a higher emission. The reasons for this might be (i) a higher moisture content of the boards, (ii) a lower degree of hardening (as stated above).
- Press temperature:
- The higher the press temperature the lower usually is the subsequent formaldehyde emission due to better hardening and to the necessity of a longer ventilation of the board during production.
- Press time:
- The longer the press time the lower is the subsequent formaldehyde emission due to better hardening and to the necessity of a longer ventilation of the board during production.
- Gluing factor (resin content of boards):
- There is rather a small influence on the subsequent formaldehyde emission. A tighter board structure due to higher gluing factor even can reduce the emission rate.

6.8.2.5. Board Specific Influence Parameters

A higher surface layer density gives a lower subsequent formaldehyde emission rate due to higher diffusion hindrance, even at the same perforator value, which is more or less independent on the board density (Ploeg 1977). Surface coatings also lower the subsequent formaldehyde emission due to diffusion hindrance.

6.8.2.6. Age of the Board, Long Term Emission, Effect of Storage

The subsequent formaldehyde emission decreases with elongated storage time of the boards. There exists however no universal mathematical formula, which would describe this decrease of the emission. Various formulas have been described in literature (Colombo et al. 1994, Dunky 1990). Due to a slow hydrolysis of hardened UF-resins the formaldehyde emission from such boards never will decrease to zero.

Questions and topics of R&D:

a) *There is a lack of reliable results concerning the decrease of the subsequent formaldehyde emission from wood based panels with the age of the boards.*

6.8.2.7. Mixture Steady State Concentration, Source-Sink-Phenomena

Emission rates of various sources within the same room cannot be summarized additively, but show some mutual influences among the various sources. Sources with lower emission potential even can absorb some formaldehyde emitted from other sources (Dunky 1989, 1990).

6.8.2.8. Post Treatment of Boards

Several methods exist (Myers 1986, Roffael and Miertzsch 1990), but are used today only in few cases:

- Ammonia treatment (Kierkegaard 1993, Harmon 1993), or
- Treatment with urea and ammonia producing compounds (EP 6 486, EP 23 002, EP 27 583).

Also coating and sealing reduces the subsequent formaldehyde emission. Open edges of boards in furniture should be sealed in order to reduce an additional formaldehyde emission (Marutzky et al. 1981).

6.8.2.9. Conclusions

The formaldehyde problem has strongly involved glue manufacturers. Research has been done to minimize emission of the final product. This action initially had effects on:

(i) The sensitivity of the board to moisture: due to adding urea or other formaldehyde scavengers the hydrolysis process provoked by the humidity of the air sometimes became a problem.

(ii) Mechanical properties: in connection with hydrolysis the initial mechanical properties turned out to be lower then before and the ageing of the board was accelerated.

(iii) The production of the board was slowed down due to the minimisation of the formaldehyde excess.

These were the main problems to deal with. Due to the close collaboration with the resin producers, the producers of wood based panels learned to produce boards with more or less the same mechanical properties as before combined with low emission.

6.8.3 Phenol

Residual unreacted phenol can be present in phenolic resins; this phenol can emit during the production of wood based panels as well as from the produced boards, however to a very small extent.

Even years ago, the general positive trend towards reduction of all types of environmental burdens led responsible phenolic resin manufactures to minimize the levels of free phenol and substituted phenols in phenolic resins. As a result of these developments, resoles with a level below 0,2% can presently produced.

6.8.4 Isocyanate

There exists a possible emission during the production of PMDI-bonded boards, partly under decomposition to the amines. Emission of PMDI-covered dust and aerosols during production has to be of concern. To solve this problem special working conditions are necessary.

A short description about MDI emissions during the production of particleboard and strandboard is given by Frinck et al. (1995). They also present results to reduce the emissions by a modification of PMDI.

6.8.5 VOCs

A good overview about measuring and controlling volatile organic compound (VOC) and particulate emissions from wood processing operations and wood based products is given by the Proceedings No. 7301 of the Forest Products Society (1995).

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7. LCA – Reuse / Recycle

Klaus Richter

7.1 Principles and Procedures of LCA

Environmental Life-Cycle Assessment (LCA) provides a framework for identifying and evaluating environmental burdens associated with the life cycles of materials and services in a “cradle-to-grave” approach. It has been derived from the Resource and Energy Profile Analysis (REPA) published in the early 1970's as a reaction to the first oil crisis and the increasing awareness of environmental problems in the industrialised world (Hunt and Franklin 1996). It was recognised in that early stage that not only the production of products, but the whole life cycle of a product (including the use and disposal) needed to be considered if the implications to the environment were to be addressed comprehensively. Since the exclusive consideration of cumulative energy proved to be a limited perspective, air and water emissions and waste (substance and mass flows) were included in the calculations in the late 1980's.

LCA aspires to identify the environmental releases and to evaluate the associated impacts caused by a product (or process, or system) over all relevant phases of their “life” with the goal to comprehend and reduce these impacts. Thus, LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, intermediate parts and the products themselves, to the phase and to the end-of life options, i.e. by reuse, recycling or final disposal. This so-called “cradle to grave” analysis involves a holistic approach, bringing the environmental impacts into one consistent framework, wherever and whenever these impacts have occurred, or will occur.

The main applications of LCA are:

- To analyse the origins of problems related to a particular products
- To compare improvement variants of a given product
- To design new products
- To compare between a number of comparable products.

The comprehensive approach and holistic nature of LCA are responsible that the necessary methodology of LCA is complex and, in some details, still in the process of development. Nevertheless, the international harmonisation of guidelines and standards has been intensified recently. These processes were stimulated and co-ordinated first by the Society of Environmental Toxicology and Chemistry (SETAC), which published the first comprehensive document summarising principles and proposing the conceptual structure of LCA studies (SETAC 1993). This concept was taken in a slightly modified version as the general framework for the standardisation process at the level of ISO (Marsmann 2000). Table 7.1.1 lists the four international standards and three technical reports established to guide LCA work.

Table 7.1.1: State of ISO standardisation in the field of LCA

Norm	Title
ISO/EN 14 040	Environmental management - Life Cycle Assessment - Principles and Framework
ISO/EN 14 041	Environmental management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis
ISO/EN 14 042	Environmental management - Life Cycle Assessment - Life Cycle Impact Assessment
ISO/EN 14 043	Environmental management - Life Cycle Assessment – Life cycle Interpretation
ISO/CD 14048	Environmental Management - Life Cycle Assessment - Data documentation format
ISO/TR 14049	Environmental Management - Life Cycle Assessment - Examples of Application of ISO 14 041 to Goal and Scope Definition and Inventory Analysis

According to ISO 14040, a LCA should contain the four phases shown in figure 7.1.1.

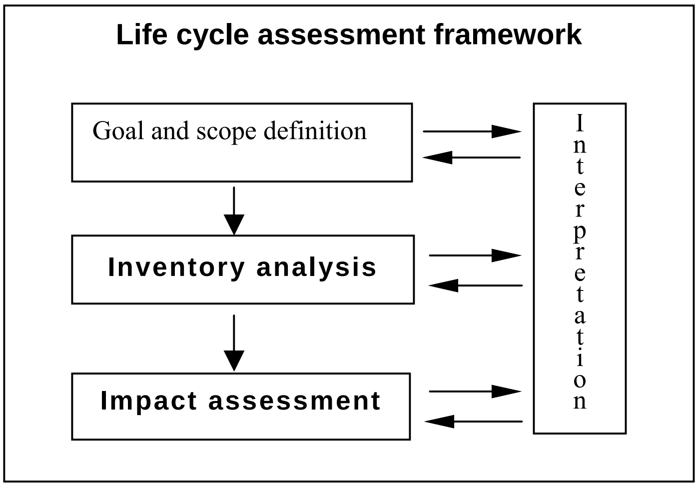

Figure 7.1.1: Components of an LCA (from ISO 1997a)

7.1.1 Goal and Scope Definition

The first step of an LCA is the goal definition. The objectives and the subject of the study as well as the intended application and audience are defined. In the scope, all information is given to ensure that the LCA becomes transparent, reproducible, compatible, and consistent. The required depth and the level of detail are given and the functional unit is described as a measure of the functional output of the product system. Further, the system boundaries are precisely traced and justified, and details on the allocation rules are given. The data quality requirements and the cut-off rules are recorded, e.g. the desirable characteristics and quality requirements of the data needed for the study are defined and procedures for quality assurance are established. These are important requirements to ensure comparability of LCA results, especially when different systems are being assessed.

7.1.2 Life Cycle Inventory (LCI)

In this phase the identification and quantification of energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharge) are established. It involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system studied. These include the use of resources and releases to air, water and soil. This is probably the most time consuming step of the LCA procedure. The data used in the inventory should be described, and assumptions and simplifications must be clearly indicated and existing data gaps must be mentioned explicitly. When documenting the results of the life cycle inventory, it is important to thoroughly describe the methodology used in the analysis, define the systems analysed and the system boundaries as well as all assumptions made in performing the inventory analysis. Physically, LCI is a list of data quantifying the amount of energy and materials consumed and the quantities of pollutants released to the environment by the functional unit of the product analysed, and is the input to the life cycle impact assessment.

7.1.3 Life Cycle Impact Assessment (LCIA)

LCIA attempts to establish a linkage between the material and energy flows caused during the life cycle of the product or process and its potential environmental impacts. It is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified in LCI. Impact assessment should address environmental and human health effects; it can also address resource depletion.

Different impact assessment methods have been developed (Braunschweig et al. 1996 Eriksson et al. 1998,BUWAL 1998; Goedkoop 1995; Goedkoop et al. 1998; Goedkoop and Spriensma 2000;

Hofstetter 1998; Steens 1999), some of them are still in the refinement phase. They all have special characteristics with regard to the chosen basis of assessment (ecological and/or political), aggregation (full / partial), geographical and temporal frame of reference and impacts evaluated. The two most prominent methods used in LCIA are the effect oriented approach published first in 1992 by the Dutch Centre of Environmental Sciences (CML) Heijungs et al. 1992 and updated recently (Guinée et al. 2001), and the Eco-Indicator method proposed by Goedkoop (1995), revised by Goedkoop et al. (1998) and extended recently (Goedkoop and Spriensma 2000). Whereas the CML methods produces single scores for each selected impact category (partial aggregation, in agreement with ISO 14042), the Eco-Indicator aims to express the total environmental burden of the product/system in one single score (full aggregation). Table 7.1.2 lists a set of default impact categories that are integrated in both assessment models.

Table 7.1.2: Impact categories used in LCIA

- abiotic depletion of resources
- global warming
- stratospheric ozone depletion
- photochemical ozone creation
- acidification
- eutrophication
- human toxicity
- ecotoxicity
- radiation
- land use

7.1.4 Interpretation

Life cycle interpretation, as the last phase of the LCA process, is a systematic technique to identify, quantify, check, and evaluate information from the results of the life cycle inventory (LCI) and the life cycle impact assessment (LCIA), and communicate them effectively. It has the following two objectives:

- Analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA and to report the results of the life cycle interpretation in a transparent manner.
- Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

7.1.5 Limitations of LCA

The broad scope of analysing a whole life cycle of a product and the holistic approach can only be achieved at the expense of simplifying other aspects. Thus the following limitations have to be taken into account as recently summarised by Guinée et al. (2001):

- LCA does not address localised aspects, it is not a local risk assessment tool
- LCA is typically a steady-state, rather than a dynamic approach
- LCA does not include market mechanisms or secondary effects on technological development
- LCA regards processes as linear, both in the economy and in the environment
- LCA focuses on environmental aspects and says nothing on social, economic and other characteristics
- LCA involves a number of technical assumptions and value choices that are not purely science based
- LCA unit process data are frequently of unknown quality and in many cases incomparable. Most data are being published in aggregated form to comply with the request of confidentiality, thus limiting the demand of extensive transparency

In some cases, progress is being made in reducing these shortcomings. Apart from the standardisation work and the activities driven by SETAC, the availability of a scientific journal (International Journal for Life Cycle Assessment, published since 1996 by EcoMed publishers), has stimulated discussions and knowledge exchange within the increasing community of LCA practitioners and users. A third international player in the field of LCA is the United Nations Environmental Programme (UNEP) focusing on the application of LCA, particularly in the developing countries. It has sponsored two easy-to-read and user-friendly publications that can be recommended for a more interested audience (UNEP 1996; UNEP 1999).

7.2 Forestry and Wood Products

7.2.1 History and Current Developments

As in other industrial sectors, the idea to apply environmental assessment to forestry and forest products started in the mid-1970s, driven by the implications of the two oil crisis and the growing awareness that climate and nature dramatically react on anthropogenic impacts. The initial research and case studies accomplished between 1976 and 1986 have focused on resource aspects and on the energy consumption of manufacturing processes (Boyd et al. 1976; Ressel 1986). In the following years, a stepwise extension of the concepts and scopes of environmental studies in direction to more comprehensive life cycle studies of timber products took place especially in Europe, focusing on the processes of the forestry-wood chain and, progressively, on all phases of a products life. A first European workshop on LCA in forestry and forest industry in 1995 (Frühwald and Solberg 1995) allowed resuming the initial results and experiences as well as limitations in applying the LCA concept to timber and paper products. Beside many positive conclusions about the potential role of LCA for the forest products industries, a number of methodological and conceptual deficiencies were identified. Some of them could be addressed in an European Concerted Research Action (COST E9, Various 2001) and a European research project (Esser and Robson 1999). Stimulated by these European activities, the North American Consortium on Renewable Industrial Materials (CORRIM) started a new initiative to build up a current, scientifically sound LCA database in the United States for wood and other bio-based products (Bowyer et al. 2001).

The concept of establishing transparent and reliable LCIs for processes and products of the forest products industries proved to be extremely valuable when the climate change issue raised in the mid 1990s. The exceptional position forests and timber play in the global C cycle was recognised in the early discussions within the International Panel on Climate Change IPCC (IPCC 2000). Meanwhile it is accepted that the size and the management of biotic carbon pools significantly effect the atmospheric CO_2 concentration. Beside living trees, litter and soil, also harvested and long-lived wood products are considered to be an important and manageable carbon pool. The carbon sequestration potential of both forests and wood products has been modelled in carbon accounting models using the information about energy and mass flows compiled in LCIs (Marland et al. 2001; Marland and Marland 1992; Marland and Schlamadinger 1998; Matthews et al. 1996; Schlamadinger and Marland 2000; Sikkema and Nabuurs 1995).

Another equally important aspect of forest products in the discussion of climate change can be referred to as the ‘material displacement’ or ‘substitution’ argument (Koch 1992; Burschel et al. 1993). It is based on the assumption that if a country increases sustainable timber production, wood can be used to ‘displace’ other materials and energy systems. This substitution will result in lower carbon emissions, if the fossil fuel intensity of the wooden material is lower than those of the alternative systems, which is often the case. This type of contribution of wood products to emissions reductions has been referred to as the ‘substitution effect’. Two types of substitution can be identified: a) direct substitution, in which wood is used as a direct source of energy (i.e. bioenergy) instead of fossil fuels (Jungmeier et al. 1998), and b) indirect substitution, in which wood is used instead of energy intensive materials, with implied reductions in fossil fuel consumption (Burschel et al. 1993; Buchanan and Honey 1995; Wegener et al. 1994; Skog and Nicholson 1998; Richter 1998).

7.2.2 Inventory Data of Round Wood Production

The production of roundwood in forests is the first link in the forestry-wood chain. Therefore, life cycle inventory data of roundwood production are necessary to evaluate the forest products in

LCA. The whole timber production system consists of a biological system (where the timber is grown) and a technical system (where the timber is processed). Because the static LCA methodology is designed to deal with industrial processes of a product system, the technical processes of forestry (forest management) are within the scope of LCA studies on wood production so far. The only exception is the hypothetical quantification of the photosynthesis proposed by (Wegener and Zimmer 1996; Wegener and Zimmer 2000), that allows modelling the carbon assimilation as described in table 7.2.1.

Table 7.2.1: Mass and energy balance of the biological production of 1 kg wood (absolutely dry) (from Wegener and Zimmer 1996)

INPUT			OUTPUT		
Solar energy	19.271 MJ 18.112 MJ	(Softwood) (Hardwood)	Heating value	19.271 MJ 18.112 MJ	(Softwood) (Hardwood)
Carbon dioxide	1.851 kg		Wood	1.000 kg	
Water	1.082 kg		Water	541 kg	
			Oxygen	1.392 kg	

The rather complex flows and feedbacks in nutrient dynamics that affect both state and changes in the biological production system of forest are not yet considered in LCA due to missing data and methodological concepts (Finér and Cortijo 2001). Similarly, the protective functions of forests especially in mountainous areas, regulation of watersheds, recreation and other environmental co-functions remain outside the system boundaries when roundwood production is addressed.

For that reason most available inventories of round wood production are based on the fuel consumption for forest management operations and transport processes. National data are reported for Finland (Karjalainen and Asikainen 1996, Mali 1999), Germany (Nickel and Liedtke 1996 (material intensities); Schweinle 2000a), Sweden (Berg 1995; Berg 1997; Athanassiadis 2000) and Switzerland (Hänger et al. 1990, Knechtle 1997; Köchli 1996; Winkler 1997). Schwaiger et al. (2001) presented a first European comparison based on a detailed questionnaire returned by twelve countries. This recent study confirmed that the fuel processes for transport processes to the forest industry exceed the consumption of harvesting and hauling operations. The demand for fuel for harvesting, hauling and transport varies from 1,7 to 6,6 kg fuel per m³ round wood. The variation is caused by a different degree of mechanisation in the participating countries and different transport distances. Compared with the solar energy stored in the wood itself, the forest operations included consume from 0,4% to 1,6%. These figures do only change marginally, if all possible forest management operations are included, as shown e.g. for the Finnish round wood production (Mali 1999). Different forest management systems of seven enterprises in Germany were analysed by Schweinle and Thoroe (2001). Even within one country, the total fossil energy input differs between 170 and 270 MJ/ton absolute dry wood, caused mainly by different logging operations.

US data for two different forest regions (South-eastern US/Pacific NW) are compiled in the CORRIM project for different harvesting systems (Bowyer et al. 2001). They report fuel consumption for the South-eastern region of 7 litres of diesel and 3,5 litres of lubricants per m³ round wood, resulting in total fossil energy inputs of 272 MJ/m³ and 136 MJ/m³, respectively. In consideration of the differences in productivity and distances the data are in a comparable range to the European values. The data compiled so far support the fact that the fossil energy inputs for round wood production are minor compared to the solar energy content stored in biomass. The same is true for the carbon emissions of the fuel combustion in relation to the carbon stored in the raw material.

A further issue related closely to forestry is the relatively large amount of land use. Land occupation by forests, timely variation of quality (nutrient balances and soil fertility), and impacts of forest management on biodiversity need to be addressed in an environmental assessment of forest products. Although several methods to account and to evaluate land use of biological production systems have been proposed in recent years (Baitz et al. 1998; Swan 1998; Schweinle 2000b; Köllner 2001), no one is universally applicable. The problem has been discussed in detail in the COST Action E9 and a recommendation is given to account for as many as possible general and forestry specific indicators in the inventory phase (Doka et al. 2001). No indicators have been identified so far that are suited to describe possible changes in biodiversity during land occupation by forests. Generally, land area used for wood production in most European forests is relatively large, but changes in land quality due to forestry are expected to be small. In the EcoIndicator'99 impact assessment method a forestry system is used as a reference system.

7.2.3 Inventory Data of Timber Processing

A first LCA-oriented environmental evaluation of timber and wood based products was published by Meier et al. 1990). Since then, numerous activities have been initialised to further complete the data inventories of a wide variety of basic processes relevant for the timber industry (Richter and Sell 1993, Frühwald et al. 1996; Speckels et al. 2000). They focus on the conversion processes in the sawmill (sawing, planing, drying) and in the veneer industry. Data compiled in table 7.2.2 confirm that especially the input of electricity is still rather low, compared with conversion processes of alternative materials. It has to be noted that the data for veneers shall not be compared to the timber data, because the functional unit (1m³ of timber /1 m³ of veneer) is rather different. The thermal energy for the drying processes in both sawmill and veneer industry is produced to more than 75% out of wood residues. Thus a remarkable degree of self-sufficiency is realised which can be increased in the future by producing electricity and heat in co-combustion. An example of a detailed inventory for the production of one tonne of sawn softwood timber for construction is given in table 7.2.3. As requested in the standards, the quantities of inputs and outputs are balanced. Note that the quantities of the materials to be converted in the process is much higher than the mass of the functional unit, caused mainly by the efficiency of the conversion process and the high water content of the round wood that evaporated during the drying process.

Table 7.2.2: Energy input for the wood conversion processes (from Frühwald et al. 2001)

	Efficiency (%)	Electricity (kWh/m³)	Therm. Energy (MJ/m³)	Primary Energy (MJ/m³)
Timber, undried	58	34		370
Kiln-drying		25	1280	1.550
Planing	83	30		325
Veneers	56	320	9.900	13.350

Table 7.2.3: Input-Output inventory data for the production of sawn timber for construction (from Speckels et al. 2000)

	Input kg/ton atro timber			**Output kg/ton atro timber**	
Raw Material	round wood	1.834,031	**Products**	timber softwood	1.000,000
	wood moisture	1.467,224	u = 63%	wood moisture	630,000
u = 80%	oil	0,475	**Co-products**	particles	321,358
Auxiliaries	lubricants	0,033		shavings	197,430
	oil filter	0,002	*(1) Packaging*	slabs, cut-offs	112,579
	anti-freeze	0,004	Emissions	bark	202,008
	paints	0,006		moisture	483,697
	water municipal sys.	29,807		strip iron	0,427
	water from well	55,221		plastic strips	0,022
	packaging foil	0,060		foils	0,050
	steel strips	0,485		stacks atro	0,656
	plastic strips	0,025		moisture	0,413
	sawblades, plane knifes	0,104		**solid:**	
				metal	0,164
				plastic	0,013
				liquid:	
				sewage	85,028
				used oil	0,333
				gaseous:	
				vapour (w. moist.)	353,114
				not recorded:	
				oil	0,142
				grease	0,033
				anti-freeze	0,004
				paints	0,006
	total Input (kg)	3.387,447		**total output (kg)**	3.387,477
	Energy:				
	Electricity (MJ equiv.)	630,008			
	Diesel (MJ)	81,843			
	wood combustion (MJ)	9,292			
	total energy (MJ)	721,143			

7.2.4 Allocation Problems

According to ISO 14 040 allocation is defined “as partitioning the input or output flows of a unit process to the product system under study”. Allocation means that the environmental interventions are partitioned among the different products and/or among different product systems. In the forestry-wood chain the generic processes where allocation is necessary are:

- Multi-output processes providing e.g. sawn timber, side-cuts and sawdust from the saw mill, where the material flows of the process and its up-stream processes have to be allocated to the various outputs,
- Multi-input processes, e.g. the combustion of different fractions of waste wood, where the emissions and the generated energy have to be allocated to the different products or product systems (typically end-of-life processes),

- Recycling and reuse processes, where primary production and final disposal may have to be allocated to several product systems.

Figure 7.2.1 illustrates the forestry-wood chain with its different interlinkages of material and energy flows where allocation might be necessary.

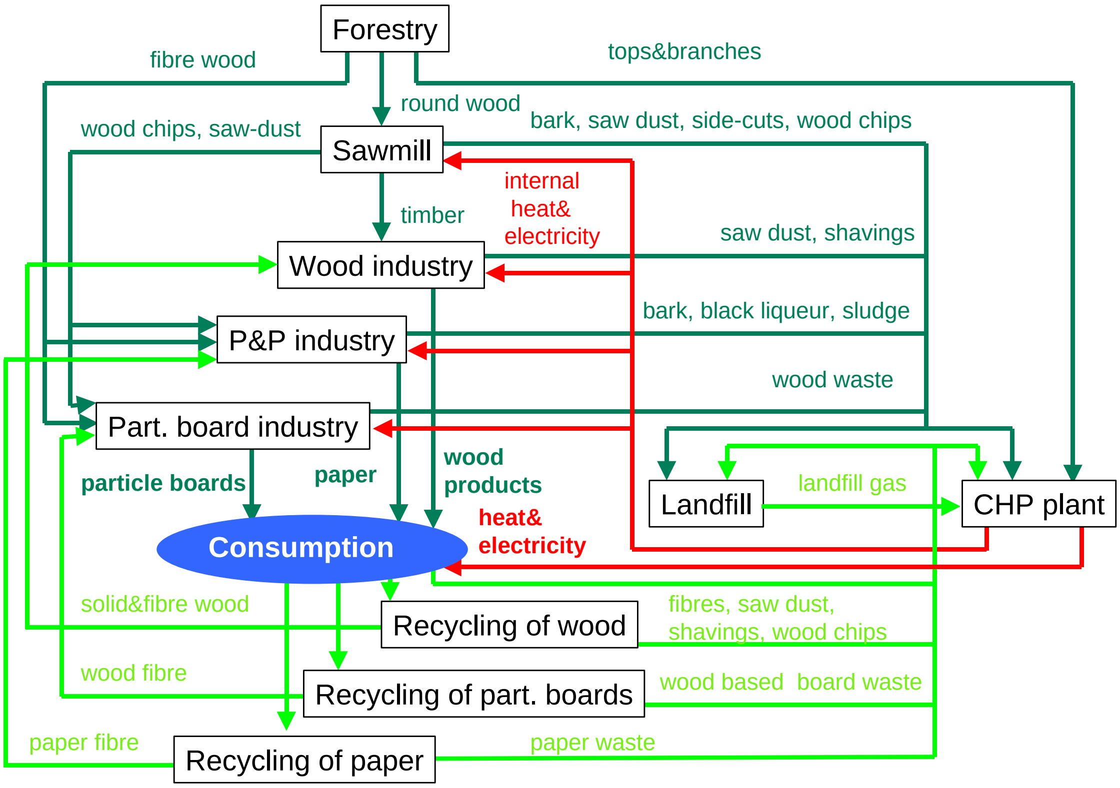

Figure 7.2.1: Processes in LCA of forest products that might require allocation (simplified, transportation and other upstream environmental aspects of processes are not shown). Dark green arrows: wood flows; red arrows: energy flows; light green arrows: recovered wood flows. From: Jungmeier et al. 2001b

The treatment of allocation in LCA of forest products has been discussed for long time and different solutions have been presented. In general it is accepted, that the influence of different allocation options on the results of LCA of forest products can be very significant. Several case studies have proven that the sensitivity of LCA results is much more affected by the way how allocation of mass and material flows is modelled than by uncertainties in data quality. Much methodological effort has already been made to properly address recycling of paper (e.g. Ekvall 2000; Plätzer et al 1996; Reichart et al. 2001; ISO 14 049, chap. 8.3.3). Two available guidelines for LC-inventorying of wooden products Fava et al. 1996; Esser and Robson 1999) provide key recommendations on how allocation should be performed in wood product LCAs, and Jungmeier et al. (2001b) addressed the allocation problem specifically within the coarse of the Cost Action E9. They point out that for the allocation issues it has to be considered that the carbon content and the embodied energy content of wood are materially inherent properties of wood. This means that carbon uptake and carbon release of wood as well as its embodied energy content are intrinsically related to the mass of wood. Further the 8 following priorities related to allocation in LCA of wood products are given:

1. Avoid allocation by extension of system boundaries by combining material and energy aspects of wood, because this reflects the characteristics of wood. This means a combination of LCA of wood products and of energy from wood with a functional unit for products and energy.
2. Substitute energy from wood with conventional energy in LCA of wood products to get the functional unit of the wood product only, but identify the criteria for the substituted energy and

document the assumptions for the choice of the substituted energy. But for transparency of results the documentation should also contain the procedure following 1).
3. Substitution of wooden products with non-wooden products in LCA of bioenergy is not advisable, because the substitution criteria are too complex.
4. In some cases it is not possible to avoid allocation, for which the reasons should be documented.
5. In general different allocations on e.g. mass and economic values are allowed in the same LCA.
6. The different allocation options must be analysed and should be documented. In many cases it seems necessary to make a sensitivity analyses on different allocation options for different environmental effects. It might also be useful to get the acceptance of the chosen allocation option by external experts or stakeholders in the starting phase of the LCA.
7. For allocation in forestry it is necessary to describe the main function of the forest where the raw material for the LCA is taken out. In some cases different types or functions of forests must be considered and described. The main function often indicates the allocation option. Where forestry is a timber production system in a LCA of forest products, the mass allocation is practicable and brings reasonable results.
8. Regarding the experiences from the examples, the following most practical allocation for some specific processes are identified:
    - Forestry: allocation based on mass and volume, or proceeds
    - Sawmill: volume, mass and market price (proceeds)
    - Wooden industry: mass and market price (proceeds)

For wooden products the recycling issue has commonly been solved by the cut-off procedure - thus mainly by system boundary setting. Werner (2001/2002) extended the scope and modelled several alternative allocation scenarios for recycling and end-of-life processes of railway sleepers and particleboards. He concluded that most of the allocation methods applied can only be used with restriction, and that statements on the effects and usefulness of recycling need the consideration of (direct) substitution effects and (indirect) environmental opportunity costs as necessary components for the consistent modelling of end-of-life scenarios in descriptive LCA (Werner 2001; Werner 2002).

7.3 Wood Adhesives

7.3.1 History and Current Development

Wood adhesives are indispensable components of many wood products fabricated in joinery, cabinet-making, and timber construction. Following the concept of LCA to assess all upstream and downstream environmental interventions of a chosen wood product, the impacts originating from the production of an adhesive as well as possible effects caused by the adhesive components during the application, the use and the final disposal need to be considered. For that reason, first, preliminary information of environmental criteria of glues and resins where already reported by Ressel (1986) focusing on energy content and Hänger et al. (1990) who extended the scope on emissions of combustion processes. For the US Market Franklin et al. (1991) were the first who systematically analysed the processes necessary to manufacture a variety of petrochemical products, and who published energy requirement data for melamine, urea and phenolic resins and polyurethane products. The next step in extending the information on basic chemical substances towards more comprehensive and transparent LC inventories was commissioned by the European Centre for Plastics in the Environment. Under their auspices a variety of reports on methodology and basic chemicals were published between 1992 and 1999, containing process data and inventories, which are needed to perform LCA of adhesives and other fossil energy based chemical products (e.g. Boustead 1992; Boustead 1993a; Boustead 1993b; Boustead 1997; Boustead 1999. These modules of basic components need to be combined with the data and information of the resin manufacturers, who often declare information on their specific recipes as confidential. That is the reason why many LCI inventories on wood adhesives still are highly aggregated (black box data) (see e.g. Digenes and Ophus 1996).

7.3.2 Inventory Data and Impact Assessment of Wood Adhesives

In figure 7.3.1, a chart of the input and output flows to be considered for the manufacture of a PF resin is shown. In order to convert these input and outputs into an LC inventory, the quantities of the flows have to be measured and related to a functional unit (1 kg of PF). It has to be noted that with the exception of water all other inputs are technical goods whose upstream processes and environmental interventions ("environmental burden") need to be known in order to include the relevant inputs and outputs in the inventory of the PF resin.

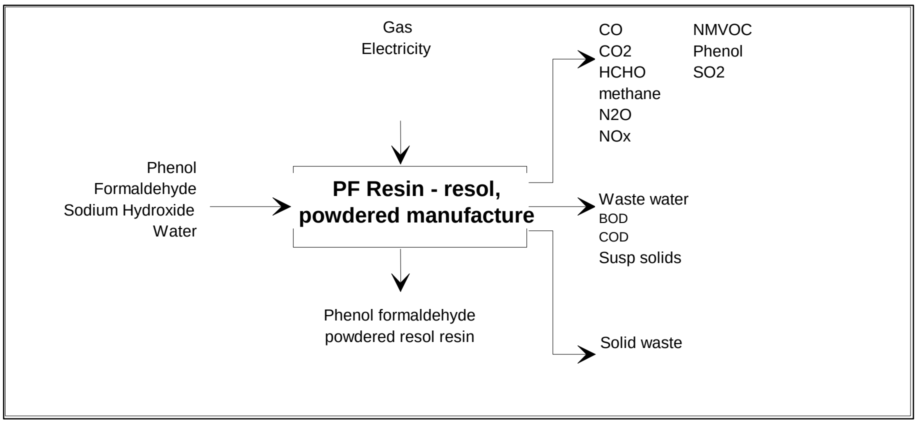

Figure 7.3.1: Process flow for the production of a PF resin

A comparison of environmental assessment data of different wood adhesives (functional unit: 1 kg solid, "cradle to gate") is shown in table 7.3.1. The background data are taken from the environmental database of the wood department of EMPA. It is obvious that the interventions increase from the polymerisation adhesives to the polycondensation types, and that within the polycondensation resins the energy demand and emissions of substances increase with increasing percentage of aromatic compounds in the resins formulations. However, the functional units in this comparison are by far not identical, because the qualities and performances of the resins are quite different.

The same restriction applies for the data presented in figure 7.3.2, quantifying impact assessment results for resins recipes ready for use in the particleboard production (functional unit: 1 kg liquid incl. waxes and water, "cradle to gate"). The background data have been compiled in a German research study, the unit process information are not published so far Kreissig (2001). The figures show that a PMDI resin per mass has the highest demand on fossil energy and ranges highest in most impact categories selected. But related to 1 m³ of particleboard, these conditions change again, because the resin inputs are quite different. This can be seen in, where the results are related to the resin input for 1 m³ of particleboard, and are scaled on the impacts of the PMDI resin.

Table 7.3.1: Impact assessment data of different wood adhesives (1 kg)

	PVAC	UF	MUF	PF
PE fossil (MJ)	50	72	126	191
PE regenerative (MJ)	0,15	0,79	1,55	1,2
GWP (kg CO_2)	2	3,46	5,99	6
ODP (kg R11-Eq)	0,0000033	0,00000087	0,00000126	0,0000124
AP (kg SO_2-Eq)	0,0073	0,029	0,058	0,00465
NP (kg PO^{4-}Eq.	0,001	0,0032	0,0082	0,0021
POCP (kg C_2H_2-Eq)	0,00359	0,0041	0,0072	0,0207
Ecoindicator 95	2,13	24,2	37,12	90,2

Table 7.3.2: LCIA data of different wood resins ready for use in the particleboard production

	MUF	MUPF	PF	PMDI	UF
	(25% H_2O)	(35%H_2O)	(40% H_2O)		(35% H_2O)
PE fossil (MJ)	34,4	34,3	33,9	98,4	26,3
PE reg (MJ)	0,08	0,08	0,06	0,29	0,09
GWP (kg CO_2)	1,71	1,68	1,05	3,80	1,33
ODP (kg R11-Eq)	1,37E-07	1,51E-07	4,01E-07	1,23E-06	8,04E-08
AP (kg SO_2-Eq)	0,00322	0,00319	0,00267	0,01237	0,00216
NP (kg PO^{4-}Eq.	0,00074	0,00074	0,00031	0,00157	0,00082
POCP (kg C_2H_2-Eq)	0,00047	0,00051	0,00135	0,00449	0,00027

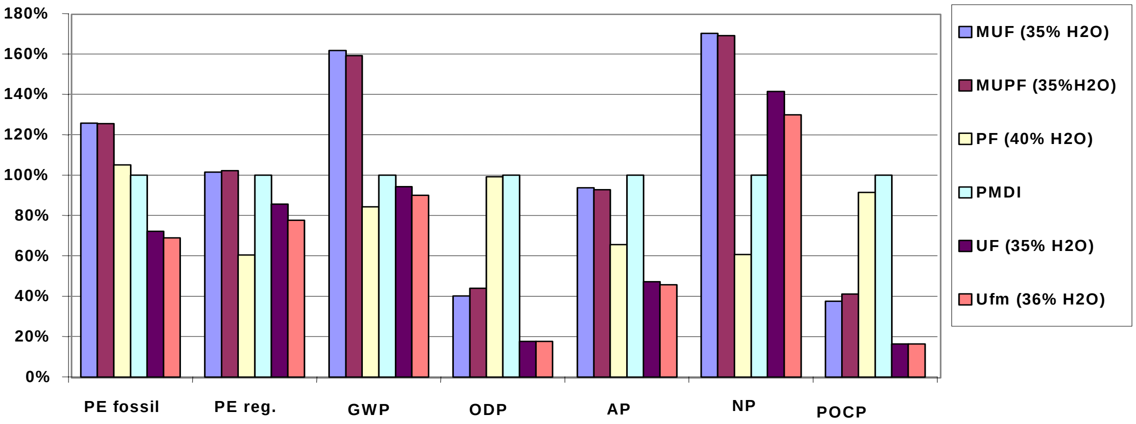

Figure 7.3.2: Impact assessment results for resin input for 1 m³ particleboard (data provided from Kreissig 2001). Data scaled on the PMDI resin results (=100%). Note that the functional units (moisture resistance of the boards) are not comparable in all cases!

It can be summarised that LC inventories are available for most commercially used adhesives. These data need to be applied in a careful way considering their technical characteristics in order to avoid misinterpretation. No LCA data have been published so far for resins based on renewable resources or components (e.g. tannins, lignins, proteins).

7.4 Glued Wood Products

7.4.1 Glued Laminated Timber

Inventory data for glulam have been compiled in different working groups and results are reported in e.g. Wegener et al. (1994); Richter and Gugerli (1996); Kristensen (1999). They include the inventory data for the subprocesses sawn timber trimmed, finger jointing, planing, glue manufacturing, and final planing. In average, 2,2 m³ round wood are needed for 1 m³ of glulam, and 13 to 16 kg of adhesive. The primary energy demand for the manufacturing process results in 1.200 MJ of thermal energy and 900 MJ of electricity, the whole glulam manipulation including transports, installation and dismantling results in 4.020 MJ thermal energy and 1.650 MJ electricity. Frühwald et al. (2001) assume in a model contemplation that the potential energy content of the wood manipulated for the production of a glulam (in total 2,2 m³) is 18.700 MJ, compared to only 5.670 MJ needed for the conversion and manipulation of this product. They conclude that even glued wooden products are very energy efficient products compared to all alternatives.

The impact of adhesives on the environmental profile of glulam is shown in figure 7.4.1. Whereas the energy input (represented in the graph the global warming potential GWP) is small, other effect categories are influenced to a much higher percentage, ranging from 25% in the eutrophication potential to 55% in the ozone depletion potential. These impacts are caused by the effects of the phenolic compounds as well as by upstream emissions from the conversion of the fossil fuels.

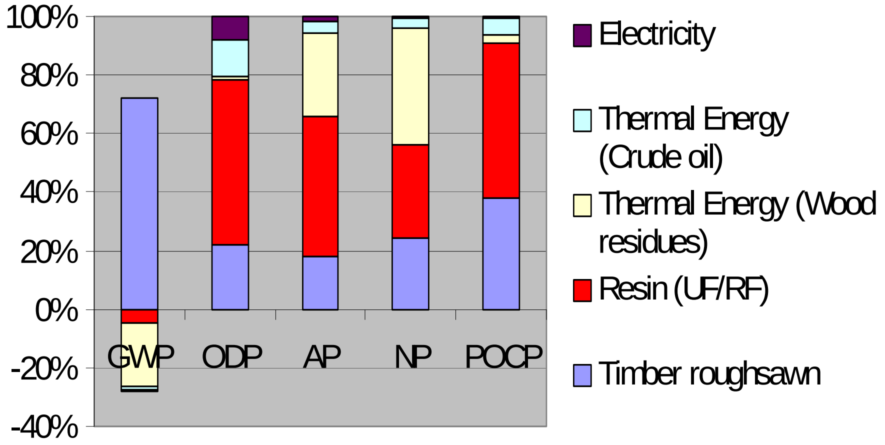

Figure 7.4.1: Contribution of products and processes to selected impacts of a glulam beam (cradle to product)

7.4.2 Wood Based Panels

The most recent and comprehensive LCI for panel production representing the situation in Germany is published by Hasch (2001). He studied the production and manufacturing of particleboards, MDF and OSB in Germany between 1998 and 2000. Approximately 80% of the environmental impacts are resulting from the use of energy, thus giving clear indications for improvements in specific processes (e.g. drying of residues, pressing). The impacts of the different resins used for the production of boards are significant in the effect categories acidification, eutrophication and ozone depletion. In table 7.4.1, the resin contributions are quantified and compared to those of the energy consumption and the wood processing. The impacts of the resins (mass content between 8 and 12% of the panels) range in all effect categories on second place and are higher than the impacts caused by the forestry-wood chain. Thus the resin manufacturing process should be analysed in more details in order to identify options for improvements.

Table 7.4.1: LCIA of different wood based panels (from Frühwald et al. 2001, Hasch 2001)

	Particleboard		MDF	OSB	
	Dry	Humid		PF-glued	PF/PMDI glued
GWP (kg CO_2-equiv,/m³)	240	275	540	235	265
% energy	42	34	64	-	-
% resin	32	40	25	35	47
% wood	12	10	5	8	7
AP (kg SO_2-equiv/m³)	1,4	2	2,1	1,7	1,6
% energy	35	25	45	-	-
% resin	25	45	30	41	41
% wood	12	5	10	9	10
NP (kg PO^{4-}equiv,/m³)	0,2	0,24	0,28	0,21	0,21
% energy	65	55	40	-	-
% resin	15	20	40	37	37
% wood	10	7	10	14	14
POCP (kg C_2H_2-Eq)	0,4	0,45	0,5	0,37	0,4
% energy	50	45	50		
% resin	7	25	12	20	30
% wood	20	15	24	31	28

In the coarse of the Life-Sys-Wood project (Esser and Robson 1999), OSB and plywood production data were compiled (Hillier 1999) and used for wood product comparison. Unfortunately, the unit process data are not published. LVL manufacture was inventoried with direct support from the Finnish producer (Zimmer and Kairi 1999). The results are presented in form of an input-output table and an assessment is made based for GWP and primary energy. The findings go in line with those reported for glulam and other wood based panels: LVL as a product has a negative global warming potential; and by a more effective thermal use of residual wood in co-generation process LVL would consume only mere 11% of the energy contained in the wood itself.

Bowyer et al. (2001) present a Life cycle inventory (production) for plywood produced in the Pacific Northwest region in the US.

7.5 Glued Wood Products in Building Application

Several studies were conducted in recent years focusing on environmental aspects of the application of glued wood products in a specific functional application in buildings and construction. This allows, according to the ISO standards, to perform comparisons to alternative products made from other materials or produced with other technologies. Preconditions for a comparative assertion is that the system boundaries are comparable, the functional units are identical and the structure and conduct of the work follows the principles of ISO 14 040 ff.

Reviews on LCI/LCA studies and projects including forest products are given in Richter (1995), Richter and Gugerli (1996), Robson (1998). The following overview summarise results with special emphasis on glued wood products.

7.5.1 Non-Load Bearing Structures

Window frames represent building products that are of considerable interest for the timber industries. Because of the high-developed requirements modern wood windows are multi-material products (wood, glues, paints, sealants, fittings, etc.), technically developed and important for the energy efficiency of the whole building. Windows are among the products that are most intensively studied in LCA, due to the endless discussion about the environmental position of alternative window frame materials (European softwoods, tropical hardwoods, PVC, aluminium); see e.g. Richter et al. (1996); Kreissig et al. (1997).

Richter (1999) analysed in different scenarios the impact of production and process alternatives in the manufacture of a wooden window frame (Richter 1999). The higher amount of PVAc adhesives necessary to produce finger jointed or laminated profiles did not result in a significant increase of environmental effects. The comparison of four window frame systems fulfilling the same functional unit is presented in figure 7.5.1. As end-of life options the wooden parts were modelled as being incinerated in a municipal waste incinerator, whereas the alternatives were recycled with optimistic recovery rates the reuse of the main materials (aluminium 80%, PVC/steel 70%). In the figure, the environmental effects are scaled on the window system with the highest impact. The aluminium frame rates highest in five of the six categories, although the longest lifetime is respected in the model. The impacts resulting from the primary processing of aluminium overshadow all other material interventions. The benefits of wooden frames are most obvious in the global warming potential, driven by the utilisation of biomass for heat production and the storage effects of regenerative carbon in the wood material. In the other categories PVC and wooden frames result indifferent. However, this holds true only for the very optimistic recovery rate for PVC.

Wooden flooring systems have been analysed in several LCA studies published (e.g. Günther and Langowski 1997; Potting and Blok 1994; Werner and Richter 1997; Jarnehammar, 1999). Werner and Richter (1997) built up an inventory for solid and two multi-layer parquets produced in Switzerland and concluded that the environmental profile for wooden systems is rather positive due to their long lifetime and the fact that they can be renovated. Jarnehammar (1999) underlined these findings and quantified that adhesives and lacquer are significant environmental influencing factors, despite the fact that they constitute only a small part of the products mass.

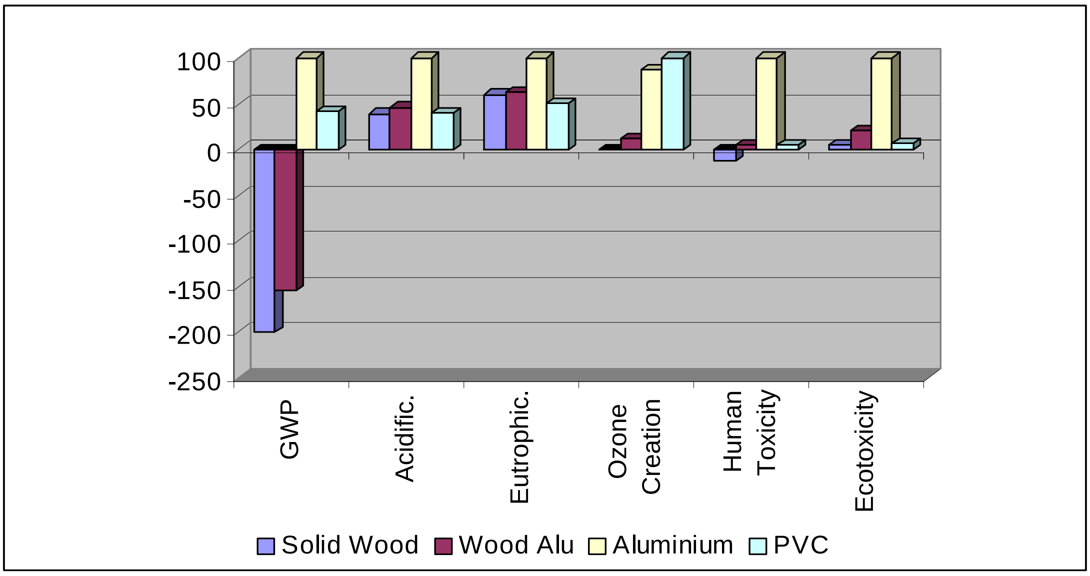

Figure 7.5.1: Comparison of the environmental effects of the different frame systems (scaled). (From Richter 1999)

To evaluate the ecological relevance of the choice of wooden and non-wooden interior building materials, a LCA has been performed for doorframes out of solid wood, particleboard and steel (Werner et al. 1997). The solid wood frames were produced of 3-layered, finger jointed spruce panels. In all but one impact categories studied, the wooden products had significantly lower ratings than the steel frame (Figure 7.5.2). The impacts on radioactivity result from the consumption of electricity, where all three products consume equal quantities. The solid wood frame reached slightly better results than the particleboard frame.

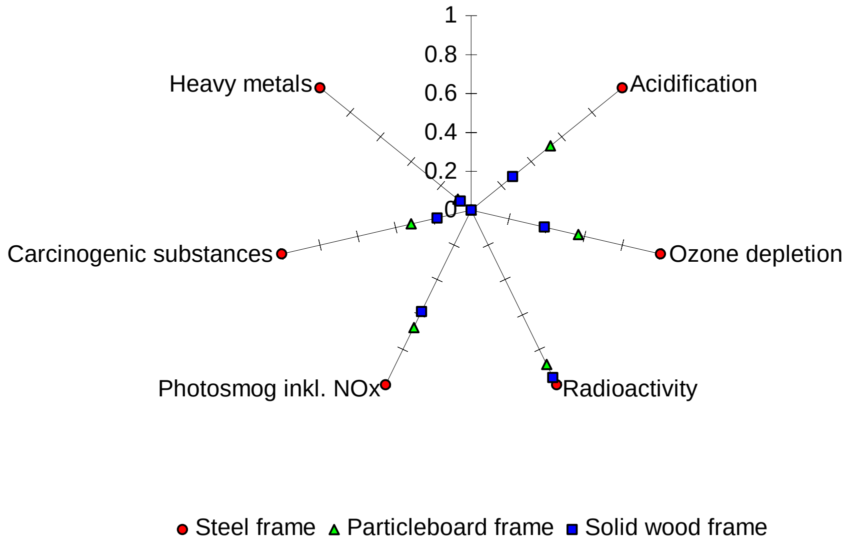

Figure 7.5.2: Standardised contribution of doorframes to environmental effects (From Werner et al. 1997)

7.5.2 Load Bearing Structures

Kristensen (1999a) compiled inventory data for comparing a warehouse frame structure made of glulam beams, concrete and steel. The wood data were collected following the decision rules of the Life-sys-wood project, whereas data for the steel and concrete design were taken from the Canadian ATHENA^{TM} Sustainable Materials database. The result of the impact assessment is shown in figure 7.5.3.

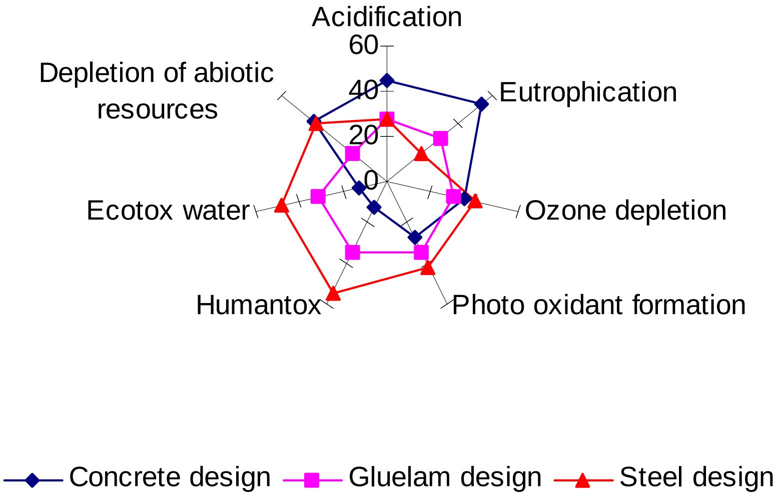

Figure 7.5.3: Environmental impact potential of warehouse frame design (From Kristensen 1999a)

None of the alternatives rated best in all categories, and concrete structures had advantages in 3 effects but were the worst alternative in acidification and eutrophication. Glulam had a little effect on the depletion of abiotic resources, and showed, as most timber constructions, clear advantages in global warming potential (-38 tons CO_2 equiv. vs. 28 tons for steel and 31 tons for concrete).

Börjesson and Gustavsson (2000) investigated the life cycle effects of a multi-storey building made with either a wood or a concrete frame. The calculated the primary energy consumption, global warming potential as well as the carbon mitigation efficiency and discussed land use perspectives. The rating of the wood design very much depend on how the wood is treated after demolition of the building. Deposition in landfill with methane production is the worst alternative, when on biogas collection is considered. For the concrete structure the authors discuss up to 50% reduction of the greenhouse gas emissions if the re-bound of CCO_2 to concrete by the carbonisation process is considered.

Concluding the information on LCA application on wood based products one can summarise, that many studies indicate positive ratings for timber products in most impact categories. However, it has also been shown, that the final assessments of timber constructions to a certain extend depend on how the end-of-life processes are modelled. This supports conclusions from (Doka 2000; Zimmermann et al. 1996) and make is necessary to have a closer look on end-of-life processes in the following chapter.

7.6 End of Life Options

7.6.1 Definitions and Classification

Due to the material characteristics of wood and its twofold nature of wood as material and energy carrier, a variety of reuse & recycling options of post-consumer used wood are possible. They are mainly restricted by the size of the used wood, particle or fibres, their homogeneity, and their content of contaminants (e.g. from preservatives, coatings, adhesives, foils, overlays, etc.).

In dependency of the area of application and the technical effort of reprocessing, the guideline VDI-2243 by Verein Deutscher Ingenieure distinguishes four options of reuse & recycling of wooden products (table 7.6.1).

Table 7.6.1: Reuse & recycling options at the end of the life cycle of wood products (after Richter 2000:10; Willeitner and Bucki 1994)

Principle	technical effort for reprocessing	Inherent material properties	Area of application product 1 → product 2	Example
Reuse in same application (“Wiederverwendung”)	small (repair, renovation)	unchanged	same	Returnable pallets, “Bauteilbörse” “Brockenhaus”
Recycling in different application (“Wiederverwertung”)	reprocessing necessary	slightly changed	same	Massive wood beam → laminated wood beam Particleboard → particle board
Reuse in different application (“Weiterverwendung”)	small	unchanged	different	Railway sleepers, utility poles in landscape architecture
Recycling in different application (“Weiterverwertung”)	reprocessing necessary	changed	mostly different	Used wood → particle board Used wood → MDF Used wood → thermal energy

The first two options are considered “closed-loop” recycling according to ISO/EN 14041, while the second two options are classified “open-loop” recycling by Richter (2000). However, the classification of a specific case to one of the four options is subjective to a certain extend. The classification becomes even more complicated when thermal utilisation has to be classified. It is difficult to decide if used wood has to be considered waste and when the incineration of wood as energy carrier is classified as thermal recycling, e.g., in the case of used wood combustion in municipal waste incinerators with thermal energy recovery. A recent survey on the end of life options and LCA integration is given by Jungmeier et al. (2001a).

Handling of post-consumer wood is located between waste treatment/disposal and exploitation of a secondary material resource for material or energy purposes (DGfH 1995; DGfH 1996; Voss and Willeitner 1994).

Reuse & recycling of post-consumer used wood offers a variety of advantages and disadvantages. Among the advantages are (Marutzky 1997; Roeffael 1997):

- Reintegration of waste into the economy,
- Careful treatment of resources and amplification of the resource basis,
- Less occupation of space in landfills,
- Substitution of fossil fuels (CO_2-neutrality of wood),
- Lower thermal energy consumption and VOC-emissions from drying processes if used (dry) wood is recycled as material,
- Higher energy efficiency due to lower moisture content compared to “fresh” wood if used for energy purposes,
- Destruction of harmful (organic) chemicals or their immobilisation and export from ecosphere (in the case of inorganic chemicals) when used for energy purposes in cement kilns.

Among the disadvantages are:

- Dispersion of pollutants if recycled as material (see below),
- Generation of harmful emissions when used for energy purposes in unsuited incineration plants,
- Displacement of other wooden raw materials such as residues from thinning or sawmills leading to lower prices for products from primary processes with already low profits or even obtaining subsidies,
- Higher requirements on logistics and transports than primary material (causing corresponding environmental impacts).

7.6.2 Direct Reuse of Wooden Products

Direct reuse of wood on industrial scale is rare because of differing shapes, quality and impurities but requiring labour-intensive, expensive reprocessing (Stahel et al. 1987). Sill, the reuse of wooden pallets (Hekkert et al. 2000) and packaging elements as well as the reuse of standardised building materials such as laths, beams or boards in small scale, decentralised single cases are common practice (Stahel et al. 1987; Orpin 1996; Plume 1996).

Another exception, also small in quantities, consists in the reuse of valuable timber, antique and handcrafted furniture, panels, wall panels, parquet floorings as well as old doors and windows in single cases. Salvaged wood products can command premium prices. Here, antique shops, “Brockenhäuser” and “Bauteilbörsen” are holding an important position (Buser 1998).

Two examples for industrial reprocessing of old floor joists or window frames out of second hand pine wood are reported from The Netherlands (Fraanje 1997).

The reuse of the wood applied in the wooden Swiss pavilion at Expo 2000 in Hanover can be considered another singular example for the reuse of used wood. Already planned during design, the wood (sufficient for about 100 detached houses) has been sold to various countries for the production of further products (Clénin 2001).

7.6.3 Recycling in Wood-Based Panels

The integration of post-consumer used wood in the wood-based board industry is the most important (and most promising) path for the material utilisation of used wood (Marutzky 1997). It is estimated that up to 20% of the total timber supply for wood based panels in Europe is based on recovered wood, whereas in Italy, wood-based boards are produced from 100% used wood (Harbeke 1998:69; Schrägle 2001)

For the recycling of post-consumer used wood in particle- and fibreboards the (potential) content of harmful substances originating especially from chemical wood preservation is a mayor limitation. But also glues, toxic pigments of coatings or colours and mineral contaminants are other sources of substances limiting further utilisation of used wood. To avoid a contamination of the newly produced particleboard due to the reintegration of recovered wood residues, the panel board manufactures and associations have defined quality specifications for used wood fractions suitable for wood-based panel production (Krooss et al. 1998; Anonymous 1996; Anonymous 1999; Schrägle 2001). But visual distinction of untreated and treated used wood, in the latter case differentiating between organic and inorganic active groups, is feasible only to a very limited extent. In practice, it is limited to certain homogenous fractions such as utility poles or railway sleepers (Peek 1998). Large-scale analytic techniques for the sorting of post-consumer used wood according to its contamination are currently investigated in pilot plants (Peylo 1998a; Peylo 1998b; Weis et al. 1999). But up to now, no labelling scheme has been put into practice. For the US market, Smith and Shiau (1998) report that there are no known commercial markets for recycled CCA-treated wood products, mainly due to environmental concerns related to residual chemicals left in the fibres and due to health and safety concerns of the mill workers

Therefore, only the utilisation of homogenous materials concerning the type of wood/wood products can be recommended under environmental guidance. In the recent years, various processes for the reintegration of particles and fibres from used boards have been developed, driven by the likehood that contamination especially in old furniture is small.

A variety of processes already patented aims to separate the wood furnish of post-consumer particleboards using thermo and/or thermo-chemical treatments to hydrolyse the UF-bonds (Roeffael, 1997; Kharazipour, 1997; Nonninger, 1997; Michanickl and Boehme 1995a). Dix et al. (1997) investigate the possibility to use recycled waste paper as additional furnish in MDF production. The technology proposed by Möller and Herrlich (1994) uses mechanical separation techniques to dismantle used furniture and to produce small building blocks that can be further processed.

The most successful and industrially applied particleboard recycling technology is probably the so-called WKI-process (Michanickl and Boehme 1995b; Wittke 1998). The technology is based on a chemical-thermal-mechanical process for the recovery of high-grade fibres and allows a simultaneous separation of metals, surface finishes and edge materials. Results show that particleboards and MDF made from recovered material have the same or even better qualities than panels exclusively made from fresh fibres. Until now, no LCA study has been performed to evaluate the environmental quality of boards manufactured from recycled fibres.

However, concepts for recycling and reintegration on a material level, which are indispensable for a sustainable management of products based on fossil and ending resources, are discussed controversial in the forest and wood industries – as long as the sustainable availability of the primary resources is guaranteed.

LCA has been used recently to analyse the basic concepts for the end-of-life options. Speckels (2001) compared three options based on German legislation for waste disposal: (a) thermal utilisation of waste wood for the generation of heat and/or electricity; (b) material recycling for making new particleboards; (c) landfill. With LCA modelling he clearly pointed out that from the ecological point of view it thermal utilisation is preferable, and that material recycling and disposal is not recommended. Similar conclusion is derived in a LCA modelling approach by Werner (2001).

7.6.4 Thermal Utilisation

Thermal use of post-consumer used wood range from industrial scale combustion to decentralised (illegal) combustion in open fireplaces of private houses (Marutzky and Seeger 1999). Among these options are:

- Combustion in municipal waste incinerators with energy recovery,
- Residual wood and used wood combustion plants, mostly associated with wood-processing industry, but also independent ones,
- Combustion in cement kilns, allowing the environmentally sound combustion of preservative-treated used wood (like creosote treated railway sleepers) due to high combustion temperature and due to the specific characteristics of clinker (Stahel et al. 1987; Anonymous 1998),
- Incineration in open fireplaces of private houses, which is related to high quantities of highly harmful emissions (Vock 2000; Nussbaumer 1994).

The thermal use of wood allows the generation of thermal energy (e.g. as vapour) and/or electricity (Nussbaumer et al. 1997).

End-of-life options from where no further utility is derived are incineration in municipal waste incinerators or thermal treatment of wood as hazardous waste without energy recovery systems, open burning, land filling, and dumping.

For LCA of glued wood products it is especially important to know how the adhesives effect the emission potential in combustion processes. Table 7.6.2 lists the elementary composition of solid wood and particleboards glued with different resins, and the heating value. As can be see, the amount of nitrogen and chlorine increases due to the resins, whereas the heating value is not affected significantly.

Table 7.6.2: Elementary composition and heating value (Hu) of solid wood and particleboards

	C	H	O	N	Cl	Ash	Heating value (MJ/kg)
Wood absolutely dry	49,5	6,3	44,2	0,2	> 0,001	0,5	
UF-particleboard	49	6	43	3	0,2	> 1	
PF-Particleboard	49	6	44	0,5	< 0,01	2	
PMDI-Paricleboard	49	6	44	1	< 0,01	0,5	

In Fig, 7.9, incineration emissions of timber based products are shown, the data were measured at WKI, Braunschweig. As can be expected from the elementary composition, especially the CO and NOx emissions are increased. However, beside the elementary composition of the wood furnish the total emission in combustion is mainly affected by the combustion process and condition (Marutzky and Seeger 1999). Strecker and Marutzky (1994) incinerated untreated and treated wood as well as particleboards in a two-stage combustion system under optimised conditions. PCDD/PCDF (dioxins) emissions values increased significantly for particleboards cured with a chlorine-based hardener.

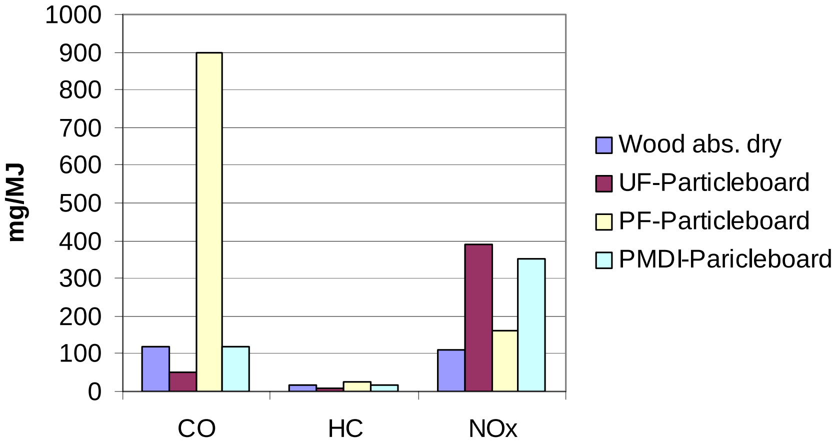

Figure 7.6.1: Incineration emissions of timber based products

The detailed design of the wood-adhesive system can therefore influence the environmental impacts to a certain extend and should be optimised based on the current knowlegde.

7.7 Open Question and Research Needs

- Improve data availability (LCI) for standard glues and adhesives
- Compile LCI for adhesives based on regenerative resources
- Model the impacts of an improved adhesive system (probably more impact during manufacturing) compared to the benefits of a better durability of the glued product
- Conduct more and extended comparative LCAs to evaluate environmental benefits of forest products
- Investigate methods the diminish the impacts of end-of-life processes, especially incineration

Glossary of Terms

Allocation: Partitioning the input or output flows of a process to the product system under study.

Effect: A specific change in human health, in eco-system or the global resource situation as a consequence of a specific impact.

Elementary flow: 1) Material or energy entering the system being studied, which has been drawn from the environment without previous human transformation; 2) Material or energy leaving the system being studied, which is discarded into the environment without subsequent human transformation.

Environmental intervention: Exchange between the atmosphere (the "economy") and the environment including resource use, emissions to air, water, or soil.

Environmental profile: Presentation of the result of a life cycle assessment, with the impact scores for each impact category ranked according to the evaluation

Final Waste: Waste which is emitted to the environment (in landfill for example) and not further processed within the economic system.

Functional unit: Quantified performance of a product system for use as a reference unit in a life cycle assessment study.

Goal and scope definition: Activity that initiates an LCA, defining its purpose, boundaries, limitations, main lines and procedures (see above).

Input: Material or energy which enters a unit process - material may include raw materials and products.

Life cycle assessment: Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle impact assessment: Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.

Life Cycle Inventory: A systematic listing of all environmental interventions of all processes included in the defined scope of an LCA, and all the market-based flows between those processes.

Output: Material or energy which leaves a unit process - material may include raw materials, products, emissions and waste

Product chain: The set of consecutive links in the production of a product. Together these links form a chain.

Product system: Collection of materially and energetically connected unit processes which performs one or more defined functions - in the ISO standard, the term “product” used alone not only includes product systems but also can include service systems.

Raw material: a substance extracted from the environment to manufacture a material or product.

Service life: Period of time after installation during which a building or its parts meet the exceed the performance requirements (ISO 15686-1).

System boundary: The boundary between those elements which are defined as a part of a given product system for a life cycle assessment, and other elements and the environment.

Waste: An output stream in solid form, which is accumulated onsite or offsite a system unit, and with potential impact on health, environment or resource impacts through discharges to air, water or soil.

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