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ADHESIVES IN TIMBER SYSTEMS

One-day Symposium 13th May 1999
Society of Chemical Industries, Belgrave Square
Adhesives in Timber Systems

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P G Nanavati  Borden Chemical UK
P Godley  Harlow Chemicals
P H Winfield  Oxford Brookes
P Jones  Harlow Chemical Co Ltd
P M Volsing  Collins and Alkman
R F Tout  FIRA
R J Bainbridge  TRADA
R J Moulds  Permabond
S J Shaw  DERA
Programme

10.00 Coffee and Registration
10.25 Welcome
10.30 OVERVIEW OF ADHESIVES USED IN THE TIMBER INDUSTRY
J Mundy, (Building Research Establishment)
11.00 ADHESIVES FOR FURNITURE
R F Tout, (FIRA)
11.30 PVA ADHESIVES
P Jones, (Harlow Chemical Co. Ltd)
12.00 THE NATURE OF ISOCYANATE TO WOOD ADHESION AND THE LOCUS OF RESIN PENETRATION
C Phanopoulos, (ICI Polyurethanes, Belgium), J J Marcinko, (ICI Polyurethanes, USA) and C Buckley, (King’s College London)
12.30 Lunch
14.15 BONDED-IN RODS FOR TIMBER STRUCTURES – TOWARDS A EUROPEAN BASIS FOR STRUCTURAL DESIGN
R J Bainbridge and C J Mattem, (TRADA Technology Ltd)
14.45 STRUCTURAL BEAM LAMINATION
C Morel-Fourrier, (Evode Ltd)
15.15 BONDED CONNECTIONS IN TIMBER STRUCTURES
A Hutchinson, (Oxford Brookes University)
15.45 Tea and Close of meeting
OVERVIEW OF ADHESIVES USED IN THE TIMBER INDUSTRY

Jo-Anne Mundy, BSc, MSc
Centre for Timber Technology and Construction, Building Research Establishment

INTRODUCTION

Timber has many excellent properties: it has a high strength to weight ratio, is easily worked, a wide range of species is available and it is usually price competitive. Adhesives have long been associated with converting timber into useful products and are widely used in the modern timber industry. Applications include extending the dimensions of solid timber available, increasing the coverage of extremely expensive, decorative timbers and producing wood-based composite materials and engineering components.

There is a substantial market for bonded timber and wood-based products. Information from the Office of National Statistics shows that the value of UK net supply (sales plus imports minus exports) of wood-based products to the construction industry reached almost £1 billion in 1996. This represents about 5 million m³ of material; just under half of which was home produced. The net supply for doors, door frames and windows accounted for around £600 million and ‘other joinery’ (which includes structural and non-structural carpentry) for just under £1 billion.

Europe consumes around 47 million m³ of wood-based panels each year. Worldwide consumption reaches around 153 million m³. There is little information available on the amounts of bonded structural timber components but the European market for glue-laminated timber (glulam) is estimated to be over £400 million.

PRODUCTS AND APPLICATIONS

The table below shows the main types of wood-based panel, their composition and general uses.

<table>
<thead>
<tr>
<th>Product type</th>
<th>Composition</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>Veneers in symmetrical balanced lay up of 0°, 60° plus UF, MUF, PF adhesive. Wide range of types and grades available. Service conditions (temperature and humidity) determine the timber and adhesive needed.</td>
<td>From structural (roofing, flooring and sheathing); I beams &amp; box beams; formwork (non-structural (interior joinery).</td>
</tr>
<tr>
<td>Particleboard</td>
<td>Chips, randomly aligned, plus UF, MUF, PF, MDI. Core usually lower density than surfaces. Range of grades available. Service conditions determine whether material suitable and which grade to use: mainly related to adhesive type.</td>
<td>From structural (roofing, flooring and sheathing); I beams &amp; box beams; formwork (non-structural (interior joinery).</td>
</tr>
</tbody>
</table>
This table shows that the vast majority of adhesives used are formaldehyde-based. This is also true for solid timber products using bonded joints and intended for structural use. The specification standards for most of these products call up BS EN 301 for specifying the adhesive, which allows only the use of phenolic or aminoplastic resins. The reason for this is that these adhesives have a long history of safe, durable performance. Adhesives such as polyurethanes, epoxies and filled acrylics could be used but such products would require an alternative certification route, for example a European Technical Approval certificate. Casein adhesives can also be used for structural joints but only under a limited range of interior conditions; they are seldom used in the UK. The range of adhesives broadens for non-structural bonds and includes polyvinyl acetates, which are widely used in joinery.

### BONDING TIMBER – THE ASPECTS TO CONSIDER

Bonding timber requires knowledge of many different issues. These fall mainly into two broad categories: technical and environmental. It is becoming increasingly necessary to know the environmental implications of technical solutions and to provide ways of improving the situation.

#### Technical

Bonding timber successfully requires many technical issues to be considered and accounted for and the principal ones are outlined below. The aspect of recyclability is included as pressure for improving the potential for this is increasing.

- timber characteristics (pH, oils, extractives, density, moisture content);
- pre-bonding treatments (preservation, fire retardants);
- post-bonding treatments (preservation);
- durability;
- recyclability.

#### Environmental

The environment has become an increasing area of concern, both in terms of human health and the broader environment. The main issues are:

- formaldehyde emissions;
• energy consumption and associated contribution to environmental impact categories in life cycle assessments;
• recyclability.

INNOVATIONS

Recent research programmes have been directed at solving some of these issues:

• 'Wet gluing'. This has been developed for jointing solid timber. 'Green' timber (moisture contents in excess of 100%) is bonded, which allows defect cutting to be done prior to kiln drying, resulting in an improved product and reduced energy and material costs.
• 'Natural' adhesives. Many different approaches have been taken; largely using local nut shells or barks high in tannins to produce a phenolic-type adhesive. Different degrees of success have been achieved; blending with a 'synthetic' adhesive (usually PF) is often needed to achieve necessary performance.
• Glued-in bolts. This technique has been developed using different bolt materials, but mainly GRP, to improve the performance of connections between structural elements made from either solid timber or wood-based components such as glulam and LVL.
• Structural repair. Studies have looked at using epoxy-type adhesives to carry out on-site repairs of timber elements to increase their service life.

THE FUTURE

Many challenges still remain in the field of adhesive bonding of timber and wood-based products. Fundamental knowledge is still needed on the subjects of surface characteristics, bond strength development; stress distributions and adhesive formulation. Further developments are needed in the areas of processing, product development, test methodology, environmental performance and recycling.

For the UK, improvements in adhesive technology and our understanding of the bonding process could produce huge improvements in the use and value of our home-grown resource. In 1997, UK production accounted for roughly 25% of the 8.6 million m$^3$ sawn softwood timber consumed. This resulted in a high level of reliance on imports (only energy and food show a higher dependency). Home-grown sawnwood is generally used for pallets, carcassing and less demanding structural applications, where it has a high market share. The output from UK forests is steadily increasing and is expected to double by 2010 to 12-15 million m$^3$ a year.
The development of synthetic adhesives over the second half of this century has had an enormous effect on both the production and design of modern furniture. For hundreds of years, only natural animal glues had been available to furniture makers, but around the middle of the century, synthetic adhesives and new bonding techniques, developed initially to meet the military requirements of World War 2, started to be introduced into the Furniture Industry. So successful were they, that within a decade or so, animal glues had been almost completely superseded by a range of highly sophisticated synthetic adhesives, each engineered to perform a particular operation, be it veneering/laminating, edgebanding or jointing.

During this period, the needs of the Furniture Industry were satisfied to a great extent by just three adhesive types, although within each type, there was a range of products for different situations. The three main adhesives were urea formaldehyde (UF), polyvinyl acetate (PVAC) and hot melts based on ethylene vinyl acetate (EVA). A similar picture applies today, although new techniques and machinery have led to the increasing usage of aqueous polyurethane adhesives for 3-dimensional lamination of wood-based panels, and moisture-curable polyurethane hot melts, for profile wrapping.

These synthetic adhesives, however, have had a much greater influence on furniture production than just improved bond quality and durability. In particular, the development of chipboard (and later medium density fibreboard or MDF) followed the introduction of urea formaldehyde resins, which are used as binders for both boards. Both of these wood-based boards have revolutionised the cabinet furniture sector, and have enabled the more efficient use of wood, an increasingly expensive and scarce resource. Additionally, these synthetic adhesives are well suited to the automatic, high speed processes which are so often demanded today.

Urea formaldehyde is a thermosetting material, resulting from the chemical reaction between urea and formaldehyde under slightly acidic conditions. The rate of this reaction, and hence the cure time, is accelerated by heat; once cured, further heating (within reason) has no effect on the adhesive, hence its good heat resistance. It also has reasonable moisture resistance, and these two properties combined with good adhesion to wood and wood-based materials and low cost has ensured its extensive use in the furniture industry.

UF adhesives are two-part systems, with the resin normally supplied as a liquid, to which must be added a hardener which triggers off the reaction that converts the liquid resin into its solid state. Some UF adhesives are also available in powder form, containing both resin and hardener, and in this case the reaction is triggered by adding water. Cure times for a typical UF is several hours at room temperature, but this will be reduced to a few minutes at 80°C and around 1 minute at 20°C.
Polyvinyl acetate adhesives are dispersions of small droplets of PVAC in water. They set or cure by loss of moisture, leaving the droplets to coalesce to form a continuous solid film. Setting times will depend on the moisture levels in the components being bonded, and the thickness of the adhesive film, but with optimum bonding conditions (i.e. low moisture contents and thin gluelines) a modern PVAC adhesive will develop a reasonable bond strength in about 15 minutes at normal ambient temperatures. Damp conditions and thick adhesive film will extend cure times.

In common with UF resins, setting times can be reduced by applying heat, but unlike UF adhesive conventional PVACs are thermoplastic and soften when heated, so that the pressing temperatures are normally restricted to about 80°C. Although not as resistant to moisture and heat as UF adhesives, conventional PVAC bonds have good dry strength and are, nevertheless, satisfactory for most interior applications. Being one-part systems, PVAC adhesives have the advantage of an indefinite pot life.

Cross-linking PVACs, having improved moisture and temperature resistance, have been available for many years now, and their use is firmly established in the furniture industry, principally for laminating and where exposure to damp conditions or occasional wetting is likely.

Hot melt adhesives, although not used by the UK furniture industry to the same extent as UF or PVAC adhesives, play an important role in furniture production in the cabinet area. They are solid at normal ambient temperatures and need to be heated to a liquid state before application. They solidify by cooling back to ambient temperature. The rate of cooling is initially high, so that bond strength develops rapidly, and this type of adhesive is therefore ideally suited for flowline production. Care is needed to ensure that the applied adhesive does not over-chill before the two surfaces are brought together, otherwise the bond will be a weak one - the rapid cooling rates are a disadvantage in this respect.

Hot melts are used extensively and very successfully on continuous edgebanding machines. They are capable of bonding most types of surface, so are also often used for small assembly applications where the bond is not load bearing, with a number of different makes of hot melt gun available.

The bonding processes used by the furniture industry can be divided into three main areas, veneering, edgebanding and jointing.

It was not many years ago that veneering referred only to surfacing substrates with wood veneers. Today, the term encompasses a wider range of surfacing materials including plastics laminates, vinyl and paper foils.

For high volume production, wood veneers and plastics laminates are generally bonded on single-daylight flow feed presses. Platen temperatures of around 120°C give cure times of about a minute, and a fast throughput. UF adhesives and cross-linking PVACs are well suited to these pressing conditions and are widely used.
Cold pressing, although not suitable for high volume production, is still carried out by small manufacturers, and PVAC adhesives would normally be used.

One area of great growth in the furniture industry over the last 20 or so years has involved the development of the membrane press, which has allowed 3-dimensional pressing of wood-based panels. In the process an aqueous polyurethane adhesive is sprayed onto the profiled surfaces and edges of the substrate panel, normally MDF. A decorative film, generally PVC, is then formed over and bonded to the profiled substrate using a thin flexible membrane under the dual action of heat and pressure. Such panels are used extensively in kitchen and bedroom furniture today.

The extensive use of chipboard as a substrate, and the introduction of flowline laminating machines, led to a demand for a fast, efficient method for edging panels with decorative materials. The modern continuous hot melt edgebander, containing trimming and often sanding facilities for cleaning up the applied edgings, certainly meets these requirements.

Assembling joints in both the cabinet and chair frame areas is normally carried out at room temperature, and so PVAC adhesives, with their short cure times at ambient temperatures, are used extensively for these operations. Dowels and mortise and tenon joints bonded with PVAC adhesive are used in the manufacture of chair frames. Dowels are used extensively in the assembly of modern cabinet furniture, although mechanical fasteners are generally used on the modern ranges of self-assembly cabinets.

The furniture industry, like many others, has benefited hugely by the introduction and advances made in synthetic adhesives. The development of ancillary machinery has been no less important. It has allowed the furniture designers to be more versatile with respect to both materials and designs, and given the manufacturers more efficient production methods.
Adhesives based on polyvinyl acetate dispersions have been successfully used in the woodworking industry and in craft trades for more than 50 years. Due to their cost/performance capability and low hazard/ease of use, the use of this class of non structural wood adhesive has progressively expanded.

Today there are a wide range of PVA based wood adhesives on the market, often differentiated by the intended method of application (e.g. spray, roller, applicator, squeeze bottle etc.) method of bond formation (e.g. clamping, press stacking, radio frequency press, post forming) and intended bond service conditions.

The performance requirements of non structural adhesives for bonding wooden surfaces is covered by European Norm. EN204 and the test methodology by EN205. Simplistically, the test standard requires the preparation of lap joint test pieces from beech boards, conditioning according to a set of defined sequences and measuring the shear adhesion of the specimens. Broadly these tests define performance as to suitability of the bond to withstand dry conditions (D1), exposure to cold water (D2, D3) and exposure to boiling water (D4). Superimposed on the minimum bond strength requirements, imposed by EN204 may be the requirement of the bond to withstand sustained load, as defined by BS4071.

PVA wood glues are almost universally produced by the emulsion polymerisation of vinyl acetate using polyvinyl alcohol as the stabilising colloid. Although the polymerisation recipes for PVA wood adhesives are relatively simple, the mechanism by which the polymerisation process is believed to proceed is quite complex.

**Figure 1**

Components required for the emulsion polymerisation of vinyl acetate suitable as a wood adhesive.

- **Vinyl Acetate**
  (Functional co-monomer)
- **Polyvinyl Alcohol**
  (Surfactants)
- **Initiator System**
  (pH buffer)
- **Water**
- **Post Additions**
  (Components in brackets are optional)
Vinyl acetate has a finite solubility in water (2.5g/100 g at 20°C) and accordingly a mechanism of homogeneous nucleation of particles, rather than micellar initiation is believed to prevail. The start of polymerisation is believed to occur in solution and as oligomers form precipitation occurs to produce tiny particles which can aggregate or act as nucleation sites for subsequent growth. Since emulsion polymerisation proceeds within discrete particles, restricting the free movement of free radicals, termination is inhibited, enabling high molecular weight polymer to be produced at high conversions. Optionally one may include a small level of functional monomer, copolymerised with vinyl acetate to further increase molecular weight, provide crosslinking sites for subsequent compounding or to enhance stability.

Polyvinyl alcohol is an essential component of PVA wood glues, typically present at levels of 5 – 12% on dry polymer and is highly influential in governing performance. Commercial grade polyvinyl alcohols used are produced by the hydrolysis of polyvinyl acetate solution polymers and have hydrolysis values in the region of 88 – 99% and molecular weights between 30,000 and 200,000.

It is not uncommon to combine so called, fully hydrolysed grades (98 – 99%) with partially hydrolysed grades (85 – 95%) in the polymerisation recipe to achieve the desired balance of properties. By selecting grades with different molecular weights the solids/viscosity relationship of the final dispersion can be controlled. The high reactivity of the vinyl acetate radical gives rise to chain transfer reactions during polymerisation and this results in a proportion of the polyvinyl alcohol being grafted to the polyvinyl acetate particles. The level of grafted polyvinyl alcohol is dependant on the nature of the free radical initiator system, the type/level of polyvinyl alcohol and the conditions of polymerisation. Other points worth noting are:-

It is the high concentration of hydroxy groups in polyvinyl alcohol which largely give PVA adhesives their substantivity to cellulose substrates.

High hydrolysis polyvinyl alcohols have significantly higher glass transition temperatures than polyvinyl acetate and therefore serve to strengthen the film (enhancing creep performance and heat resistance).

Polyvinyl alcohol functions as a protective colloid around the PVA particles, conferring stability to both mechanical processing and post compounding.

The importance of some of the main factors which can be controlled by design of the polymerisation recipe and the conditions under which it is performed, on the adhesive performance is illustrated in Figure 2.

It is always necessary to make post additions to PVA's after polymerisation. Typically post added ingredients include redox post treatments to reduce residual free monomer, bactericide, antifoam and coalescent or plasticiser.
PVA's typically, have a glass transition temperature around 30°C and although they are plasticised by moisture and generally exhibit lower film forming temperatures, it is necessary to include a solvent/plasticiser to depress the minimum film forming temperature to below 5°C. Where creep resistance is required, a low boiling coalescing solvent is commonly used.

Turning to the more onerous requirements of hot and cold water resistance, it is generally necessary to significantly reduce the hydrosensitivity of the adhesive and this is achieved by crosslinking the polyvinyl alcohol component. With D4 adhesives, more extreme crosslinking is required to overcome the inherent thermoplasticity of the coating. It is possible to crosslink polyvinyl alcohol by a variety of routes but the key requirements are to achieve a reactive system which is stable 'in can' but which crosslinks during or after film formation to confer the desired water resistance. In practice, the two most relevant reactions that can be considered are acetal formation or co-ordination crosslinking using a metal salt (e.g. a Lewis acid).

Where more extreme crosslinking is required, a water emulsifiable polyisocyanate may be added which reacts with polyvinyl alcohol to form carbamate ester linkages. The high reactivity of such additives inevitably means that the pot life of the adhesive is limited and may be no more than a few hours. Quite typically D4, PVA adhesives are marketed as two component systems.

Whilst the technology of non water resistant PVA adhesives can be regarded as well established and generally static, technology development continues at the water resistant end. New products coming onto the market have improved shelf life with reduced tendency to structure, exhibit faster rate of bonding, possess superior elevated temperature resistance, produce bonds less prone to brittle failure, have better resistance to discoloration of the glue line on staining timbers and have reduced formaldehyde levels. These improvements are achieved both by improved polymer design and novel compounding/crosslinking. Typical of new products exemplifying improvements are Mowilith LDL2555W (D3) and Mowilith LDL2510 (D4).

Dr. P.B. Jones  
Harlow Chemical Co. Ltd.
**KEY PROPERTIES OF PVA WOOD GLUES AS AFFECTED BY POLYMERISATION PARAMETERS**

<table>
<thead>
<tr>
<th>CONTROLLABLES</th>
<th>COST</th>
<th>ADHESIVE FAILURE MODE</th>
<th>BOND STRENGTH</th>
<th>CREEP/HEAT RESISTANCE</th>
<th>APPLICATION METHOD</th>
<th>RHEOLOGY</th>
<th>OPEN TIME</th>
<th>SETTING SPEED RATE OF BONDING</th>
<th>WATER RESISTANCE</th>
<th>MECHANICAL STABILITY</th>
<th>FREEZE/THAW STABILITY</th>
<th>STORAGE STABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solids Content/Viscosity</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Particle Size/Distribution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecular Weight/Gel Content</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl Alcohol</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Water Phase</td>
<td></td>
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<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
The Nature of Isocyanate-to-Wood Adhesion and the Locus of Resin Penetration.

C. Phanopoulos (ICI Polyurethanes, R&T, Belgium)
J. J. Marcinko (ICI Polyurethanes, RDC, USA)
and
C. J. Buckley (King's College, University of London, Dept. of Physics)

Summary of Presentation

The use of isocyanate-based resins as wood adhesives started over twenty years ago. The consumption of isocyanates in wood binding applications has been steadily growing from those early years to a present day 100000 tonnes. Isocyanates are mainly employed in the manufacturing of panels (OSB, MDF, and PB).

The term isocyanates in the context of wood binding refers to most commonly, polymeric methylene bis-(phenylisocyanate), referred to as pMDI. In fact pMDI is a mixture of the di-isocyanate and higher oligomers. The average isocyanate functionality being 2.7 and the typical NCOv (% weight isocyanate group on total weight) is 30.5%.

To make a wood composite panel, the wood is first cut or refined to required shape and dimensions, dried to a target moisture content, blended with the resin, pressed to a certain thickness, trimmed, conditioned and then shipped for sale.

This presentation will go through some of these stages of manufacture with regard to how the isocyanate interacts chemically and physically with the wood.

After the initial cutting of wood and the drying, isocyanates are generally sprayed in the wood. The isocyanate wets, spreads, penetrates and even starts reacting with various components at this stage.

All these processes depend upon the prevailing conditions; several wood related aspects and of course on several resin related aspects as listed in table 1.

Table 1. Factors affecting the wetting, spread and penetration of isocyanate based wood adhesives

<table>
<thead>
<tr>
<th>Physical Aspects</th>
<th>Chemical Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevailing Conditions</td>
<td>Temperature</td>
</tr>
<tr>
<td>Wood Related Aspects</td>
<td>Temperature</td>
</tr>
<tr>
<td>Resin Related Aspects</td>
<td>Temperature</td>
</tr>
<tr>
<td>Droplet Size</td>
<td>Species</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Resin Content</td>
</tr>
<tr>
<td>Rate(&amp;Temperature) of Drying</td>
<td>Quality of Wood</td>
</tr>
<tr>
<td>Cut (tangential/radial)</td>
<td>Ratio of Components</td>
</tr>
<tr>
<td>Viscosity</td>
<td>Hydrophobic/hydrophilic balance</td>
</tr>
<tr>
<td>Surface Tension</td>
<td>Reactivity</td>
</tr>
</tbody>
</table>

As an example of the type of impact these factors can have, table 2 shows the influence of the rate of drying for two different species of wood.
Table 2. Impact of rate of wood drying on penetration behaviour of isocyanate based adhesives

<table>
<thead>
<tr>
<th>Species</th>
<th>Temperature of Drying °C</th>
<th>Target Moisture Content %</th>
<th>Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spread/mm²</td>
</tr>
<tr>
<td>Black Poplar</td>
<td>105</td>
<td>8</td>
<td>61.2</td>
</tr>
<tr>
<td>Aspen</td>
<td>105</td>
<td>8</td>
<td>94.7</td>
</tr>
<tr>
<td>Aspen</td>
<td>200</td>
<td>8</td>
<td>89.9</td>
</tr>
</tbody>
</table>

As can be seen, both the species and the rate of drying (higher temperature of drying implies a higher rate of drying) impact significantly on the penetration behaviour of the resin.

Penetration and spread of resin is measured using a fluorescence optical microscopy. Glue of a defined volume is loaded onto the surface of a piece of wood a second piece of wood is then used to cover the resin droplet and the assembly is cured. Micromilled sections are then cut perpendicular to the glue line and the sections are observed under the microscope. The depth of penetration and the spread of resin from each section are measured and since the thickness of each section is known, the spread in the second direction can also be determined. The results can be depicted as a 3D contour map, see example in figure 1. Volumes, depths and depth distributions, as well as along grain and parallel to grain spreads and total spread areas can be determined.

Figure 1. Example of 3D contour map of the penetration of isocyanate based adhesives into wood.

The rate of resin penetration has been found to be very large. Isocyanate resins penetrate into the wood in tens of seconds and so penetration is completed soon after application of the resin and long before the wood is consolidated into a panel.

Penetration at the cellular level has also been investigated using x-ray microscopy. Details of this technique will be given in the presentation. It has been found that isocyanates readily wet the inner cell wall surfaces of certain cells and penetrate into the cell wall itself.

Having penetrated on the macroscopic and cellular level into the wood and the cell walls, reaction kinetic studies show that even at the low pre-press temperatures some reactions occur. The isocyanate can react with the wood extractives to form a number of reaction products, as revealed...
by infra red spectroscopy, with lignin and to some extent with water. Although isocyanates are 'unstable' in water, the affinity of MDI to water is very low – they do not easily mix.

Reaction kinetic, infra red and NMR studies all showed that there is a strong affinity between isocyanates and lignin. Reactions with lignins and water have lower activation energies and higher rates than all other possible reactions.

The resin penetrated wood mats are then conveyed into a press where they are compressed and heated. Compression varies throughout the matt and is on average of the order of 60 – 70% in the truly overlapped regions. The wood/isocyanate matt is heated by convection heat and due to the migration of steam from the surface to the core. The heat and steam induce further reactions – isocyanate-isocyanate, isocyanate-lignin, isocyanate-extractives and isocyanate-water. The penetrated resin inside the cell walls and the cell lumen thus increases its molecular weight and since it is mixed at the molecular level with wood matrix components an interpenetrating network is established. However due to the concentration gradient of isocyanate from the surface into the wood, the network is essentially a diffusion interphase.

NMR studies have shown that relaxation times of both the lignin and the hemicellulose components of wood change due to the interactions with isocyanates. The changes are consistent with chemical interactions for the lignins and secondary bond formations, such as hydrogen bonds, for the hemicelluloses. The diffusion interphase seems thus to be additionally 'anchored' to the wood by the formation of hydrogen bonds to the low molecular weight hydrocarbon components.

During this heating stage, relatively complex chemistry is occurring. There are a number of competing reactions, some of which are reversible. The abundance of the each reaction product is dependent on the local heat and moisture conditions. These vary depending on the position in the matt, the quality of wood at that location, the dynamic moisture content, the dynamic heat content and the temperature at any particular time.
BONDED-IN RODS FOR TIMBER STRUCTURES - TOWARDS A EUROPEAN BASIS FOR STRUCTURAL DESIGN

R.J. Bainbridge, TRADA Technology, UK.
C.J. Mettem, TRADA Technology, UK.

ABSTRACT

This paper presents an overview of work-in-progress in relation to the use of commercial adhesives to bond rods into oversized holes in order to achieve structural connections in timber and timber based composite products. The work presented forms a 3-year European project titled "GIROD - Glued In Rods For Timber Structures", performed through collaborative activities between partners from UK, Germany and Sweden. The objectives, study items and progress to date is summarised, with particular emphasis upon issues of fatigue and design code development.

1. INTRODUCTION

Well-designed and executed adhesive bonded structural connections can be extremely efficient and may possess many desirable attributes in terms of manufacture, performance, aesthetics and cost. As identified through a recent review of innovative and improved connection methods [1], the use of bonded-in rods is an important feature of many of the timber engineering methods for achieving connections using adhesives.

2. CURRENT DESIGN METHOD FOR BONDED-IN RODS

The method presented in an Informative Annex of Eurocode 5: Part 2 [3] presents four criteria for consideration in joints employing steel rods:

- Rod failure through yielding
- Shear failure in the adhesive
- Localised timber failure around the bond
- Failure of the host timber member

The yield failure of rods is identified as the preferred design mode. The yielding of the steel is a ductile failure mode, reserving capacity to transmit loads even after failure, albeit at excessive deformation levels. Parallels can be drawn here with the 'under-reinforcement' approach employed in design of concrete structures. This approach currently poses obstacles to utilising non-ferrous rods (e.g. GFRP), but again there is precedent of use that can be drawn from reinforced concrete to account for the absence of yield and subsequent plastic capacity.

To date it has generally been considered that the requirements of adhesives in these cases are to achieve good adhesion to the timber, attain sufficient shear strength to maintain integrity across the adhesive layer and to provide anchorage to the rod through combined adhesion and mechanical interlock. Due to the practicalities of surface preparation for steel rods in construction environments, it has become standard practice to employ textured or threaded rods in order to maximise mechanical interlock. Due to the uncertainties about the behaviour of such connections and lack of reliable calculation methods, they have not yet been introduced in the main part of the draft standard and instead have been placed in a informative annex. CEN.TC250/SC5 has decided in principle to try to include bonded-in rods also in Eurocode 5 - Part 1: General rules and rules for buildings [4]. In 1992 it was agreed to put bonded-in rods on the
programme of work for CEN.TC124 and a working group (WG6) was set up.

The group confirmed the need for standards in this field and a work programme including product, production and test standards was drafted. The group came to the conclusion that existing knowledge was insufficient to draft standards that would be acceptable to all European countries. To develop suitable test methods, the mechanical behaviour of bonded-in rod connections had to be known to a greater extent. It was also identified that factors such as durability, creep and creep-rupture behaviour of the adhesive bond had to be studied in more detail.

In addition to the structural wood adhesives, which are rather brittle, ductile adhesives such as two component polyurethanes have been used in bonded-in rods. For the latter adhesive types, no standardised test procedures and requirements with respect to applications in timber structures and in metal to wood bonds exists. Therefore CEN.TC193/SC1 (Adhesives for wood) in 1992 was asked by CEN.TC124 to put adhesives for bonded-in rods on the list of work items. In spring 1996 CEN.TC193/SC1 formed a working group (WG6) for this task. The group did, however, conclude that existing knowledge was insufficient to draft standards.

In order to address this situation, the European Project “GIROD” was initiated, and is now in progress.

3. OBJECTIVES OF THE GIROD PROJECT

There are three key objectives in the GIROD research project:

a) Perform theoretical and experimental work leading to a calculation model for axially loaded bonded-in rods based on the adhesive bond properties as well as the wood and rod material properties. This must take into account the effect of varying climatic and loading conditions as well as fatigue. This step will give information required by CEN.TC250/SC5 in preparation for Eurocode 5 - Design of Timber Structures.

b) Develop test methods for the evaluation of adhesives for bonded-in rods with respect to strength, durability, creep and creep-rupture behaviour under different climatic conditions. This will support the work of CEN.TC193/SC1 (Wood Adhesives).

c) Derive test methods for the production control of structural bonded-in rod connections. This will support the work of CEN.TC124/WG5 (Bonded-in rods in timber structures).

4. TECHNICAL WORK PROGRAMME

The main steps in each of the three parts of the project are described in Figure 2.

Part 1 is the most comprehensive one. To the development of the calibration model are linked minor sub-projects aiming at finding out under what conditions the model is valid and what restrictions are necessary. The technical activities under the whole GIROD project are summarised in Table 1.
anchored parallel and perpendicular to grain are shown in Figure 3.

Figure 3 Typical Test Specimens

It is important to note that the basis for experimentation diverges from the normal design solutions in that specimens are usually designed with the intent of making rod capacity non-critical. This enables investigation of the relative performance of the different adhesives, since otherwise the tests would merely be an elaborate means of clamping and testing steel bars.

The main investigative programme considers three generic classes of adhesive, each sourced from normal industrial suppliers. These are used to bond threaded steel rods into softwood glulam (bonded laminated coniferous timber). The adhesives under investigation are described in Table 2.

<table>
<thead>
<tr>
<th>Adhesive Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRF</td>
<td>Filled Phenol-resorcinol formaldehyde (prototype formulation)</td>
</tr>
<tr>
<td>EP</td>
<td>Epoxy Resin</td>
</tr>
<tr>
<td>PUR</td>
<td>2 Part Polyurethane</td>
</tr>
</tbody>
</table>

Table 2 Adhesive Types

Although related studies have indicated potential advantages for adoption of thicker bond lines with epoxy [5], a common nominal bond line thickness of 0.5mm (i.e. holes drilled 1mm greater than nominal rod diameter) has been adopted for the three adhesive types investigated in the programme,

The target of achieving methods which are practicable under site conditions is reflected in the rod choice - threaded galvanised rods with minimal preparation, being just wiped clean prior to bonding.

There are also limited investigations within this programme into the use of FRP rods as alternatives to steel. In this case, smooth pultruded glass fibre reinforced polyester rods (volume fraction approx. 63%) have been employed. These have been used in direct substitution in the test series in terms of dimensions of specimen to derive data in direct comparison with steel. Since the tests on FRP are a minor component of the programme, they have only been employed in combination with the Epoxy adhesive. Here surface preparation consists of sanding by hand to remove surface contaminants such as die release agents, followed by wiping clean with a cloth dampened with alcohol.

In addition to the tests performed in the GIROD programme, the studies also comprise elements of development work drawing upon the knowledge gained through previous research projects, which have led to foundation proposals for design methods [6], existing best practice educational guidance [7] and experimental data on various aspects of the subject at hand. A selection of key publications is included at the end of this paper [6-16].

The full programme on bonded-in rod technologies for timber is too diverse to detail in a single paper, so the focus of the remainder of this paper will primarily be upon the issue of fatigue testing and development of design clauses, as these represent work programmes conducted under the leadership of the authors.

6. PROGRESS TO DATE

At the time of writing (12 months into the project), the research project is on schedule, and significant progress has been made in all work areas.

6.1 General Observations

From the outset, it was known that the investigations would produce multi-faceted and multi-dimensioned illustrations of performance of the bonded-in rods, in part due to the massively different material properties inherent in the timber, adhesives and steel/FRP rods.

Considering issues of variations in geometry, service conditions and load variation aside, and focusing on the performance of the adhesives, it has been noted across the studies that the three resins have marked differences in their performance as part of the bonded-in rod solution. Figure 4 illustrates the difference of typical test failure modes in PRF and PUR rods subjected to axial tension.

Figure 4 Typical Failure Of Bonded Rods From Samples Loaded Axially And Fixed Perpendicular To The Grain
- a) PRF, b) PUR

Typical observations noted through ramp load testing are compiled in Table 3.
Adhesives In Timber Systems
Society Of Chemical Industry, Belgrave Square, London
13th May 1999

Adhesive Type | Typical Failure Features
---|---
PRF | • Cohesive failure (failure within adhesive).
   • Brittle adhesive
   • Good adhesion to wood.
   • Low adhesion to steel; rod often sits loose in hole after hardening.

EP | • Wood failure around glue line,
   • Hardened adhesive and rod come out as a “plug” with wood fibres.
   • Excellent adhesion to both steel and wood.

PUR | • Wood-adhesive interface failure.
   • Often adhesive surface contains bubbles, probably due to wood moisture.
   • Good adhesion to metal, but poorer adhesion to wood surface.

Table 3 Key Features Of Failure Observed With Each Adhesive

This reflects some of the key observations of previous work, resulting in classification of brittle and non-brittle adhesives as summarised in Table 4 [6], although the different character of the PRF and Epoxy samples requires further consideration in the context of this classification.

<table>
<thead>
<tr>
<th>Brittle Adhesive Types</th>
<th>‘Less Brittle’ or ‘Ductile’ Adhesive Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
<td>PRF*</td>
</tr>
</tbody>
</table>
| Notes: | * Derived from experimental observation
** Suggestion based on comparison of brittleness

Table 4 Adhesive Classifications As Suggested By Riberholt [6]

6.2 Effect Of Fatigue
Guidance on the background of fatigue behaviour and fatigue based experimental methods for wood and wood products is available [17,18], having been established in studies concerning severe fatigue applications such as those experienced in wind turbines [10,11].

Current Eurocode structural timber design treatment employs a reduction factor to derive a design fatigue strength as summarised in Table 5 and equation (1).

\[ f_{fat,d} = k_{fat} \frac{f_k}{\gamma_{M, fat}} \]  

(1)

where: \( f_{fat,d} \) = design fatigue strength
\( f_k \) = characteristic strength for static load
\( k_{fat} \) = fatigue modification factor, see Table 5.
\( \gamma_{M, fat} \) = fatigue material safety factor

Progress to date on the subject of fatigue in bonded-in rods for timber structures has resulted in clarification of the focus of investigations, establishment of contributory fatigue effects in the given structural context, establishment of the component material fatigue properties and development of test proposals.

The test specimens are of the form illustrated in Figure 5 and are designed to replicate ramp load specimens and be subject to axial fatigue only.

![Figure 5 Fatigue Test Specimens](image-url)

The aim of the tests in what is recognised as only a limited study, is to construct approximate \( a-\log n \) graphs for each adhesive under low frequency reversed loading, of the form sketched in Figure 6. This will allow direct comparison with the modification approach highlighted in Table 5.

![Figure 6 Targeted Result - A a-log n Graph](image-url)
6.3 Drafting Design Rules For Eurocode 5
Based on early project meetings, an initial draft of the proposed Code rules has been created, leaving blanks or indications where theoretical equation results are expected, and markers for information anticipated in later stages of the project. Eurocode formatting, protocols and terminology have been used. This is structured primarily around the informative Annex A of Eurocode 5: Part 2 - 'Glued-in Bolts', but also incorporates Fatigue guidance drawing from ECS: Part 2, key principles from EC1: Part 1 [18] and a number of items from the EUROCOMP design guide [20].

As stages of the project progress, this draft will be updated, along with the accompanying documentation. As it becomes appropriate, linkage with project-external committees, e.g. CEN, will be sought.

7. INTERIM CONCLUSIONS & FORWARD LOOK

The GIROD project is on course to define a European basis for structural design of adhesive bonded rods to achieve connections in structural timber.

Studies to date indicate that adhesive bonded structural connections can be extremely efficient, provided they are well-designed and executed with appreciation for the specific adhesive being used. Many desirable attributes in terms of manufacture, performance, aesthetics and cost may be achievable with these connection methods.

The work performed to date has already facilitated initial drafting of a set of design rules which will be updated as information is developed through the remainder of the GIROD project.

ACKNOWLEDGEMENTS

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REFERENCES

[2] GIROD Project Website: http://www.sp.se/building/wood/girod.htm

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1 – INTRODUCTION

The scope of this presentation is to give an overview of the technology of structural beam lamination with outstanding examples of what can be achieved. As adhesive suppliers to this industry, we will discuss the broad range of products available for this type of structural bonding as well as the process involved in the manufacturing of laminated beams. We will review the standards and performance requirements any adhesive and timber structure should meet.

2 – GENERAL FEATURES

2 – 1 – Definitions

A timber structure is usually made of several laminated beams connected together by wood to wood or metal to wood bonds or connections.

The definition of a laminated beam or glulam is given in BS-EN 386 as follows: "Structural member formed by bonding together timber laminations with their grain running essentially parallel."

The idea of assembling small wood pieces to give a beam dates back to the early 16th century. Metal tighteners were used. In 1904, the first glued laminated beam was manufactured using casein glue. The development of synthetic adhesives in the early 30’s helped improve properties and design increasingly demanding structures, reviving the interest for an old building material: timber.

2 – 2 – Advantages

Why laminate wood?

Compared to solid wood beams, incredibly larger, more resistant, longer bearing beams can be made by laminating small pieces of wood with a proper adhesive.

A timber structure has several advantages when compared to alternatives like concrete and steel structures. One of them is obviously weight. For similar overall resistance, a timber structure will be 5 times lighter than a concrete structure. The other advantage is not obvious when wood is involved but is actually very important: timber structures are exceedingly safer than any other in case of a fire is. When exposed to fire, a wooden structure will slowly burn at a rate of approx. 0.7 mm / minute, giving people enough time to escape. It is then usually not damaged by extinguishing products. A metal structure will collapse very rapidly when exposed to high temperatures. A concrete structure is usually damaged by water. Other advantages are aesthetics and environment issues.

2 – 3 – Drawbacks

In fact, most of the problems encountered with wooden structures are related to errors in the conception, the production and more often the treatment of the beams. Problems like surface fissuring, joint splitting and high water intake can be solved but good manufacturing practices usually ensure they do not appear.

2 – 4 – Examples

In continental Europe, structural timber structures are used for a wide range of applications, from high profile buildings to 2-metre posts sold in DIY stores. Among stunning constructions, the Utopia hall in Lisbon built for the Expo 98 great exhibition. It had a “beret” shape and the structure, made by a French timber company, is entirely in wood. Spherical structures of IMAX cinemas have been made of wooden beams. A project for the Millennium in France consists of a 200-metre high tower with a laminated oak structure.

Wooden structures are widely used for the construction of:
- Sports halls: gymnasiums, swimming pools, stadiums,
- Churches,
- Shopping centres,
- Warehouses and factories,
- Exhibition centres.

Architects have also been recommending this kind of structure for private houses particularly in northern Europe.
2 – 5 – Market

The European market for laminated timber structures has been evaluated in 1997 at approximately 1 million m³. Germany is the main producer with 45% of the production. Its neighbours have strong positions as well: 12% in Austria, 10% in France/Belgium and 5% in Switzerland. Scandinavian countries have always been traditionally important producers as well as timber suppliers to entire Europe (Sweden, Norway and Denmark with a total of 20%). Southern Europe countries are also present (Italy 5%, Spain) with local wood species. For adhesive consumption, it is generally assumed that 1 m³ of laminated timber needs approx. 12 kg of adhesive.

2 – 6 – Calculation of timber structures

A number of rules have been edited in every country, to ensure timber structures are conceived safely in terms of mechanical performances but also that contractors and architects take into account the variability of the main raw material: wood.

3 – SUBSTRATES

3 – 1 – Wood

Solid wood can be defined as an organic, heterogeneous, anisotropic and hygroscopic material composed of cells with cylindrical form.

For the chemist, wood is composed of 3 polymers: cellulose (40-50%), hemicellulose (20-35%) and lignin (15-35%). Other chemicals will confer properties such as colour, odour and durability. Water is also present at very high levels (wood fibres are saturated at 30% moisture content). Numerous factors such as the high polarity and potential reactivity of these polymers (the unit of cellulose polymer is cellobiose which contains 6 hydroxyl groups), the cellular structure of wood, contribute to the formation of a proper bond with wood substrates via theories such as:

- mechanical adhesion with penetration of liquid adhesive into the pores,
- specific adhesion, involving polarity and surface tension,
- chemical adhesion by reaction with OH groups.

3 – 2 – Wood species

Coniferous species are mainly used for timber structures. Spruce (Picea abies) is widely available and gives a very good compromise of mechanical performances and weight. It is usually grown in Scandinavia. Other species such as European redwood or Northern Pine (Pinus sylvestris), Douglas Fir (Pseudotsuga douglasii) and Larch (Larix decidua) can be used. They all have a density of 0.4 to 0.7 and a compressive strength of 30 to 50 MPa.

Broad leaved species such as Oak or Poplar are quite common. Due to increasing availability and aesthetics, a number of tropical species have been used (Iroko, Wenge...).

Any species can be used provided that compatibility with the adhesive has been confirmed. Species can be ruled out due to the presence of resin or oil, or because of too closed surfaces, too thin (or too wide) growth rings or too many knots.

3 – 3 – Wood treatment

In order to improve durability and resistance to water and micro-organisms, a specific treatment is applied usually to the finished beam, sometimes to the laminations prior to bonding. It involves impregnation with a solution of CCA salts (Chromium/Copper/Arsenic). Although these names might not sound environmentally friendly, very few alternatives are available for wood in exterior use.

4 – ADHESIVES

A wide spectrum of adhesives involving various chemistries is available for the manufacture and strengthening of laminated timber structures. These adhesives must have a set of important properties:

- High creep resistance,
- Good adhesion on wood,
- High bond strength,
- Gap filling properties: a glue line is usually 0.1 mm but with wood, and particularly arched beams, glue lines can be as thick as 1 to 1.3 mm,
- Water and heat resistance. Most of the evaluation tests are carried out in boiling water,
- Resistance to micro-organisms and fungi.
- Good compatibility with wood components (cellulose)

3/7
Casein glues were originally used for the lamination but have been rapidly replaced by synthetic adhesives. Water and heat-resistance were acceptable for interior use only.

Urea Formaldehyde resins and Phenolic resins appeared in the thirties. Resorcinol modified phenolic resins are still widely used for laminated timber. UF resins can be used provided that they are heavily plasticised to cope with thick glue lines. Melamine-Urea-Formaldehyde (MUF) resins have been widely used for 2 decades mainly for small-size, straight beams and hot cure.

Polyurethane adhesives appeared recently and do not yet give entire satisfaction particularly as gap-filling adhesives.

Epoxy adhesives are mainly used for the filling of cracks, the strengthening of beams and metal to wood connections.

Adhesives based on other materials, for example Polyvinyl Acetate emulsions, are not used for structural bonding because of their poor creep resistance.

### 4 - 1 - Aminoplastic resins

They are derived from the polymerisation of formaldehyde and urea. The reaction is basically a two-step process:

- Condensation of formaldehyde on urea under basic conditions to give methylol urea
- Polymerisation of methylol urea under acidic conditions

Once the degree of polymerisation is obtained, the resin is stabilised at a basic pH and supplied as a solution in water with a very limited shelf life. The formulation of these resins involves addition of a plasticiser to overcome brittleness of UF resin glue lines.

These resins are thermoreactive and pH-dependent. They can be cured with an acidic hardener and heat which resume and speed up the polycondensation process. However, even at the cured state, they have limited water resistance.

Other resins (MUF) are obtained by subsequent condensation of melamine onto a UF resin. Melamine brings water resistance and this property is usually improved by combining the resin with an acid hardener containing resorcinol.

UF and MUF resins are usually supplied in a liquid form but can be atomised to give very stable, remoistenable powders.

#### UF resins:

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price</td>
<td>2-part system</td>
</tr>
<tr>
<td>Light colour</td>
<td>Limited water resistance</td>
</tr>
<tr>
<td>Very good adhesion on wood</td>
<td>Formaldehyde</td>
</tr>
<tr>
<td></td>
<td>Limited shelf life</td>
</tr>
</tbody>
</table>

UF resins are recommended for interior use only. They are widely used for finger jointing.

#### MUF resins:

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light colour</td>
<td>Not reliable for cold setting</td>
</tr>
<tr>
<td>Not labelled</td>
<td>Limited shelf life</td>
</tr>
<tr>
<td></td>
<td>Limited pot life</td>
</tr>
</tbody>
</table>

MUF resins are mainly used in northern countries for short, straight beams with either hot cure or RF cure.

### 4 - 2 – Phenolic resins

Phenolic resins for laminated timber are phenol-resorcinol-formaldehyde resins in a water and alcohol solution. Resorcinol being a diphenol, it is extremely reactive towards formaldehyde and it is water-soluble. However, the cost of this raw material is particularly high and unstable, as it is available only from two manufacturers.

The usual process is a three-step reaction:

- Addition of formaldehyde to phenol with a base catalyst to give methylol phenols,
- Addition of resorcinol and reaction with the available methylol groups
- Addition of formaldehyde for further polymerisation

The resin thus obtained is a novolak (non-thermosetting) and very stable. They can be cured (as 2 part systems) with a hardener providing an excess of formaldehyde to the resin. Resorcinol reacts at room temperature with formaldehyde and crosslinks because of its trifunctional phenolic ring to give good cohesion to the bond line.
**RPF resins:**

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outstanding water resistance</td>
<td>Two-part systems</td>
</tr>
<tr>
<td>Very reliable</td>
<td>Toxic (phenol)</td>
</tr>
<tr>
<td>Long shelf life</td>
<td>Dark colour</td>
</tr>
<tr>
<td></td>
<td>Limited adhesion to some wood species</td>
</tr>
</tbody>
</table>

RPF resins are still widely used, particularly for large volume structures and exterior use.

### 4 – 3 – Polyurethane Adhesives

A polyurethane adhesive is usually a copolymer of polyether (or polyester)-polyol with an isocyanate (MDI, TDI). In the case of single-part systems such as the products used for timber lamination, the low-molecular weight polymer is produced using an excess of isocyanate. Terminal isocyanate groups can react with water (moisture) to produce amines, which react with other isocyanates, for further crosslinking of the polymer by creating polyurea links. However, the hydrolysis reaction produces CO₂ and this usually causes bubbles in the glue line and accounts for the poor ability of these adhesives to cope with gap joints. Good chemical adhesion to wood is provided by reaction of isocyanates on hydroxyl groups of cellulose. The reactivity of polyurethane adhesives towards moisture usually means that they need air-free application systems.

**PU adhesives:**

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single part systems</td>
<td>Specific application equipment</td>
</tr>
<tr>
<td>Light colour</td>
<td>Not suitable for gap-joint filling</td>
</tr>
<tr>
<td>No formaldehyde</td>
<td>Price</td>
</tr>
<tr>
<td></td>
<td>Isocyanate</td>
</tr>
</tbody>
</table>

They are used mainly in Germany and Switzerland. The main problem so far with PU adhesives is that the European standards giving performance requirements on adhesives for timber structures explicitly indicate that these adhesives should be either phenolic or aminoplastic resins.

### 4 – 4 – Epoxy resins

Epoxy adhesives have a very specific role to play in timber structures. They are usually proposed for two applications:
- Bonding of metal to wood or concrete to wood: bonded connections, bonded-in rods.
- Strengthening of structures: filling of split glue lines or deep fissuring.

Basically, an epoxy resin is obtained by condensing Bisphenol A on epichlorohydrin. The choice of raw materials and further blending of the resin with additives and filler will ensure good adhesion on wood and metal, good flexibility, gap-filling properties and high performances. These adhesives are two-part systems and the hardener is an amine, which gives further polycondensation of the resin by opening of the epoxy rings.

### 5 – PROCESS

The process of making laminated timber involves a lot of different steps including selection and preparation of the raw materials, preparation and application of the adhesive, construction and clamping of the beam and final stabilisation before installation.

#### 5 – 1 – Preparation of timber

After selection of the wood species, cross section of the laminations depending on the service class, all wood pieces have to be stabilised in a temperature and humidity controlled room in order to reach the moisture content the beam will have during service: 10% for interior use, 12% for interior unheated, 14% for exterior use. A good control of moisture content of timber is extremely important and it is recommended that all the single laminations are evaluated so two consecutive laminations will not differ by more than 2% in order to give a durable bond. Stress induced by the deformation of wood during drying process is usually a major cause of joint splitting.
Planing of the laminations has to be carried out not more than 24 hours before bonding, usually in-line immediately before glue application. This operation improves mechanical adhesion on wood surfaces by opening the pores.

Another important step in the preparation of laminations is the jointing by finger joints in order to reach the necessary length.

5 – 2 – Mixing and application of adhesive

Adhesive systems used in the laminated timber industry are generally two-part systems. Therefore, parameters such as ambient temperature and pot-life are very important. Any amount of adhesive mixture that has not been used within the pot-life must be discarded.

Resin and hardener need to be accurately weighed and thoroughly mixed. Anything from volumetric dosing with a bucket and hand-mixing with a broomstick to state-of-the-art dosing/mixing systems can be found on this market. New mixing systems are based on static mixing heads, directly connected to the applicator, which have the enormous advantage to reduce considerably the amount of water needed to clean the system.

Separate application of resin and hardener is also possible when very short cure times are requested. This is the case for finger jointing. If mixed, the two components would set in 1 minute. They are instead applied on each end of the assembly. When pressure is applied, curing can take place and the assembly can be manipulated after several minutes only.

Application of the mixed system is usually carried out with a curtain coater in thin, parallel beads. It is the only system that allows very high coating weight (approx. 300 to 500 g of adhesive per square metre) to be applied at high speeds (80 to 120 metres per minute).

5 – 3 – Curing process

After glue application, the laminations are stacked to desired dimensions and pressed for final curing of the adhesive. This process usually occurs at room temperature but as any chemical reaction, it can be considerably shortened at higher temperatures. The table below shows several possibilities:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Pressing mode</th>
<th>Pressing time</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-20°C</td>
<td>built-in clamps</td>
<td>16 hours</td>
<td>General purpose. Large size beams, curved beams.</td>
</tr>
<tr>
<td>15-20°C</td>
<td>carousel press</td>
<td>1-4 hours</td>
<td>Small size beams, for DIY</td>
</tr>
<tr>
<td>30-40°C</td>
<td>Press</td>
<td>5-10 hours</td>
<td>Heating tunnel: small size, straight beams</td>
</tr>
<tr>
<td>80-100°C</td>
<td>Press</td>
<td>2-10 minutes</td>
<td>RF press. Straight beams, all sizes.</td>
</tr>
</tbody>
</table>

Radiofrequency curing is very interesting for laminated timber. It can considerably shorten the pressing time, as it is a very selective way of heating only the adhesive, evenly throughout the glue line. This is compared to normal hot pressing where only the surface of the material is heated and heat is transferred slowly due to insulating properties of wood.

5 – 4 – Stabilisation

Laminated beams should be stabilised for at least a week to reach maximum mechanical and water resistance performances. This is particularly true if the beams need to be treated by impregnation with a CCA solution under pressure. They are then planed, sanded and cut to size. Metal connections are fitted in place and final adjustments are made in the factory prior to shipping of the beams.

5 – 5 – Waste disposal

Usually, off-cuts and sawdust are recycled to produce heat. The main problem is for discarded adhesive and cleaning water. They contain phenol, formaldehyde and various chemicals and cannot be disposed of in regular sewage.

For adhesive waste, the only possibility is to let it cure and send it to special contractors for disposal as solid special waste. The solution lies in trying to reduce the amount of unused adhesive mixture.

For cleaning water, solutions exist once the remaining adhesive in suspension has been filtered:
- Liquid waste is sprayed on sawdust and burned
- Water is treated with Fenton reagent for total oxidation of organic materials and reused for cleaning.

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6 – STANDARDS

A number of standards have been issued for timber lamination. The European Union, via its Standardisation Committee, has re-written most of them in the past 10 years and usually all 15 members agree and work to EN standards.

6 – 1 – European Standards for adhesives

The main document of utmost importance for adhesive manufacturers is EN 301. It establishes the performance requirement needed by an adhesive for the manufacture of load-bearing timber structures. It only covers UF/MUF and RPF polycondensation products. The document is being revised at the moment. Associated with EN 301 are EN 302 – part 1 to EN 302 – part 7, which describe the test methods for assessing the compliance of adhesives with EN301. Parts 1 to 4 are currently being revised and parts 5 to 7 were created recently and have been submitted to enquiry.

6 – 2 – European Standards for finished products

Any laminated timber producer should work under the conditions described in EN 386 which specifies requirements for the components and the production of glued laminated timber for structural use. It refers to the following standards:
- EN301: see above. Decision on what adhesive should be used.
- EN385: performance and production requirements for finger jointed structural timber.
- EN391: delamination test of glue lines.
- EN392: shear test of glue lines.
- EN518: grading of timber.
- EN335: service class and requirements for wood treatment.

7 – CONCLUSION

Laminated timber structures involve a very old and well-known raw material: wood, which is totally natural and gives an impression of warmth and comfort. But as a structural bonding application, it benefits from state-of-the-art adhesive technology and application systems. Working procedures and performance requirements are also strictly defined by a set of standards and regulations.
Resin-bonded connections, both in new build and in timber repair, typically involve various epoxy resin formulations in combination with either metallic or non-metallic plates or bars. A major advantage of using epoxy resin bonded systems is that formulations may be selected with properties specific to the situation of each repair.

Resin-bonded methods of repair to timber structures were developed in the early 1970s. Some typical examples of repair situations are for the restoration of beam-ends and column-ends, for fissure repairs, and for the upgrading of beams. The resins themselves may be used either in the form of a structural adhesive or as a volume grout for replacing damaged sections of timber. Among the advantages of resin methods are the ability to carry out in situ repairs with little or no disruption to the historic fabric of a building or structure, and to provide concealed connections. Resins may also be used for making joints in new structures, particularly those exploiting modern timber composites.

Well designed and executed bonded structural connections in timber can be very efficient. However it is essential to establish a proper basis for design which encompasses all relevant variables such as: loading; timber species and condition, including moisture content; timber grain orientation relative to reinforcement; section size and properties; reinforcement type, form and size; resin system, including primers; size of holes or slots; condition of timber surface; geometrical considerations, edge and
A detailed understanding of the important parameters involved in timber repair was developed in a project managed by TRADA Technology Ltd (TTL) during 1995-98; Oxford Brookes was the academic partner in this Department of the Environment-funded venture. During the experimental parts of this project a number of adhesive systems were evaluated with a variety of timber species. Other work, both experimental and theoretical, examined the pull-out behaviour of different types of reinforcement bonded parallel to the grain. This provided valuable insight into the effect of variables such as joint geometry, adhesive properties, bondline thickness and timber moisture content at the time of bonding.

New timber structures can benefit from the use of adhesive bonding in the development of efficient joints incorporating concealed bonded-in reinforcement. There is however no proper basis for design and any relevant information is rather ad-hoc. A current EPSRC project on ‘Improved Timber Connections Using Bonded-in Rods’ is being undertaken by Oxford Brookes, the University of Bath and TTL. This project seeks to apply adhesives and polymer composites to connections, to disseminate guidance on the appropriate use of new materials and to propose design methods.

A further development for new build involves the use of thin FRP pultrusions bonded into beams, specifically glued laminated (GLULAM) beams. Such structural macro-composites are extremely efficient in bending, enabling excellent structural performance
to be obtained from such elements. This enables the properties of relatively inferior timber to be exploited, as well as reducing significantly the amount of timber necessary to provide a particular level of performance.

This paper will bring together the aspects of materials selection and design guidance for making joints in timber structures, whether in new build or in repair. Specifically the paper will address:

• adhesives and adhesive bonding technology
• adhesion to timber
• polymer composite technology
• timber repair
• joint design principles for bonded joints in timber structures.