Adhesives

STEP lecture A12
E. Raknes
The Norwegian Institute of Wood Technology

Objectives

To give an overview of the different structural wood adhesives and to show how they are used in timber products and timber structures.

Prerequisite

A4 Wood as a building material.

Summary

The theory of adhesive bonding is briefly described, and reference is made to the present situation concerning EC5 and adhesive approval. A brief description of current and potential structural wood adhesives is given relating to composition, durability, application, classification. Types of joints (parallel, end-to-end, crosswise) and the process of bonding are described in principle, and bonding of pressure-treated wood is briefly mentioned.

Introduction

Structural wood adhesives are used to bind two or more wooden parts together in such a way that the product behaves as a static unit. The task of the adhesive is to fill the voids between the wooden members, and to produce adhesive bonds to each member which are equally strong and durable as the cohesive forces within the members. In addition, the adhesive layer itself must have sufficient strength and durability to retain its integrity in the assigned service class throughout the expected life of the structure.

The attraction forces between adhesive and wood are of the same type as the cohesion forces in the wood, i.e. electric attraction forces between molecules. The resulting bonds are mostly of the secondary bond type, i.e. hydrogen and van der Waals bonds. Some primary bonds, for instance covalent, are also likely to be produced with some adhesives. In order to provide the intimate contact necessary to produce bonds of this type, the adhesive must, at some stage in the bonding process, be in the liquid form. The bonding process consists of two steps:

- application of a liquid adhesive which wets the surface of both adherents so that attraction forces between adhesive molecules and wood molecules are created across the borderlines,
- transformation of the liquid adhesive, which fills the voids between the members, into a solid of sufficient strength and durability to retain its integrity throughout the service life of the construction.

The latter process is called hardening. It may be brought about in three ways:

- by a physical process, like the removal of solvents, or the solidifying of a melt as in thermoplastic adhesives like Polyvinylacetate (PVAc) and hot melts,
- by a chemical process, in which the adhesive molecules react with each other, forming primary bonds and creating a polymeric network such as in epoxies and polyurethanes,

- by combination of solvent removal and chemical reaction (urea-, melamine-, phenol- and resorcinol-formaldehyde).

With structural adhesives there is always a chemical reaction involved. Adhesives relying purely on physical curing such as thermoplastics have, generally, too much creep to be used for structural purposes.

EC5 classification of adhesives

At present there is only one established EN-standard for classification of structural wood adhesives, namely EN 301, "Adhesives, phenolic and aminoplastic, for load bearing timber structures: Classification and performance requirements". The corresponding test standard is EN 302, "Adhesives for load-bearing timber structures - Test methods, part 1-4". The standards apply to phenolic and aminoplastic adhesives only. These adhesives are classified as:

- type I-adhesives, which will stand full outdoor exposure, and temperatures above 50 °C,
- type II-adhesives, which may be used in heated and ventilated buildings, and exterior protected from the weather. They will stand short exposure to the weather, but not prolonged exposure to weather or to temperatures above 50 °C.

According to EC5 only adhesives complying with EN 301 may be approved at the moment.

Plywood and particle board are used as elements in some timber structures. There is, at present, no EN-standard for the classification of the adhesives used in these products, and hence they have to be evaluated using national standards. (e.g. BS 1203, "Specification for synthetic resin adhesives for plywood", BS 1455, "Specification for plywood manufactured from tropical hardwoods", DIN 53255, "Bestimmung der Bindefestigheit von Sperrholzleimungen im Zugversuch und im Aufstechverfahren" and DIN 68705, "Sperrholz, Begriffe, allgemeine Anforderungen, Prüfung".

Current types of structural wood adhesives

Resorcinol-formaldehyde (RF) and Phenol-resorcinol-formaldehyde (PRF) adhesives

The pure resorcinols are made by reacting resorcinol (a phenolic compound) with formaldehyde. The process is carried out with a deficit of formaldehyde, and the reaction stops when this is consumed. The adhesive, which is a liquid, is used with a "hardener" containing formaldehyde. This completes the cure of the resin to an infusible state. In addition, the hardener usually contains inert fillers of various kinds, in order to make the glue "gapfilling". As resorcinol is an expensive chemical, some of it is now usually replaced with other, cheaper phenols. For both types, curing may take place at room-temperature (15-20 °C) or at elevated temperature. These adhesives are suitable for radio-frequency curing. The bonds formed in the reaction between resorcinol and other phenols with formaldehyde are of the -C-C- (Carbon to Carbon) type. These bonds are very strong and durable, and not susceptible to hydrolysis. The RF's and PRF's therefore give very durable bonds: they are fully water-, boil- and weather-resistant, and will also withstand salt-water exposure (Selbo 1965).

Members glued with these adhesives will not delaminate in a fire. Permissible glueline thicknesses are up to approximately 1 *mm* with ordinary adhesives and up to 2 *mm* with special, gap-filling types. The gluelines are neutral, i.e. neither acid nor alkaline, and hence they will not damage the wood or corrode metals. They are very dark in colour. The cured adhesive will not emit formaldehyde or other harmful chemicals. RF's and PRF's are type I adhesives according to EN 301. They are used in laminated beams and arches, fingerjointing of structural members, I-beams, box beams, gusset joints, nail-gluing etc., both indoors and outdoors.

Phenol-formaldehyde adhesives (PF), hot-setting

These are made by reacting phenol with formaldehyde under alkaline condition, at elevated temperature. The reaction is stopped by cooling. The adhesive may be supplied as liquid, powder or film and is alkaline. It is cured by the application of heat (110-140 °C), and, for some types containing more reactive phenols, by a combination of heat and the addition of a formaldehyde-containing hardener. The gluelines are very dark. They have the same durability properties as the RF- and PRF-adhesives.

Hot-setting PF's are typically hot-press adhesives, and they are used in structural and marine plywood, in fibreboard, etc. Radio frequency-curing is not possible because of "burning", but microwave curing is used for some products, like laminated veneer lumber (LVL) beams. Hot-setting PF's cannot be classified according to EN 301. When tested to BS 1203 or BS 1455, they will meet the most severe requirements (WBP, "Weather and boil proof").

Phenol-formaldehyde adhesives (PF), cold-setting

In order to make a PF cure at room-temperature it must be made acidic. This is not possible in an aqueous solution, as the acid would precipitate the resin. The adhesive is, therefore, dissolved in alcohol, and made to cure by the addition of a strong acid. The glueline itself has the same strength and durability properties as the other phenolic-type adhesives, i.e. fully water-, boil- and weather-resistant. The hardener, however, is so strongly acidic that it is liable to damage the wood surfaces.

Cold-setting PF's are classified according to EN 301, but the current types are likely to be eliminated by the "acid damage test" given in EN 302-3. These adhesives were used to some extent in the fifties and sixties in glulam production. Some of these buildings actually collapsed many years later, and there is reason to believe that acid damage from the adhesive is the cause. Cold-setting (acid-curing) PF's of current type, therefore, should not be used for structural purposes.

Urea-formaldehyde adhesives (UF)

UF's are made by reacting urea with formaldehyde. The reaction is speeded up by acid and heat. At a suitable stage the reaction is stopped by cooling and neutralising. It is started again by adding an acid-releasing hardener and, for some types, by heating in addition. UF's are a very versatile adhesive family. They may be supplied as liquids or powders (sometimes with hardener added), and they may be cured at any temperature from 10 °C upwards. Speed of curing may be adapted to the process. They are also suitable for radio frequency-curing. The gluelines are light in colour.

The hot-press types are used for non-structural plywood and chipboard etc. They are classified by for instance BS 1203 and BS 1455 where they meet the two lowest requirements only (INT, "Interior", or MR, "Moisture resistant"). Only special cold-setting UF's are suitable for structural purposes. They must not be too acidic, and they must have filler added to make them gap-filling (up to 1 *mm*), otherwise the gluelines will crack on their own if thicker than 0,1 *mm*. Even these adhesives have limited heat- and water-resistance, and they are broken down fairly quickly by combined heat and high relative humidity. In a fire they will tend to delaminate. UF's for structural purposes are classified according to EN 301 as type II-adhesives. They are used in glulam production and fingerjointing for interior construction.

Melamine-urea formaldehyde adhesives (MUF)

These adhesives are closely related to UF adhesives, but some of the urea is replaced with melamine in order to increase the water- and weather-resistance. Some of them even contain resorcinol for the same purpose. MUF-adhesives are supplied as hot-press adhesives, for plywood etc., with intermediate water-resistance, and as cold set where together with hot set adhesives they are used for glulam and fingerjointing.

The cold set ones are classified according to EN 301. Some of them will be type II-adhesives, with properties comparable with UF's. The best will meet the type I-requirements, and thus be classified as "weather-resistant". They are, however, less resistant than the resorcinols, and not suitable for marine purposes (Selbo 1965). However, MUF's are often preferred for economic reasons, and because of their lighter colour.

Casein adhesives

The main constituent of these adhesives is the milk protein, casein. The adhesive is delivered as a powder, consisting of casein and various inorganic salts. When the powder is mixed with water a series of chemical reactions occur. After approximately 15 minutes these have resulted in the casein being dissolved as Sodium Caseinate. After 4-8 hours this has been transformed to Calcium Caseinate, which is fairly insoluble in water ("Curing-reaction"). The gluelines are fairly light in colour. They are less water resistant than UF gluelines, but more resistant to combined heat and high relative humidity.

Caseins are probably the oldest type of structural adhesive and have been used for industrial glulam production since before 1920. They have proved suitable for indoor and protected outdoor construction, but have to be protected against mould attack with a suitable fungicide. Caseins do not meet the requirements of EN 301.

Environment	RF/PRF	PF(hot)	MUF	UF	Casein
Exterior	+	+	(+)	x	x
> 50 °C	+	+	(+)	x	x
> 85 % r.h.	+	+	(+)	x	x
Marine	+	+	x	x	x
≤ 50 °C, ≤ 85 % r.h.	+	+	+	+	+
Glueline colour	Dark	Dark	Light	Light	Light
EN-class	301-1	-	301 - I/II	301 - II	-

+ Suitable x Not suitable (+) Some brands suitable
- Not covered by existing EN-standards

Table 1 Suitability of current structural wood adhesives.

Potential new structural wood adhesives

Test methods developed for one or more types of adhesives, like those in EN 302, are not necessarily suitable for other types. Approval of a new adhesive type, therefore, will involve two steps:

- establish with adequate confidence that the long-term durability of the new type is satisfactory,
- devise short-term tests which are able to distinguish between the good and the bad brands of the new type.

A general methodology for this is given in the CIB-publication 96 (1987).

The following four adhesive types are at present considered as potential structural wood adhesives.

Epoxy adhesives

These are two part adhesives:

- part I is an epoxy resin whose molecules are terminated with epoxy groups,
- part II usually consists of bifunctional amine(s).

None of them contain solvents. When mixed together epoxy and amine react to make up an infusible resin.

Epoxy adhesives may be "tailored" to the area of application, and some of them are definitely suitable for wood gluing. They have very good gapfilling properties. However, due to their high price and their application properties they have only been used in special cases for wood bonding, for instance:

- building of wooden boats,
- repairing delaminated glulam beams,
- bonding of metal, plastics, rubber etc. to wood,
- repairing wood with decay or other damage ("casting"),
- glued-in bolts.

Epoxies have very good strength and durability properties, and the weather resistance for the best ones lies between MUF's and PRF's.

Two-part polyurethanes

Part I consists of bi- or trifunctional isocyanate and part II of bi- or trifunctional alcohols. Both are solvent-free. When mixed together they react to form a polyurethane resin. These adhesives have good strength and durability, but experience seems to indicate that they are not weather-resistant, at least not all of them (Hedlund 1987). As for wood bonding they have mostly been used for special purposes, for instance:

- aluminium to plywood in sandwich constructions,
- corrugated steel plates to plywood for load-bearing roof elements (used in Scandinavia for more than 10 years),
- glued-in bolts.

One-part polyurethanes
The reactive component is an isocyanate. When applied to wood, part of it will react with moisture and be converted to amine. This reacts with the remaining isocyanate to form a poly-urea resin. Carbon dioxide is formed during the curing, and this will make the adhesive foam if the glueline is thick. Strength and durability properties are much the same as for two-part PU's, or slightly inferior. They are not gap-filling.

In Germany two brands of one-part PU's have been approved for use as a structural wood adhesive, both indoors and outdoors. They are limited to 6 *m* spans and 0,3 *mm* glueline thickness.

Emulsion polymer isocyanates (EPI)
These are also two-part adhesives:

- part I: Emulsified polymer, e.g. polyvinylacetate (PVAc),
- part II: "Blocked", emulsified isocyanate.

Working properties and initial curing is much the same as for PVAc-adhesives, but when the glueline dries, the isocyanate is released and acts as a crosslinker. Strength and durability are reported to be very good for these adhesives, and some brands are approved by the American Institute of Timber Construction as exterior grade adhesives for structural wood bonding. Others have been found to be less durable (Yoshida 1986).

Within each of these four adhesive types there are brands of very different properties. Some of them may be suitable as structural wood adhesives, and some are definitely not. The problem is that at present there are no short-term approval tests to identify the suitable brands.

Property	Epoxy	Two-part PU	One-part PU	EPI
Weather resistance	?	?	?	?
Heat resistance	?	?	?	?
Water resistance	?	?	?	?
Creep	?	?	?	?
Toughness	+	+	+	+
Gapfilling	+	+	x	x
Adhesion	?	+	+	o
Easy to use	x	x	x	+
Curing time	o	o	o	+

+ Good, probably better than current adhesives.
o Comparable to current adhesives.
x Inferior to current adhesives.
? Uncertain, large variations between brands.

Table 2 Potential new structural adhesives.

The use of structural wood adhesives
Three ways of bonding wood may be distinguished.

Parallel (sideways) joints
Here the glue must match the shear strength parallel and the tensile strength perpendicular to the grain direction of the timber. Approved adhesives will match these requirements without problems. Swelling and shrinking stresses will be small, since all the members are in line with each other.

End-to-end joints
In this case the adhesive should match the tensile strength of the timber in the grain direction. Structural butt end jointing of timber, which implies that the adhesive must match the tensile strength of the timber, is not possible with current techniques. Instead, the jointing is carried out in such a way that tensile stresses in the member are transformed to shear stresses in the gluelines. This may be done in various ways, but the method used industrially is fingerjointing. In this joint the combined shear strength of all the finger areas should ideally match the tensile strength of the cross-section of the member. Since the shear strength is only 1/10 of the tensile strength, the glueline area should be approximately 10 times the cross-section area. Again members are in line with each other, minimising swelling and shrinking problems.

Crosswise jointing
In this case the adhesive must match the shear strength parallel and the transverse tensile strength of the wood, which is not a problem. The jointed members will, however, be at (more or less) right angles to each other, and this can cause great stresses in the gluelines due to moisture movement of the wood. Such gluing is, therefore, mostly limited to two cases:

- the members to be jointed are so thin that they will restrain the movement of each other (fairly) effectively e.g. in plywood, OSB, particle board, fibreboard,
- restrained members like plywood and particle board are glued to solid wood members which are fairly narrow e.g. in I-beams, box beams, gusset joints.

In such products the small lengthwise movement of the solid wood members will match approximately with the restrained movement of the woodbased panel. Stresses along the glueline are therefore rather small, but they may be high across the glueline if the members are wide, or the moisture fluctuations great. This may produce fatigue failure in the joint with time.

The bonding process
This consists of the following steps:

- conditioning the timber to a moisture content corresponding to the average moisture content which is likely to apply in service,
- machining of the surfaces to be bonded, preferably just before bonding, because freshly cut dust free surfaces give the best gluelines. This must be done with sharp tools, to prevent damaging the surfaces,
- mixing and application of adhesive,
- application of sufficient pressure to hold the members in contact with each other until the adhesive has got sufficient handling strength,
- in some cases: application of heat during the pressing period in order to

speed up curing,

- conditioning of the bonded members to obtain postcuring and temperature- and moisture-equilibrium.

Bonding of chemically treated wood

Chemical treatment may be used to protect wood against decay, or to make it fire-resistant or water-repellant. If the members are used in glulam production afterwards, they will have to be planed before gluing. This requires a certain penetration of the chemical, or most of it will be removed by the planing.

Such treatment of timber may affect the gluing properties, dependant on the type of treatment. As a rule the treatment/adhesive-combination should be tried out beforehand. The following guidelines may be applied:

- creosote and other oilbased treatments. Gluing is difficult but possible with PRF and polyurethane-adhesives. Gluing first and impregnating afterwards is recommended.

- water-soluble salts. The copper-chrome-arsenic salts usually give no difficulties. Salts containing free acid (e.g. boric acid) or compounds able to react with formaldehyde (e.g. ammonium salts) may give problems. Some of the decay protecting and most of the fire protecting salts are of this type.

References

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