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Adhesives for on-site bonding: Characteristics, testing and prospects

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HIGHLIGHTS

- Products used on-site have specific characteristics different from other adhesives.
- Properties of epoxies, polyurethanes and PRF are related to industrial formulation.
- Testing methodologies specifically set-up for on-site adhesives are described.
- Effects related to long-term duration of loads are briefly reported.
- Future issues for on-site products which are of particular interest are introduced.

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ABSTRACT

The manuscript deals with the main characteristics of those adhesives normally used for the reinforcement of timber structures, achieved through site-applied bonding. The characteristics relate to a combination of chemical composition and product formulation. A section describes testing procedures for products to be used on site, as this aspect does not exist in current European standards. The principal issues associated with the use of those products, mainly relating to long-term duration, are considered, focusing more on the adhesive characteristics rather than to the wood substrate properties. Finally, possible challenges are introduced in order to stimulate research in this field.

1. Introduction

The adhesive products which may be used on site have specific properties which are not usually achieved in aminoplastic adhesives for the reasons indicated below:

(a) The quality of wood surfaces is not easy to control on site in contrast to that which may be encountered in a manufacturing plant, in particular where there is effective control of the surfaces to be bonded. Often the surfaces are freshly machined by sanding or planing in a clean environment with the correct temperature and humidity, which enables the moisture content of the wood surfaces to be regulated and facilitates a good bonding surface. This is in contrast to the conditions on site where all of the above factors may be variable and/or not easily controllable.

(b) Appropriate bonding pressure of the timber components is not easily achievable on site, in contrast to a factory situation where bonding is almost always carried out under controlled pressure. The adhesive manufacturers often specify the minimum and maximum application temperatures and pressures to be applied to the assembled components.

(c) It follows from the above that factory produced bonded assemblies usually have bond line thicknesses of 0.5 mm or lower, in contrast to the bond line thicknesses found in on-site bonding which may be between 1 and 12 mm.

These three conditions indicate that there is a requirement to use types of adhesives on site which are characterised by good substrate wetting properties, high internal cohesive strength, plus final adhesion properties that are not only related to mechanical interlocking (whose efficacy is strongly associated with the application of pressure during bonding) but also to a variety of other adhesion mechanisms, such as specific adhesion. As reported

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previously by Custodio et al. [1], practical applications on site generally utilise epoxy, polyurethane adhesives and additionally some polyester products for structural bonding applications on timber. Of these varieties, epoxy adhesives have been used for more than forty years and they are currently still the most widely used choice for bonding structural timber on site. Epoxy types intended to be used for site bonding of timber components implies that in practice they have to be able to cure at moderately low temperatures. These epoxy systems are two-part thermosetting adhesives, and include a wide range of formulations and varying commercial products with distinct characteristics. These are required for practical reasons to include good gap-filling shrink resistant properties, excellent tensile/shear strength, high dry and wet strength, and good resistance against moisture and certain chemicals. Although being the optimum choice, epoxies have some limitations: they have poor peel strength and may often delaminate when subjected to in-service repeated wetting and drying.

The fact that epoxy adhesives can be effectively used as structural adhesives for applications on timber has been evidenced in experimental tests: for the development of an epoxy adhesive specific for glulam consolidation, Radovic and Goth [2] applied all the EN 302 methods [3–9] to thin bondline joints finding full compliance with EN 301 requirements (in terms of: tensile shear strength in normal conditions, after 4 days immersion in water at 20 °C, and after 6 h immersion in boiling water followed by additional 2 h in water at 20 °C; fibre damage; shrinkage stress; accelerated ageing, this latter in conditions different from those considered in current version of EN 301 [10]). Although no specific standards for epoxy adhesives exist to date, it is widely accepted that they are suitable for limited exterior service environments corresponding to the Service Classes 1 and 2 as defined in EN 1995-1-1 [11].

Another class of adhesive products commonly used for interventions on site are two-component polyurethanes. In contrast, monocomponent polyurethanes, although largely used in manufacturing plants to construct glulam components, are not, in general, preferred for applications on site owing to their tendency to develop gas bubbles within the thick glue line, thus compromising the cohesive strength of the bonded components. In specific European countries, phenol–resorcinol based (PRF) adhesives were occasionally used to repair timber on site, for instance to bond glued-in rods or to glue side plates for beam reinforcement. Although these applications have not been widely used they are mentioned in order to present a complete picture.

Apart from the difference in chemistry which will be briefly considered in Section 2, all classes of products display similar characteristics and problems in their use on site. For instance, they can be used in a range of rheological states from thixotropic pastes to fairly low viscosity fluids. Moreover, they are lacking with regard to specific standards for testing and usage when applied on site. This is the reason why no distinction will be made amongst them with respect to testing in Section 3. However, previous tests have evidenced certain differences in performance: several experimental trials carried out in the past showed that steel rods bonded with an epoxy adhesive exhibited timber failures close to and along the adhesive/timber interface, with higher pull-out strengths compared to both polyurethane and PRF adhesives, which instead exhibited cohesive adhesive or adhesion failures [12–15]. Moreover, fatigue tests also indicated better performance for epoxies than for the other two adhesives [15] and, with polyurethanes tested under load, significant short term strength losses were measured for glued-in rods at a temperature of just above 40 °C. However, in the case of a particular epoxy product this strength decrease was observed at temperatures above 50 °C [16]. Additionally, due to low adhesion to steel, specimens prepared with PRF suffered failure in less time than anticipated after long-duration application of load [15]. In contrast, performances in gluing glass fibre reinforced polymers (GFRP) seemed more encouraging when evaluated after moisture-induced cyclic delamination tests, although considerable variability was found depending on the combination between PRF adhesive and fibre reinforced polymers (FRP) [17]. However, also in the case of FRP bonding, structural epoxy adhesives are the generally accepted products in bonded FRP–wood connections. On the other hand, a different behaviour concerning the adhesion to high-moisture-content substrates can also be observed. More in detail, in the case of epoxies the moisture content of wood at time of bonding must be lower than 20–22%, irrespective of timber species [18]. In contrast, in the case of polyurethanes even when gluing at higher moisture levels the obtained resistance is in accordance with the wood resistance at that corresponding moisture content [19]. Appreciable delay in curing can be expected in PRF resins, due to the slow-down of the water release process (water molecules come from both the adhesive mixture and the polycondensation reaction, see below). It must also be noted that there is limited experience on the long-term behaviour of the assemblies prepared on site with PRF resins. In fact, these adhesives do require consistent and relatively high and even pressure across the joining area, and there are only very rare site situations where it would remotely possible to use these factory products with any commercial viable clamping method. This is one reason why they are less useful as site-based materials compared to their excellent use in humidity and temperature factory controlled conditions.

It is relevant to emphasise at this juncture that all the above-mentioned results strongly depended on the specific composition of the products, as will be made clear in Section 2. It is highly possible that the results obtained are formulation specific to a particular adhesive type.

Aim of present work is describing the main characteristics of most common adhesives intended to be used on site for the reinforcement of timber elements, by emphasising how these characteristics can be related to a combination of chemical composition and product formulation. The principal issues associated to long-term behaviour are also described. Furthermore, some challenging aspects are discussed, which include testing procedures specific for on-site products (they are currently not considered in European standards) and future prospects related to this type of adhesives.

2. Adhesive material composition

In this section epoxy, polyurethane and PRF resin chemistry is introduced, including remarks concerning the generic effects of several parameters affecting the curing behaviour of these products.

2.1. Epoxy resins

Epoxy resins used for the reinforcement/repair of structural timber elements are two-component systems in which the prepolymer (average molecular weight usually lower than 700 g/mol), usually called *Part A*, is a component containing epoxy functional groups, whereas the hardener or curing agent, usually known as *Part B*, includes H-containing moieties able to react with the epoxy ring, thus forming intermolecular bonds constituting a cross-linked three-dimensional structure. Although several multi-functional molecules can be used, often the Part A is a prepolymer of diglycidyl ether of bisphenol A, generally referred to as DGEBA, whose monomer can be schematically shown in Fig. 1.

It is worth noting that the molecular weight of this monomer is 340 g/mol, which implies that Part A is usually constituted by a