



Epoxy resins used for the repair of timber structures: The problem of short- and long-term performance evaluation

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Abstract

Epoxy-based adhesives are currently adopted for repair works on site, as they are suitable for jobs where the use of pressure is not possible and clean regular gluing edges are difficult to get. However, some factors have limited a wider use of structural adhesives, namely in historical timber structures. One reason is that a long service life has not yet been fully proven for synthetic adhesives since the natural ageing of actual glued joints is no older than sixty years and standard accelerated ageing tests are not yet available. Several research projects have been recently set aiming to gather a wider and systematic knowledge on the long-term performance of epoxy adhesives as well as the bonding durability under high service temperature or humidity, and the influence of variables like pre-ageing, moisture content or hardwood species. The present paper discusses a number of test methods that have been proposed to evaluate the performance of epoxy bonds, outlining the corresponding difficulties, application and significance.

1 Introduction

Rehabilitation of buildings has an increasing economical and social importance in most European countries. A great number of these buildings either are of "common" timber frame construction or incorporate more or less complex timber structures that need specific interventions, including reinforcement or repair due to previous overloading, insect attack or decay due to fungal activity, or to glue line delamination in glued members.

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Reinforcement techniques based on the use of structural adhesives on site, mostly in conjunction with steel plates or fibre-reinforced materials, have been applied for some decades to timber structures. These techniques minimise disturbance to the building and to its occupants during the intervention, are versatile, effective, and less time and cost consuming than alternative traditional methods and materials.

Epoxy based adhesives are currently adopted for these repair works, as they are suitable for in situ jobs, where the use of pressure is not possible and clean regular gluing edges are difficult to get.

Despite a reasonable experience on the use of epoxy adhesives for indoor and even outdoor works, a wider use of these structural adhesives, namely in historical timber structures, is frequently restrained on the basis of lack of knowledge or reliability considerations.

One reason is that a sufficiently long service life has not yet been fully proven for synthetic adhesives, since the natural ageing of actual glued joints is no older than sixty years and standard accelerated ageing tests are not yet available.

2 Evaluation and acceptance of adhesives and glued products for load-bearing applications

2.1 Current standards for testing and classification

A number of test methods have been developed to evaluate the suitability of adhesives for different applications and to predict the performance of glued products. This has been done on the basis of best guess of the mechanical, physical and chemical loads applied to the glue line during its service life, as well as of their effect on glue line integrity and durability.

Current European standards or documents in preparation dealing with the approval of new adhesives or with the quality control for the acceptance of glued products include the following list.

- *EN 301:1992 (in revision)- Adhesives, phenolic and aminoplastic, for load bearing timber structures: Classification and performance requirements* (for several exposure conditions)
- *EN 302-1:1992 (in revision) - Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of bond strength in longitudinal tensile shear*
- *EN 302-2:1992 (in revision) – Part 2: Determination of resistance to delamination (Laboratory method).* (Applied to glued laminated wood)
- *EN 302-3:1992 (in revision) – Part 3: Determination of the effect of acid damage of wood fibres by temperature and humidity cycling on the transverse tensile strength*
- *EN 302-4:1992 (in revision) – Part 4: Determination of the effects of wood shrinkage on the shear strength*

- *EN 302-5 (in preparation) – Part 5: Determination of conventional assembly time.* (for phenolic and aminoplastic polycondensation adhesives)
- *EN 302-6 (in preparation) – Part 6: Determination of the conventional pressing time.* (at 3 specified climates for phenolic and aminoplastic polycondensation adhesives)
- *EN 302-7 (in preparation) – Part 7: Determination of the conventional working life.* (by a viscosity test)
- *In preparation: Document: prEN12436 – Adhesives for load bearing timber structures - Casein adhesives - Classification and performance requirements.*
- *In preparation: Document: CEN/TC 193/SC 1 – Determination of static load resistance of wood adhesives in different atmospheric conditions (HRT 92)* (increasing temperature conditions).
- *EN 385 – Finger jointed structural timber - Performance requirements and minimum production requirements*
- *EN 386 – Glued laminated timber. Performance requirements and minimum production requirements.*
- *EN 387 – Glued laminated timber; production requirements for large finger joints*
- *EN 391 – Glued laminated timber. Delamination of glue lines.* (3 delamination methods for continuous quality control of glulam).
- *EN 392 – Glued laminated timber. Shear test of glue lines* (Applicable for continuous quality control of glue line).
- *EN 1193 – Timber structures. Solid finger jointing. Production requirements.*

2.2 Evaluation and acceptance of epoxy adhesives

The acceptance of adhesives is currently based on three major requirements: strength properties (shear strength, tensile strength), wood failure and delamination of the glue line (for measuring permanence of strength).

The existing test methods to evaluate glue line performance were developed for industrially used adhesives, especially phenolic or aminoplastic based products, and have repeatedly proven to be inadequate to assess the behaviour of epoxy type adhesives or epoxy glued products. Standard test specimens like the ones proposed by EN302-2, EN391, EN392 are not only difficult to produce from hard epoxy glued timber but are also inadequate to reproduce thick glue lines, as it is the case of most common on site reinforcement uses. It has also been argued that their application to epoxy glued products does not describe the reported long-term performance of these adhesives on site.

2.3 Strength assessment

Measurement of strength of a bond area under load may be mistaken by the unknown stress distribution. Due to stress concentration, the maximum load may be first reached at the edges, causing failure there before it propagates to the rest of the bond.

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For this reason, larger (longer) specimens normally produce lower unit strengths, because the inner part of the glued surface is not called to collaborate. Low-modulus adhesives tend to be more sensitive to the actual bonded area as they are able to transmit stress more efficiently. On the contrary, high-modulus, brittle adhesives do not undergo the deformation necessary to transmit stress; so, they build up higher stress concentration near the edges of the bond area leading to premature failure.

Geometry is known to have a profound effect on the performance of an adhesive bond. However, since epoxy adhesives family comprehend products with a very wide range of Modulus of Elasticity, stress concentration effects will not easily be overcome by specimen size being stipulated by standardised test procedures.

Therefore, the predictive value of a specimen is related to how close the geometry of the specimen simulates that of the ultimate glued product it represents.

The geometry of the above specimens resemble that of the ultimate glued product they mean to represent (glued laminated timber members), corresponding to a straightforward industrialised production. However, when bonding on site existing structures, a great number of configurations may be obtained, thus complicating the design of a standard specimen able to simulating what the adhesive will experience in an actual construction.

The test methods proposed in the literature to evaluate strength of epoxy bonded products generally include variations of pull-out tests (of steel or fibre reinforced polymers glued to timber blocks) and shear block tests prepared in their final dimensions with a specified glue line thickness.

Another problem is that on site application of adhesives is a delicate job, in the way that properties of reinforced elements very much depend on the care put in the work. Many factors that are likely to affect bond properties (like wood surface preparation, moisture content gradients, adhesive thickness or environmental conditions) are difficult to simulate in a standard test procedure. Ideally, specimens should be cut out from real reinforced members, in order to provide some evidence of tolerance to fabrication conditions.

Besides, the access to timber members being repaired is not always easy and complete, and one should be confident that adhesive penetration is enough. Although a standard procedure for performing repair works is not possible and probably not even desirable, quick tests for controlling the adhesive quality and for checking penetration of the adhesive (injection of fissures, holes) would be of extreme importance and should be given some thought.

2.4 Durability assessment

A reliable use of structural adhesives requires information on how it will perform in a given environment, but also for how long. The issue of the adhesive durability is even more difficult to address than its strength.

Known durability of proper structural adhesives as based on natural ageing goes back to some decades only. Although not yet comparable to the experience



acquired during the ages with other more traditional materials, there are many reinforcement case studies from the mid XX century where epoxy adhesives were used described in the literature.

Unfortunately, not so many descriptions can be found in the literature on the re-assessment of these old reinforcement works. Another point is that for commercial reasons, many reports refer to the epoxy adhesives being tested by a given code number. Traceability of the specific adhesive used is also difficult in many situations where a well-known trade name is abandoned due to slight changes in the adhesive formulation.

Accelerated ageing tests suitable for epoxy adhesives are still under development.

Ideally, long-term exposures should be conducted to correlate with short-term accelerated tests to validate them. With a few exceptions of long used adhesives, it is not really known how to expose a specimen in a laboratory so that results can be extrapolated into long-term natural exposure.

A common way to assess strength permanence, in other words durability, consists of subjecting test specimens to a certain combination of climatic cycles, with various levels of humidity, temperature (and load), and different number and duration of cycles. A number of existing test standards describes accelerated ageing tests, as for instance boiling of glued products. Other laboratory tests include climatic cycles, varying from consecutive heat, water and freezing cycles.

Water may have several effects on the adhesive depending on its chemical nature (a simple immersion test can reject an adhesive for certain uses) and some effects on the wood, namely dimension change and strength change, that may vary among species and sizes of the wood elements. Specimen species and size will affect the rate of water absorption and the amount of stress generated. Heat may have several effects on adhesives (softening, breakdown or even further curing) and some effects on the wood (temporary and permanent strength loss, dimension change and drying). The amount of stress generated is dependent upon the species of wood (density), thickness of the wood, moisture gradient, and grain direction on either side of the bond. Strong development of wood fissures during exposure tests will release internal stresses that would otherwise reflect on the glue line.

However, the way each of these parameters is likely to affect the glue line strongly depends on the chemical nature and physical properties of the particular adhesive. Thus, the relative score of a number of adhesives intended for the same end-use may vary considerably with any particular test method. Should test method and evaluation criteria be specified as a function of the nature of the adhesive?

Accelerate tests have to impose severe conditions to account for the shorter time of exposure as compared to natural ageing.

How much severity (heat/water)? is one question.

How much strength loss after exposure is acceptable? is another question.

For given exposure conditions and test specimen size and shape, test results are generally evaluated through delamination (glue line opening right after testing) and strength loss after exposure test (either wet or after reconditioning to a standard moisture content of the wood).

2.5 Wood failure

While delamination and strength are directly measured quantities, wood failure may be very difficult to evaluate and is subject to a great deal of interpretation.

Two types may be identified: shallow wood failure and deep wood failure (10 or more cells deep below the surface). Shallow wood failure suggests inadequate penetration and repair of subsurface damage (Marra, [1]); it is sometimes referred to as fuzzy fibre pull, and is often not counted as wood failure.

Besides, glue lines made with strong woods are likely to have negligible wood failure when tested and still produce strong durable glue lines, therefore the percentage of wood failure criteria should be given further consideration.

3 Further studies and standards development

Several research projects have been recently set aiming to gather a wider and more systematic knowledge on the short and long-term performance of epoxy adhesives.

Extensive pre-normative research and thorough consideration of some problems are still required, including the bonding durability under high service temperature or humidity, and the influence of variables like pre-ageing, moisture content when gluing, species or preservative treatment of timber on the short and long-term performance of the final products. Some of these problems will be addressed in a recently launched European project called LICONS.

The need for development of European standards for the evaluation of bonding durability as well as the long-term performance of epoxy adhesives has been identified by COST E13 (Wood adhesion and glued products) [2].

In parallel, the European Committee for Standardisation (CEN), has recently set a programme of work dealing with adhesives for on-site assembling or restoration of timber structures (CEN/TC193/SC1/WG11), which will prepare two new standards, on

- Initial evaluation and approval
- On-site acceptance testing

The principle of the on-site acceptance test standard will be based on:

- On-site sampling and measurement of the adhesive's cure schedule (with the "thermal cup" method);
- On-site sampling and subsequent laboratory measurement of the adhesive joint's shear strength ("with the "bonded planks" method) ;
- On-site sampling and proof-loading of the adhesive joint's strength (with the "pull-out" method)

4 Conclusions

Test methods must be designed having in mind a specific type of adhesive (that determines degradation mechanisms), an individual timber product (specific performance requirements) and a given service environment (imposed actions). Most existing test methods were developed for adhesives other than epoxy mixtures and their practical application to these adhesives is difficult and probably not very informative of the actual performance of glued products.

In the case of structural adhesives for bonding on site, mainly for strengthening existing structures, a wide variety of possible uses (either on their own or in conjunction with steel or FRP profiles) determine a great number of glued products geometry, imposed actions and performance requirements.

Furthermore, epoxy adhesives comprehend a wide family of products, with highly varied viscosity, strength and elasticity, thermal properties and compatibility with timber and other materials.

Besides, on-site application of adhesives is a delicate job and properties of reinforced elements very much depend on the care put in the work. Despite being done by specialised teams, with the necessary skills and knowledge, on-site methods are felt necessary in order to check step-by-step the quality of the work.

For these reasons, standardisation of test specimens and test methods is not an obvious and straightforward issue and has received further consideration. Some test standards are already in preparation in order to overcome this gap, covering not only laboratory testing but also quick on-site assessment.

At last, the authors consider that very useful information can be collected from re-assessing old timber structures that have been repaired or reinforced using epoxy adhesives. Even though the actual epoxy formulation, the specific surface conditions and preparation, as well as the routine of adhesive application may not be well described, these provides invaluable knowledge on the long-term performance under natural exposure conditions and should therefore be carried out wherever possible.

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References

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