www.elsevier.com/locate/ijadhadh

Mechanical performance of full scale steel-timber epoxy joints after exposure to extreme environmental conditions

Alberto Cavalli, Marino Malavolti, Alessandro Morosini, Antonella Salvini, Marco Togni

PII: S0143-7496(14)00101-8
DOI: http://dx.doi.org/10.1016/j.ijadhadh.2014.05.005
Reference: JAAD1539

To appear in: *International Journal of Adhesion & Adhesives*

Accepted date: 20 April 2014

Cite this article as: Alberto Cavalli, Marino Malavolti, Alessandro Morosini, Antonella Salvini, Marco Togni, Mechanical performance of full scale steel-timber epoxy joints after exposure to extreme environmental conditions, *International Journal of Adhesion & Adhesives,* http://dx.doi.org/10.1016/j.ijadhadh.2014.05.005

MECHANICAL PERFORMANCE OF FULL SCALE STEEL-TIMBER EPOXY JOINTS AFTER EXPOSURE TO EXTREME ENVIRONMENTAL CONDITIONS

Alberto Cavalli[a], Marino Malavolti[b], Alessandro Morosini[a], Antonella Salvini[b], Marco Togni[a]

[a] Department of Agricultural, Food and Forestry Systems – Section Forestry, Environment, Wood, Landscape, University of Florence, Via San Bonaventura, 13 - 50145 - Florence (FI), Italy.

[b] Department of Chemistry "Ugo Schiff", University of Florence, Via della Lastruccia 3/13 - 50019 - Sesto Fiorentino (FI), Italy.

Abstract

The use of adhesive joints with bonded-in steel rods or plates is of great interest nowadays for both new large timber structures design and timber strengthening. Bonded-in joints offer some advantages: high stiffness, high strength, ductile behaviour in some cases, easiness of factory production and possibility of *in situ* realization. Their use in Service Class 1 and 2 is possible but not in Service Class 3, due to the extreme conditions. While the effect of the environmental conditions on the wood is well known, their effect on epoxy glue and on the mechanical properties of full scale timber joints requires *ad hoc* tests. In order to verify the effects of extreme environmental conditions, on the durability of the epoxy resin and on the mechanical behaviour of full scale ordinary joints, different epoxy specimens and timber joints were exposed to various conditions and ageing cycles: immersion in water (demineralized and swimming pool water), high and low temperature treatments cycles, treatments at different temperature and RH. Epoxy specimens showed transformation only in the case of immersion in swimming pool water. Full scale timber joints showed a shear strength variation due only to the moisture content variation between 12-24%. Joints submerged in water showed a strength reduction higher than the one expected for the reached moisture content, demonstrating that extreme conditions affect not only the timber strength, but also the performance of the full joints.

Keywords: epoxy resin, timber joints, mechanical properties, infrared spectroscopy.

1. Introduction

Adhesive joints have been used for structural purpose for decades especially in Europe and North America, for new building as well as for repairing and strengthening the existing ones. Different types of joints have been proposed and studied until today, especially joints based on glued in rods or plates realized using epoxy resins.

The durability of adhesive joints is strongly related to the environmental conditions: shrinkage and swelling of wood, as a consequence of the air temperature and humidity variation can cause stresses, formation of cracks and, in some cases, loss of adhesion and strength. The use of adhesive joints should be limited to the Service Classes 1 and 2, as defined in the Eurocode 5 [1], corresponding to a moisture content (MC) of about 12% and 20% respectively. The use in the Service Class 3 (MC> 20%) should be avoided [2].

Some authors [3], [4], [5], [6] investigated the influence of the timber MC at the time of bonding on the strength and mechanical behaviour of bonded-in rods while Jänkänpää [7] tested glued-in rods after exposing them to climatic conditions as severe as the ones corresponding to the Service Class 3, obtaining high strength loss for specimens loaded in direction parallel and perpendicular to the grain.

The epoxy resin used is of key importance because different formulations show different mechanical behaviour which influences the performance of the joints [8]. Several epoxy formulations are available as commercial products in order to obtain high strength, high thermal stability, chemical resistance and mechanical properties suitable for different applications. A different chemical composition influences the curing behaviour (time and temperature) as well as the modulus of elasticity of the cured material.

Various researches have been realized in order to correlate the chemical structure of the epoxy resins or the composition of their formulation with the performance [9], [10], [11], [12], [13], [14].

A high resistance of the cured resins is required when epoxy materials are used in outdoor conditions. Also in indoor condition, if moisture or some contaminants as chlorine or acid compounds are present in the environment, a good chemical resistance is required [15]. In particular, water absorption and corrosion phenomena are important problems in the use of epoxy adhesives and several studies have been performed with the aim to analyse the water diffusion mechanisms [16], [17], [18], [19], [20]. Water absorption was studied using different techniques, such as near infrared (FT-NIR) water absorbance at 5200 cm^{-1} or gravimetry [15], [18], [19]. FT-IR spectroscopy has also been used with DSC and NMR techniques for analysing the curing behaviour [10], [12].

The effect of environmental conditions on timber strength and stiffness is quite well known but their influence on the behaviour of particular full scale adhesive timber joint, is unknown. The goal of this research is to verify the effect of extreme environmental conditions on both epoxy resin and on the mechanical behaviour of a full scale timber joint.

2 Adhesive and timber joint specimens

2.1 Epoxy resin specimens

A commercial bicomponent epoxy resin (Xepox 26), same adhesive also selected for the structural joints, was used in order to prepare nine samples (I-IX). The composition of Xepox 26, as given by the manufacturer, is for component A: epoxy resin from bisphenol A (average MW < 700) (50-75%), calcium carbonate (5-10%), oxirane, mono (C12-14-alkyloxyl) methyl derivatives (3-5%), 1,4-Bis (2,3-epoxypropoxy) butane (1-3%). Component B contains: 3-aminomethyl-3,5,5-trimethylcyclohexylamine (25-30%), benzyl alcohol (15-20%), calcium carbonate (10-15%), 2-piperazin-1-ylethylamine (1-3%), 1-methoxy-2-propanol (0,1-0,2%). The components A and B were mixed in the recommended ratio (2:1) and moulded at room temperature (20°C) as triangular prisms (triangle side 10 mm, length 50 mm). The weight of all samples was measured after curing and after exposition at different environmental conditions. For all samples, the weight remained constant during the experiment time in agreement with the absence of absorption phenomena or significant chemical transformations. At the end, a small amount (5 mg) of each sample was recovered from the surface and used in order to recorder the FT-IR spectra.

2.2 Full scale timber Joint

Test specimens were obtained from glulam beam cross sections (160x160 mm^2) made of spruce (*Picea abies* Karst.). Glulam elements, whose length was 420 mm, were factory produced, according to standardized procedures, in strength class GL24 using lamellas machine graded C24 and melamine-urea formaldehyde resin – MUF. The joints were designed by the factory for particular indoor and outdoor applications, especially for the needs to hide steel plates into the wood. A groove of about 100 mm depth and 16 mm thickness was cut across the cross section lamellas at each end of the specimens, perpendicular to the lamellas. A steel sandblasted plate was placed into each groove. The plates were 200 mm long, 100 mm wide and 6 mm thick, and the nominal bond thickness was 5 mm for each part (minimum 4.6 mm, maximum 5.4 mm, CV = 7%). The portion of the plates bonded into the timber contains five holes (diameter of each hole of about 12 mm), according to the standard factory production.

The specimen dimensions and configuration are shown in Figure 1. All the specimens were glued in the same environmental conditions, using the same epoxy resin used for specimens reported in 2.1 (Xepox 26, physical and mechanical properties reported in table 1). The initial MC, measured in June 2010 by means of a wood hygrometer for all the specimens, was between 12 and 13%.

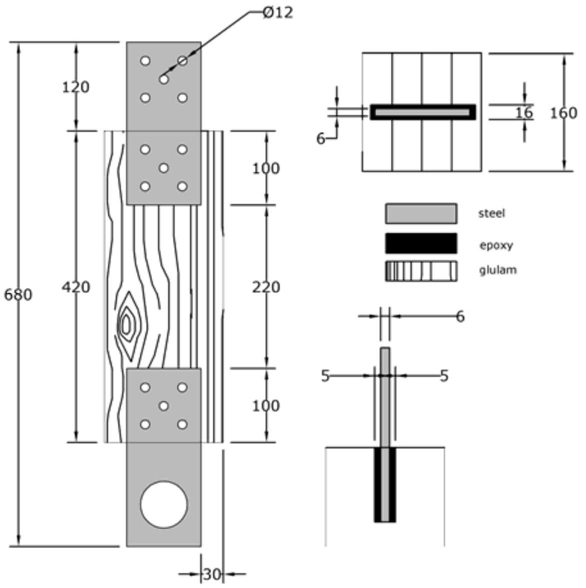

Figure 1 – Full scale timber joint geometry according to the factory specification. Dimensions in mm.

Schematic illustration, not to scale.

Table 1 – Principal physical and mechanical properties of Xepox 26 (form technical data sheet).

Properties	Standard	Value
Specific weight (kg/dm^3)	ASTM D 792-66	1,45
Thermal expansion coefficient (°C^{-1})	ASTM D 696	7,5x10^{-5}
Compressive strength (MPa)	ASTM D 695	≥80
Shear strength (MPa)	ASTM D 732	≥40
Flexural stress (MPa)	ASTM D 790	≥50
Modulus of elasticity (MPa)	ASTM D 695	≥7200

3 Experimental tests

3.1 Epoxy resin tests

The cured samples were maintained in different conditions for three months as reported in Table 2. In particular, sample I was maintained in outdoor conditions while the other samples were exposed indoor, with different environmental conditions of temperature and relative humidity (R.H.) or immersed in different kind of water. Sample II was maintained in the laboratory room with standard conditions (T 20°C and R.H. 40-50%). Temperature and/or relative humidity were changed for samples III (T 20°C, R.H. 100%), IV (T 60°C, R.H. 100%) and V (T 60°C, R.H. 12%). R.H. 100% was obtained in a desiccator containing a beaker with demineralized water in order to obtain a water vapour saturated environment. R.H. 12% was obtained maintaining the sample in an oven at 60 °C. The temperature of 60 °C correspond to the maximum one at which the timber joints were exposed (Table 3).The sample VI was maintained in a desiccator containing a beaker with a solution of D-POOL 63 (product from JOHNSON DIVERSEY) in demineralised water, 1% w/w (T 20°C, R.H. 100%). This solution can be considered to be similar to swimming pool water although with a higher concentration of disinfectant. Finally, the last samples were immersed in demineralized water (sample VII), sea water (sample VIII) and “swimming pool water”, obtained as above reported (sample IX). Fourier Transform Infrared Spectroscopy (FT-IR) spectra were recorded with a Shimadzu FTIR-8400S spectrometer with a resolution of 4.0 cm^{-1} and 16 scans per sample, and elaborated with the Spectrum v.3.02.02 software. Spectra of solid samples were analysed as KBr pellets, obtained by mixing the powder with spectroscopic grade KBr. The effect of different environmental conditions on the chemical composition have been studied recording FT-IR spectra in the 4000-400 cm^{-1} range.

Table 2- Epoxy resin samples exposed at different environmental conditions.

Code	**Environmental conditions**[a]
I	Outdoor
II	Indoor (T 20°C RH 40-50%)
III	Indoor (T 20°C, R.H. 100%)
IV	Indoor (T 60°C, R.H. 100%)
V	Indoor (T 60°C, R.H. 12%)
VI	Indoor (T 20°C, R.H. 100%, Cl_2)
VII	Demineralized water immersion
VIII	Sea water immersion
IX	Swimming pool water immersion

[a] Time of exposition: 3 months

3.2 Timber joint MC and ageing cycles

In order to simulate the environmental conditions corresponding to the 3 Service Classes as reported in Eurocode 5 [1], 12 joints were stored in different environmental conditions for 8 months (Table 3) to obtain equilibrium conditions: treatment A – RH 100%, 30° C (average MC at time of test 24%); treatment B – RH 65%, 20° C (average MC at time of test 12%); treatment C – immersion in water, room temperature (average MC at time of test 36%). In the water of the treatment C the biocide benzalkonium chloride (*N*-alkyl-*N*-benzyl-*N,N*-dimethyl-ammonium chloride - ADBAC) was added to prevent any kind of wood degradation or decay. The treatment A and C increased the MC of wood reducing strongly its strength and stiffness and the stress gradient along the bonded surface; on the other hand the uptake of water in the adhesive results in a plasticization of the epoxy resin reducing the stress concentration along the bonded surface [21].

The effect of temperature on the joints performances have been investigated in previous works: Richter and Steiger [22] reported that temperatures higher that 70° C reduce the shear stress in both short and long term loading. On the other hand Aicher and Dill-Langer [23] found that on elevated temperature without loading results in a post curing effect that increases the short term load capacity. Pizzo *et al.* [24] investigated the effect related to the different thermal expansion behaviour of steel, wood and epoxy resin: the thermal stress at the interfaces between epoxy-steel and wood-epoxy was identified as the responsible of inducing shear stress. In order to stress the joint and to verify the effect of the different thermal expansion of the materials involved, two different ageing cycles, corresponding to reasonably expected environmental conditions, were adopted: treatment D -20°C / +60°C (average MC at time of test 7%); treatment E +5°C / +60°C (average MC at time of test 6%). The ageing cycles consist of one day at -20°C/+5° C and one day at +60° C. The ageing cycles were carried out for 3 weeks before the mechanical tests started. The treatments D and E were analysed together because no significant difference of MC between the two was observed. Such exceptional environmental conditions can be expected in different kinds of structures (e.g. a warehouse roof, the frame of a swimming pool etc.), or they could occur due to unexpected events, difficult to predict (e.g. the leaching of water from roofing, condensation due to differences in temperature and so on).

To simulate a representative on-site case, the specimens were tested just after the conditioning period, except for the submerged specimens (treatment C) whose surfaces were coarsely wiped up. For these, it was assumed that a post-treatment in a climatic chamber (RH 65%, T 20°C) wouldn't alter their actual performance.

The environmental conditions reproduced by treatment A can be reached in a swimming pool [25] and the extreme temperatures, used for the ageing cycles D and E, are reachable in many climates [26]. Treatment C reproduces the conditions in which a timber joint is directly exposed to rainfall in outdoor conditions or in case of indoor exceptional events as, e.g., rainwater seepage.

Table 3 – Test matrix for full dimension specimens with bonded-in steel plates.

Treatment	**Environmental conditions**	**MC at time of test (average)**
A	RH 100%; T 30°C	24%
B	RH 65%; T 20°C	12%
C	water immersion; room temperature	36%
D	ageing cycle T -20°C/+60°C	7%
E	ageing cycle T +5°C/+60°C	6%

3.3 Pull out bonded-in plates tests

All the mechanical tests were carried out at the GESAAF (Department of Agricultural, Food and Forestry Systems) laboratory at the University of Florence using a METRO-COM 200 kN universal testing machine. The steel plates of the specimens were connected to the testing machine through 5 bolts on the upper plate and a 62 mm diameter rod on the lower one. The presence of the large diameter rod in the lower part and of the spherical joint in the upper part (Figure 2) ensured that the joint could be aligned during the test.

All the specimens were inspected before the test in order to identify debonding, cracks and deformation due to the different treatments and to register the actual cross sections. The displacements were measured by means of 4 LVDT transducers (linearity ±0.5%). The elongation and the applied load were recorded using a Measurement Computing 16 bit DAQ connected to an ordinary personal computer.

The tests to failure were conducted achieving failure within 420 seconds, in order to perform a static short term test, as requested by the standard for testing full size timber elements (e.g. EN 408 [27]).

The shear strength was calculated for both adhesive/wood and adhesive/steel interface by dividing the ultimate load by the bonded area (eq. 1 and eq. 2). After the tests, the joints were cut open and the bonded surfaces measured. For the calculation of the adhesive/wood interface shear strength all the bonded timber surfaces were considered. Thus, according to the particular geometry of the joint (Figure 3), the surface of timber covered by adhesive was larger than the one for steel.

$$\tau_{steel} = \frac{F_{\max}}{2(b_s h_s)} \qquad (1)$$

$$\tau_{wood} = \frac{F_{\max}}{2(b_w h_w)} \qquad (2)$$

Where τ is the shear strength [MPa]; F_{max} is the load at failure [N]; b and h are respectively the width and height of the bonded surfaces subscript (s for steel and w for wood; $b_w h_w > b_s h_s$) [mm].

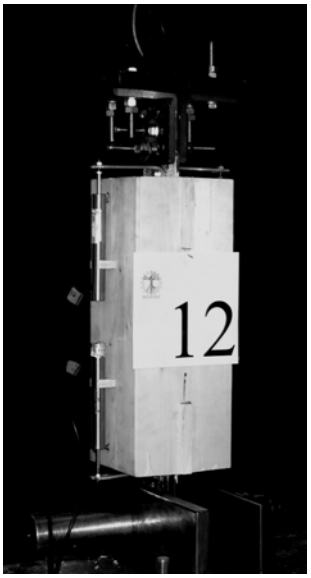

Figure 2 – Pull out test set up.

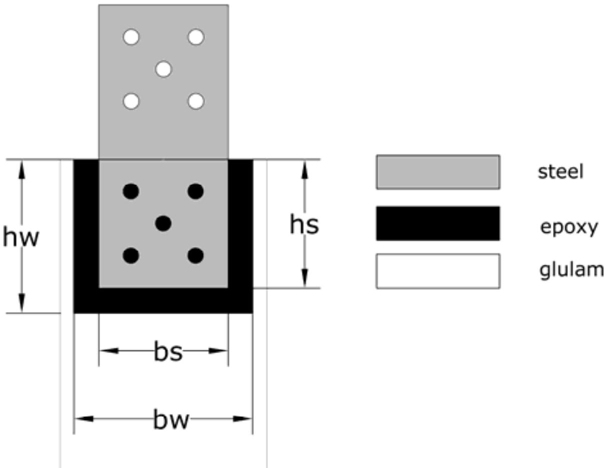

Figure 3 – Schematic representation of the surfaces considered for the shear strength calculation (equation 1 and equation 2). $2(b_w h_w)$ = bonded surfaces on timber; $2(b_s h_s)$= bonded surfaces on steel.

After the test two specimens were extracted from the middle part of each timber joint, in order to calculate the density (as the weight to volume ratio) and the MC of the timber at the time of test. After that, one specimen was seasoned and density and MC were calculated again, correcting the density at 12% of MC. Additionally, for the specimens subjected to treatments A, C, D and E, moisture gradients, in direction perpendicular to the grain, were calculated according to the Italian standard UNI 8829 [28]. For treatment B it was assumed that no moisture gradients exist because the joints remained in the climatic chamber for 8 months (RH 65%, T 20° C) and their MC at the beginning of the treatment, evaluated by means of a wood hygrometer at various depth, was close to the equilibrium moisture content (EMC) achievable inside the climatic chamber.

4 Results and discussion

4.1 Epoxy resin behaviour

The effect of the different physical treatments and chemical agents on the chemical structure of the adhesive components was studied using FT-IR spectroscopy (Figures 4-5).

The assignments of characteristics absorption bands for epoxy formulations have been reported from several authors. In particular S. G. Hong *et al.* [10] describe the variations of FT-IR spectrum after curing, analysing the influence of curing temperature and type of solvent on the final composition. A similar result was reported by other authors [8], [22], [23].

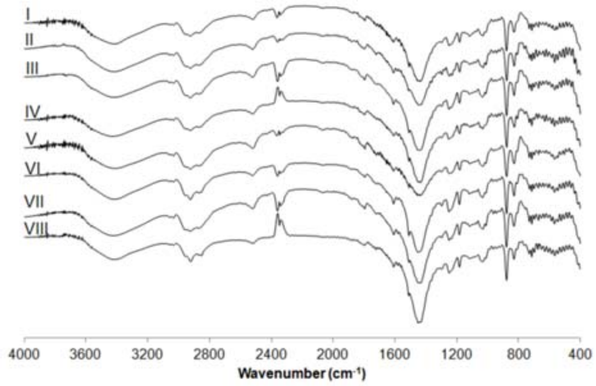

Figure 4 - FT-IR spectra of samples I - VIII (bands at 2360 and 2340 cm^{-1} correspond to atmospheric CO_2).

The formulation used contains calcium carbonate as additive (amount from 7 to 12%, as given by the manufacturer). Consequently, an intense band at 1440 cm^{-1} was present in all spectra attributable to calcium carbonate together with other bands at 2525 (w), 1798 (w) and 878 (m) cm^{-1}. The remaining bands, present in the FT-IR spectra, were compared as frequency and relative intensity and were attributable to the cured epoxy resin: bands at 3414 (m, broad, O-H stretching), 3059 (vw, C-H aromatic stretching), 2926 (m, C-H aliphatic stretching), 2872 (m, C-H aliphatic stretching), 1609 (w, C=C aromatic stretching), 1506 (sp, C=C aromatic stretching), 1298 (vw, C-O stretching), 1246 (w, C-O stretching), 1180 (w, C-O stretching), 1115 (w, C-O stretching), 1032 (w, C-O stretching), 829 (m, C-H aromatic deformation) cm^{-1}.

All spectra recorded on the samples I, II, III, IV, V, VI, VII and VIII were identical (Figure 4). FT-IR absorption bands attributable to reactive groups were not present in agreement with a complete curing process. Moreover, other chemical transformations were not produced in the cured resin in the environmental conditions selected for these samples. Only the submersion in water containing chlorine (sample IX) changed the intensities of several absorptions. In particular, in the FT-IR spectrum of sample IX (trace IX, Figure 5), the bands at 2525 (w), 1788 (w), 1450 (s) and 878 (m) cm^{-1} appear reduced as intensity and shifted with respect the analogous bands in the other spectra (traces I-VIII, Figure 4). This variation can be related to a smaller amount of carbonate, probably attributable to the action of the agents present in the water treated with a commercial disinfectant (which produces chlorine and acids such trichloroisocyanuric acid or the hypochlorous acid). As a consequence of this reactivity, the carbonate can be transformed into a different salt and the intensity of the bands attributable to the epoxy resin increase with respect to those of carbonate group. An analogous reactivity was not observed when the sample VI was exposed at the atmosphere present in a swimming pool.

In agreement with the behaviour described for sample IX, sample II (trace II, Figure 5) was transformed after immersion in 0,1 M HCl solution, at pH 1 (trace II_A, Figure 5) or after immersion in concentrated solution of the chlorinating agent for swimming pool water treatment, at pH 5 (trace II_B, Figure 5). The complete transformation of calcium carbonate was observed in the presence of 0,1M chloridric acid solution and therefore the bands attributable to epoxy resin were visible. On the contrary, only a partial reduction of bands attributable to calcium carbonate was observed after immersion in concentrated solution of the chlorinating agent due to the lower acidity (pH 5).

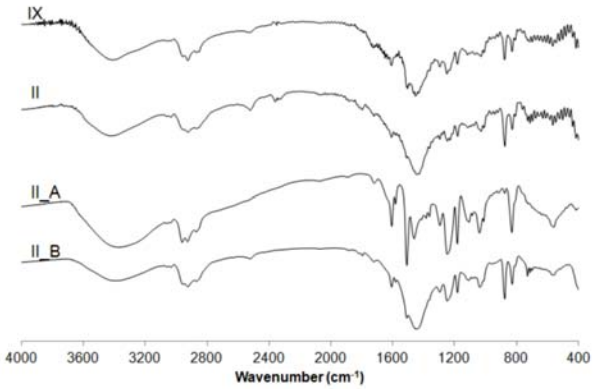

Figure 5 - FT-IR spectra of samples: IX (trace IX), II (trace II), II after immersion in HCl solution, 0,1M (trace II_A), II after immersion in 1% w/w solution of the chlorinating agent for swimming pool water treatment (trace II_B).

4.2 Timber joints behaviour

4.2.1 Shear strength

The shear strength values are reported in Table 4 and calculated according to equation 1 and 2.

Table 4 – physical, mechanical properties and failure modes for the tested specimens.

Specimen	**Treatment**	**MC at time of test [%]**	**Density at 12% MC [kg/m^3]**	**F_{max} [kN]**	**τ_{wood} [MPa]**	**τ_{steel} [MPa]**	**Locus of failure**
1	A	24	426	75.7	2.9	3.5	a/c
2	A	25	403	56.7	2.1	2.6	a/c
3	A	25	396	67.1	2.5	3.1	a/c
Average		**24**	**409**	**66.5**	**2.5**	**3.1**	
5	B	12	430	75.4	3.1	3.5	a/b
7	B	12	424	72.3	2.9	3.4	a/b
8	B	13	419	79.0	3.0	3.6	a/b
Average		**12**	**424**	**75.6**	**3.0**	**3.5**	
4	C	31	456	45.1	1.7	2.1	b/c
6	C	42	477	40.5	1.5	1.9	b/c
9	C	36	459	58.9	2.2	2.7	b/c
Average		**36**	**464**	**48.2**	**1.8**	**2.2**	
10	D	7	459	105.6	4.1	5.0	a
11	E	6	428	99.5	4.0	4.6	a

12	E	6	417	101.0	3.8	4.7	a
Average		**6**	**435**	**102.1**	**3.9**	**4.8**	

Locus of failure: a) cohesive in timber; b) cohesive in timber (thin timber layer); c) adhesive.

Due to the small number of observations (12 joints), a specific non-parametric test has been used, for the variance analysis, instead of a parametric one. In fact, when the sample is small, the parametric tests cannot be use, because they assume normal data distribution, but non-parametric tests are valid, because not based on the normal distribution concept. The data were compared using the Kruskal-Wallis non-parametric test for the variance analysis, after checking the homogeneity of variance (homoscedasticity) by Leven's test. As the computed p-values were always lower than the significance level at 0.01 (failure load, τ_{wood}, τ_{steel}) the null hypothesis was always rejected and the samples cannot be considered as coming from the same population. The average shear stress at failure was highest for treatment D/E; and then in descending order for treatment B, treatment A and treatment C (corresponding respectively to average MC of about 6%, 12%, 24% and 36%). Wilson [31] and Leont'ev [32] reported that the shear strength of wood decreases linearly as a function of the MC increasing, up to the fibre saturation point (FSP).

The data expressed as percentage values (100% = shear strength at 12% MC) were compared to the ones reported in [31] for Red spruce and Sitka spruce (Figure 6). The two curves are similar around 24% MC (80% of the shear strength at 12% MC). Large difference can be observed for the shear strength at 6% and 36% MC, demonstrating that the MC is not the only justification for the shear strength variations.

While it is well known that the density of wood affects its strength, its effect on the pull-out strength of timber joints is controversial: Aicher *et al.* [33] found moderate influence of density on shear strength of timber glued-in rods; Azlan *et al.* [34] reported that shear strength depends very much on timber density; Tlustochowicz *et al.* [35] assert that the density should have a secondary effect on shear strength of glued-in rods joints, affecting the shear strength of wood, reducing adhesion between wood and resin, increasing wood stiffness. In this case the density was not considered as the cause of strength variation because of the very low variability among the specimens (CV=6%). Similarly, the bond thickness is recognized as a factor that can affect the joint strength, but in this research its low variability (CV=7%) doesn't allow to make any consideration.

The shear strength for treatment B is similar to one obtained by Azlan *et al.* [34] testing mild steel plates inserted in small hardwood specimens.

The high strength values recorded for the specimens at 6% MC can be explained as the consequence of the post-curing effect, due to treatment at 60° C; while, according to Pizzo *et al.*[24] no effect can be related to the different thermal expansion behaviour of the three involved materials, due to the characteristics of the epoxy used for the joint preparation (thermal expansion coefficient around 7.5 10^{-5} °C^{-1}) that is close to the one for Spruce in transversal direction and not so different from steel (order of magnitude of 10^{-5} °C^{-1}).

As reported by Wilson [31] the great reduction of strength (40% less than treatment B) for the specimens with a MC over the FSP (treatment C) can be related to the enduring of the extreme environmental condition (specimens submerged in water for 8 months). In such conditions the strength reduction can be related to different aspects: adhesive damages due to water effects, internal stresses increasing due to plasticization of adhesive, swelling of wood and timber strength reduction [8].

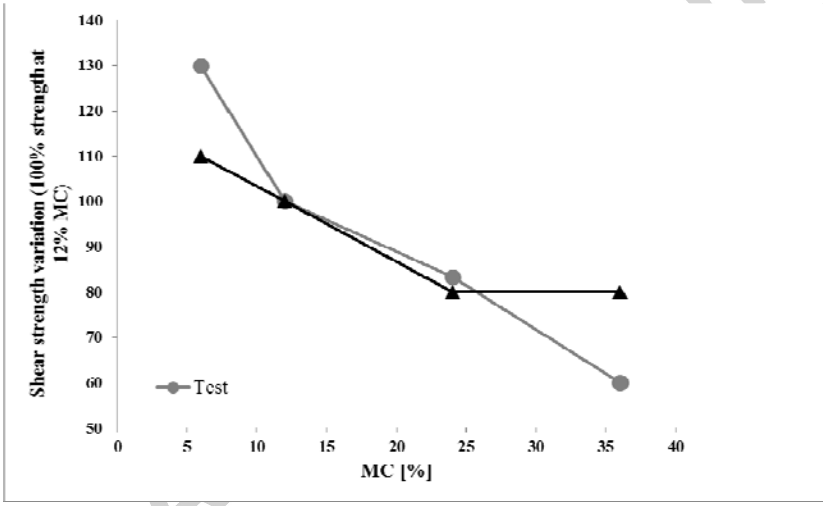

Figure 6 - Shear strength variation for wood at different MC: comparison between literature [30] and experimental data.

4.2.2 Shear stress-slip behaviour

The stress in the stress-slip curves in Figure 7 were obtained adopting equation 2 and the slip was calculated, for each specimen, as average deformation recorded by means of the 4 LVDT.

In most cases the curves show one or two stress drops, not always associated to a stiffness variation, between 80% and 95% of the stress at failure. The slip curves are similar for treatment C and A below 1 MPa of stress, and for treatment B and D/E up to 2.5 MPa.

The stress-slip curves indicate a brittle behaviour of the joints until failure for all the specimens while only 5 of them showed a more ductile behaviour (treatment A and C).

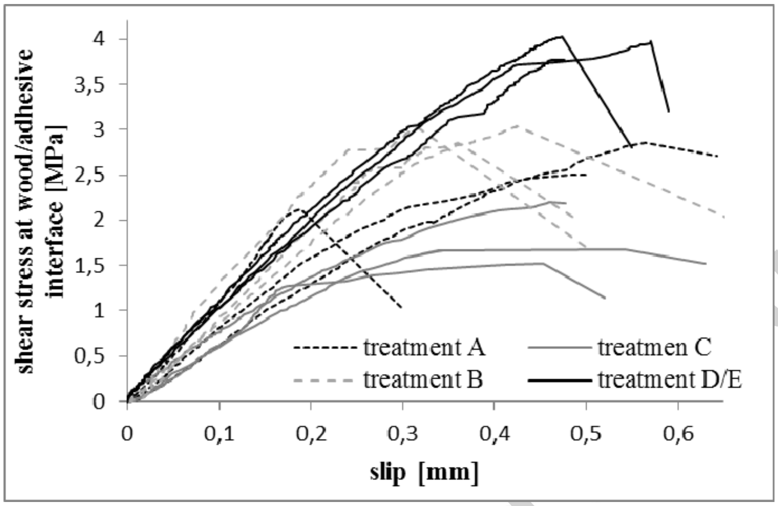

Figure 7 - Stress-slip curves for axially loaded bonded-in steel plates (different treatments).

4.2.3 Locus of failure

Contrary to the results reported by Azlan *et al.* [34], the failure occurs mainly at the wood/epoxy interface. The observed failure mode was predominantly cohesive failure for treatment B and D (Figure 8b and 8d) with a very thin layer of wood for treatment B.

In this paper we consider the failure as adhesive, when it happens between the adhesive and one of the materials connected, and cohesive, when it happens in one of the materials connected.

For the specimens subjected to treatment A the failure mode was mixed (Figure 8a): cohesive deeply in the wood and adhesive at the timber/adhesive interface. For treatment C the failure was mixed: cohesive in wood (thin layer of wood) and adhesive at timber/adhesive interface. According to Serrano [36] this type of failure is due to a weak boundary layer between adhesive and wood: the fibre were visible in correspondence of the earlywood, while only adhesive can be detect at the latewood/adhesive interface. This phenomenon is probably related to the effect of water and to the higher density of the latewood relative the earlywood. Higher density corresponds to less adhesion between adhesive and wood, so the weakening effect of water on adhesion strength was larger where the adhesion forces were weaker.

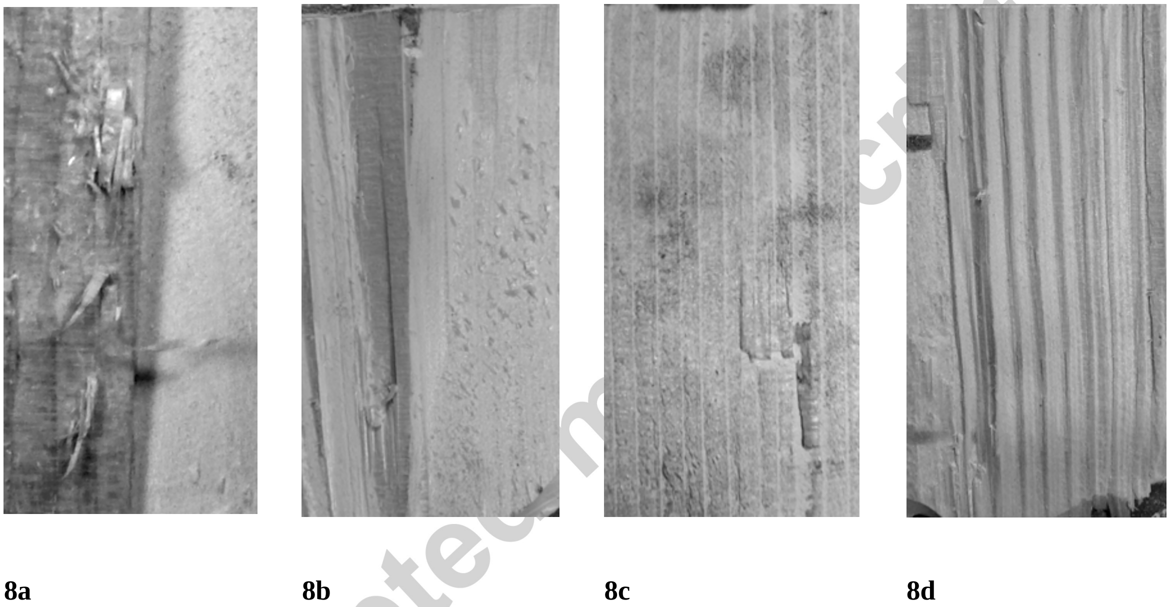

Figure 8 - Predominant locus of failure: 8a) treatment A; 8b) treatment B; 8c) treatment C; 8d) treatment D.

5 Conclusions

Epoxy resin specimens and 12 glulam joints of structural dimensions, realized inserting steel plates at the ends, were tested in order to determine, respectively, chemical transformation and mechanical behaviour after different environmental conditions exposure. The shear strength of joints tested at MC between 12% and 24% can be related to the natural wood strength variation, due to its MC, while the shear strength of the joints treated at high temperature, or submerged in water, differ significantly from the values reported in literature for their respective MC. For the joints treated at high temperature, higher strength values were observed, up to 1/3rd more than specimens of the treatment B (as reference), as a consequence of the post-curing effect. In this case the use of a specific epoxy resin, with a thermal expansion coefficient close to the one of wood and steel, didn’t affect the bond durability, because the expansion of the resin and wood/steel were quite similar.

For the joints submerged in water the lower shear strength, 36% lower than specimens of the reference treatment (B), can be related to the weakening effect due to the severe condition endured for a long time (8 months). In such conditions the strength reduction can be related to different aspects: adhesive damages due to water effects; internal stresses increasing due to plasticization and swelling of adhesive and timber strength reduction

Chemical transformations were not observed in the cured resin after exposure to extreme environmental conditions. Only the submersion in water treated with a commercial disinfectant produces a partial transformation of calcium carbonate present as additive. Consequently, the intensity of the FT-IR bands attributable to the epoxy resin increases with respect to those of carbonate group (and it would stimulate to choose the correct additive in relation to the environmental conditions).

Although all the studied conditions must be considered as exceptional, in general the possible interactions resin-wood-environment demonstrate that the use of bonded-in joints in severe conditions must be considered with great caution and requires a specific design.

Acknowledgments

The research was performed on the full size specimens prepared by MORETTI INTERHOLZ s.r.l. The Authors thank the whole personnel involved, especially Ing. Alberto Agostini.

References

[1] “ENV 1995-2 Eurocode 5 - Design of timber structure.” .

[2] C. J. Johansson, “Glued-in bolts. Timber engineering, STEP 1: Lecture C14, Centrum Hout, Almere.” 1995.

[3] G. C. Mays and A. R. Hutchinson, *Adhesives in Civil Engineering*. Cambridge: Cambridge University Press, 1992, p. 326.

[4] A. Wheeler and A. R. Hutchinson, “Resin repairs to timber structures.,” *Int J Adhes Adhes*, vol. 18, no. 1, pp. 1–13, 1998.

[5] J. G. Broughton and A. R. Hutchinson, “Adhesive systems for structural connections in timber,” *Int. J. Adhes. Adhes. Vol.*, vol. 21, pp. 177–186, 2001.

[6] J. G. Broughton and A. R. Hutchinson, “Effect of timber moisture content on bonded-in rods,” *Constr. Build. Mater.*, vol. 15, no. 1, pp. 17–25, Feb. 2001.

[7] J. Jänkänpää, “Limmade förband i stora träkonstruktioner,” Lulea University of Technology, Sweden, 2008.

[8] J. Custodio, J. Broughton, and H. Cruz, “A review of factors influencing the durability of structural bonded timber joints,” *Int. J. Adhes. Adhes.*, vol. 29, no. 2, pp. 173–185, Mar. 2009.

[9] T. Guthner and B. Hammer, “Curing of epoxy resins with dicyandiamide and urones,” *J. Appl. Polym. Sci.*, vol. 50, pp. 1453–1459, 1993.

[10] M. F. Grenier-Loustalot, M. Florence, M. P. Bente, and P. Grenier, “Reactivity of dicyandiamide toward oxygen and nitrogen epoxide groups. 1. Reaction mechanism,” *Eur. Polym. J.*, vol. 27, pp. 1201–1216, 1991.

[11] M. D. Gilbert, N. S. Schneider, and W. J. MacKnight, “Mechanism of the Dicyandiamide/ Epoxide Reaction,” *Macromolecules*, vol. 24, pp. 360–369, 1991.

[12] M. Opresnik, A. Sebenik, M. Zigon, and U. Osredkar, “The curing kinetics of brominated epoxy resins,” *Thermochim. Acta*, vol. 178, pp. 127–134, 1991.

[13] S. G. Hong and C. S. Wu, “DSC and FTIR analysis of the curing behaviors of epoxy/DICY/solvent open systems,” *Thermochim. Acta*, vol. 316, pp. 167–175, 1998.

[14] S. Choi, A. P. Janisse, C. Liu, and E. P. Douglas, “Effect of Water Addition on the Cure Kinetics of an Epoxy-Amine Thermoset,” *J. Polym. Sci.*, vol. Part A 49, pp. 4650–4659, 2011.

[15] J. Chen, T. Nakamura, K. Aoki, Y. Aoki, and T. Utsunomiya, “Curing of Epoxy Resin Contaminated with Water,” *J. Appl. Polym. Sci.*, vol. 79, pp. 214–220, 2001.

[16] J. Comyn, “Diffusion and adhesion,” in *Polymer Permeability*, C. J., Ed. London, UK: Chapman & Hall, 1985, pp. 177–215.

[17] J. C. Cabanelas, S. G. Prolongo, B. Serrano, J. Bravo, and J. Baselga, “Water absorption in polyaminosiloxane-epoxy thermosetting polymers,” *J. Mater. Process. Technol.*, vol. 143, pp. 311–315, 2003.

[18] S. Cotugno, G. Mensitieri, P. Musto, and L. Sanguigno, “Molecular Interactions in and Transport Properties of Densely Cross-Linked Networks: A Time-Resolved FT-IR Spectroscopy Investigation of the Epoxy/H2O System,” *Macromolecules*, vol. 38, pp. 801–811, 2005.

[19] L. Li, S. Y. Zhang, Y. H. Chen, M. J. Liu, Y. F. Ding, X. W. Luo, Z. Pu, W. F. Zhou, and S. Li, “Water Transportation in Epoxy Resin,” *Chem. Mater.*, vol. 17, pp. 839–845, 2005.

[20] M. Liu, P. Wu, Y. Ding, G. Chen, and S. Li, “Two-Dimensional (2D) ATR-FTIR Spectroscopic Study on Water Diffusion in Cured Epoxy Resins,” *Macromolecules*, vol. 35, pp. 5500–5507, 2002.

[21] C. Bengtsson and C. J. Johansson, “GIROD - Glued in Rods for Timber Structures. SP Report 2002:26,” Boras, Sweden, 2002.

[22] K. Richter and R. Steiger, “Thermal stability of wood–wood and wood–FRP bonding with polyurethane and epoxy adhesives,” *Adv. Eng. Mater.*, vol. 7, no. 5, pp. 419–426, 2005.

[23] S. Aicher and G. Dill-Langer, “Influence of moistuire, temperature and load duration on performance of glued-in rods,” in *Joints in Timber Structures*, 2000, p. 649.

[24] B. Pizzo, G. Rizzo, P. Lavisci, B. Megna, and S. Berti, “Comparison of thermal expansion of wood and epoxy adhesives,” *Holz als Roh- und Werkst.*, vol. 60, no. 4, pp. 285–290, Aug. 2002.

[25] L. Jorge and A. Dias, “X-Lam panels in swimming-pool building – monitoring the environment and the performance,” *Adv. Mater. Res.*, vol. 778, pp. 779–785, 2013.

[26] J. E. Winandy, A. Ten Wolde, R. H. Falk, U. F. Service, and H. M. Barnes, “Temperature histories of plywood roof sheating and roof rafters as used in north american light-framed construction,” in *7th World Conference on Timber Engineering, WCTE 2002*, 2002, pp. 114–121.

[27] “EN 408:2010 Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties. European Committee for Standardization.” .

[28] UNI 8829, “UNI Segati di legno - Determinazione del gradiente di umidità.” 1986.

[29] Y. G. Lin, H. Sautereau, and J. P. Pascault, “BDMA-catalyzed DDA-epoxy resin system: temperature and composition effects on curing mechanism,” *J. Polym. Sci., Part A*, vol. 24, pp. 2171–2184, 1986.

[30] T. F. Saunders, M. F. Levy, and J. F. Serino, “Mechanism of the tertiary amine-catalyzed dicyandiamide cure of epoxy resins,” *J. Polym. Sci., Part A*, vol. 1, no. 5, pp. 1609–1617, 1967.

[31] T. R. C. Wilson, *Strength-moisture relations for wood.* Washington D. C., 1932.

[32] N. L. Leont’ev, “The strength of wood at varying moisture content,” *Derev. Prom.*, vol. 4, pp. 14–15, 1960.

[33] S. Aicher, P. J. Gustafsson, and M. Wolf, “Load displacement and bond strength of glued-in rods in timber influenced by adhesive, wood density, rod slenderness and diameter,” in *First RILEM Symposium on Timber Engineering*, 1999, pp. 369–378.

[34] H. M. Azlan, Z. Ahmad, R. Hassan, and A. Jamadin, “Shear strength of steel and CFRP to timber interface,” in *IEEE Symposium on Humanities, Science and Engineering Research*, 2012, pp. 1465–1470.

[35] G. Tlustochowicz, E. Serrano, and R. Steiger, “State-of-the-art review on timber connections with glued-in steel rods,” *Mater. Struct.*, vol. 44, no. 5, pp. 997–1020, 2010.

[36] E. Serrano, “Glued-in rods for timber structures. An experimental study of softening behaviour,” *Mater. Struct.*, vol. 34, no. 4, pp. 228–234, May 2001.