Use of natural resins in repairing damaged timber beams – An experimental investigation

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Use of natural resins in repairing damaged timber beams – An experimental investigation

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Abstract. Different techniques including the application of steel elements, composite materials and polymeric resins have been used in the past to repair damaged timber beams. However, there is a growing need to replace these materials with those with minimal environmental impact. In addition, stringent requirements of conservation authorities on the compatibility between repair and parent materials have also necessitated search for innovative repair materials for timber beams. Therefore, an increasing shift of focus towards the use of materials derived from natural sources in repairing and reinforcing timber structures is currently experienced. This paper presents the results of an exploratory study on the use of natural resins (rosin and bone glue) in repairing oak timber beams. 15 oak timber beams with cross section dimensions of 67 x 67 mm and 1100 mm in length were tested in four-point bending to failure. Undamaged, damaged (unrepaired) and damaged but repaired timber beams (with rosin and bone glue) were tested. The effectiveness of the repair material and technique was analysed based on the bending capacity and mid span deflection at failure. The initial results show negligible effectiveness of rosin in repairing timber beams. In fact, about 16% reduction (average) in load carrying capacity with a corresponding 5% decrease (average) in maximum displacement was recorded. Relatively higher level of effectiveness was recorded with the use of bone glue (about 10 % average increase in load carrying capacity). However, over 30% corresponding average increase in the maximum displacement was also recorded. Further work investigating different repair techniques and other natural resins is presently underway.

Key words: bending capacity, damaged timber beams, environmental impact, natural resins, repair material

1. Introduction

Wood is one of the most widely used materials, particular in construction. Its extensive use in construction can be associated with its characteristic lightweight, high tensile and compressive strength and relatively low cost [1]. However, wood degradation and decay is commonplace due to effects such as biological and chemical attacks. Structural elements made from wood, particularly timber beams, often experience damage during their service life due to attacks from biotic agents (insects, fungi, etc.) and non-biotic agents (fire, impacts, etc.), age of the material and variation and intensity of the dead and imposed load [2].

For a long period of time in the last century (1960-1990s), demolition of damaged old timber structure and substitution with a modern reinforced concrete (RC) or steel structure was quite common. However, it has been demonstrated that this kind of solution has several drawbacks: cost of demolition of the timber and overhanging structure, low compatibility of RC with existing masonry structure (walls), high increases in weight of the new structure, inappropriate use of new materials in the context of architectural heritage, etc. Furthermore, it is not unusual that timber structures, during usage, are decorated with valuable architectural features, making their demolition questionable and only justifiable when there are serious structural implications.

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In combating the effects of damage, wooden elements were traditionally removed and replaced with reinforced concrete or steel structural elements. This practice is usually characterized with many disadvantages: high cost, low compatibility of the new material with existing structure, as well as loss of the architectural features that wooden structures offer. Based on the aforementioned, alternative to demolition should always be sought and wooden structures should only be demolished when there are serious structural implications. Damaged wooden structures should therefore be repaired and reinforced where feasible through techniques that allow direct intervention on the damaged structural element, at least temporarily, until a permanent solution is found [3].

Among these techniques, of considerable interest is the use of composite materials such as FRP (Fiber Reinforced Polymers). These composite materials are usually made by impregnating high strength fibers with a polymer, i.e. matrix [4]. The most commonly used resins are epoxy and polyester resins, due to their superior adhesion. Numerous work on the use of various materials and techniques to reinforce damaged wooden structures have been documented. These include, composite materials derived from synthetic polymers, e.g. Carbon and Glass FRP [5-7], flexible polymer [8], steel ropes [4] and natural fibres [9-10].

Although, enhancement of the mechanical behavior of the repaired wooden element compared to the damaged one was recorded, some of the methods and materials used are not environmentally friendly. For example, most of the work on the FRP repaired wooden element focused on the specialized use of resins [11-14]. Among the most widely used resins are those of synthetic origin (epoxy resin) due to their excellent adhesive capacity and high mechanical performance. Balsite and Araldite 427, a two-component epoxy-based materials, have also shown good physical-mechanical properties and excellent applicability for grouting or integration of degraded wooden parts. However, increasing consideration and importance is now given to the environmental impact and sustainability of repair materials and techniques. In this light, engineers and designers are now exploring the use of naturally derived materials over synthetic materials. It follows, therefore, the choice of natural materials (resins) as restoration/reinforcing material for damaged wood elements (beams), which is the focus of this work

2. Natural Resins

Natural resins are most of the times in solid or liquid state and have been known since ancient times. They can be of plant or animal origin and usually have interesting adhesive, film-forming and water-repellent properties, making them a popular choice for many industrial applications. There industrial usage is quite wide, including as transparent protective films and adhesive blend and fillers. This work investigates the use of two different types of natural resins (bone glue and rosin) for the repair of damaged timber beams.

2.1. Bone glue

Bone glue is a type of animal glue that exploits the properties of the collagen contained in animal bones and waste, from which the glue itself derives. It comes in the form of amber beads but can also be in coarse powdery or cubic forms. Bone glue has been used for centuries for the production of adhesives and binders and it is still in use today [15-16]. Its elasticity and reversibility properties are responsible for its wide usage.

The properties of animal glues largely depend on both their origins (source of collagen) and the extraction and preparation method. These have significant impact on the glue performance and influences its strength, mechanical behavior, sensitivity to environmental factors and ageing characteristics. Bone glues are known for their excellent properties and ability to cure in a relatively short time. However, they are plagued with low resistance to humidity, and are therefore mostly used for internal applications [12]. The present study is focused on timber beams which are usually internal structural members. Thus, the humidity resistance will not be an essential characteristic.

2.2. Rosin (or Greek Pitch)

Rosin, also known as Greek pitch, is a solid, transparent and translucent natural resin. It is usually yellow or brown in colour and obtained as a residue from the distillation of coniferous resins, dissolved in a suitable solvent (e.g. ether, alcohol and acetone). Rosin has been used since the ancient time and was historically employed for the production of paints, soaps, adhesives, inks, and in the tensile industry [12].

3. Test set up

The test set up included an actuator and a testing steel frame with data acquisition system as shown in figure 1. To achieve four-point bending, a spreader beam which allowed the force from the actuator to be applied at two locations along the length of the beam was used. The tests were displacement controlled at a rate of 4 mm/min. Bending load was applied until failure for all beam specimens tested.

Figure 1. Test set-up (span between supports = 1004 mm and load span = 400 mm).

Bending tests were carried out over a span of 1000 mm. Supports were made of steel cylinders with a diameter of 25 mm and the distance between the two point loads was kept at 400 mm. The actuator, through which vertical load was applied on the spreader beam, which in turn apply two point loads on the beam specimens, is of the model 2518-113/UK068 and characterized by a 250 kN capacity load cell. The layout of the timber beam, supports and load application points are shown in figure 1.

Linear Variable Displacement Transducer (LVDT) was used to measure maximum beam deflection (at mid-span) for every load increase as shown in figure 2. To attach the LVDT, a steel plate was glued to the tension side of the beam at the mid-span and the transducer sensor was set up such that it just touches the underside of the steel plate. The Instron machine and the linear transducer were then synchronized to ensure corresponding output at a frequency of 1 Hz were obtained.

Figure 2. Measurement of vertical deflection at mid-span using LVDT.

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4. Experimental campaign

A total number of 15 small timber beams were tested in four-point bending. The timber beams were from European Oak (D30) with nominal dimensions of 67 x 67 x 1100 mm and approximate density of 670 kg/m^3. Applied load and mid span displacement at failure were measured and recorded. Prior to testing, the beams were numbered, measured, weighed. The moisture content of each beam was also measured (table 1). Subsequently, controlled damage, represented by a machined cut of 2.85 mm thickness and 20 mm height were introduced in 12 of the beam specimens (figure 3), while the remaining three were used as control specimens.

The following series of tests were carried out: 1. Control beam tests (CT series) on 3 undamaged beams; 2. Damaged/Unrepaired beam tests (DUT series) on 4 beams with controlled damage without any kind of repair or reinforcement, 3. Bone glue repaired beam tests (BRT) on 4 damaged beams repaired by filling the cut with bone glue; 4. Rosin repaired beam tests (RRT) on 4 damaged beams repaired by filling the cut with rosin. The aim was to compare the behavior of repaired beams with that of the undamaged or damaged, but unrepaired beams, in order to verify the effectiveness of the applied natural resins in repairing damaged structural timber beams.

Figure 3. Damaged beam specimens (cut dimensions: 20 x 67 mm).

Table 1. Test matrix.

Test No.	Timber weigth density (kg/m^3)	Moisture content (%)	Damage	Resin used for repair
CT-1	600.4	11	No	-
CT-2	716.3	12	No	-
CT-3	653.5	11	No	-
DUT-1	674.9	12	Yes	-
DUT-2	700.4	12	Yes	-
DUT-3	678.7	11	Yes	-
DUT-4	716.8	12	Yes	-
BRT-1	615.3	13	Yes	Bone glue
BRT-2	682.6	11	Yes	Bone glue
BRT-3	743.3	13	Yes	Bone glue
BRT-4	601.4	11	Yes	Bone glue
RRT-1	624.7	12	Yes	Rosin
RRT-2	622.4	13	Yes	Rosin
RRT-3	715.6	11	Yes	Rosin
RRT-4	650.0	12	Yes	Rosin

4.1. Specimen preparation

The resins used in this work were provided by Phase Italia, Pisa, Italy. The bone glue was supplied in form of pearls while the rosin (with its solvent - acetone) were provided in a liquid form (figure 4). Resins were prepared before they were used to repair damaged timber beams as detailed in the following sub-sections.

4.1.1. Bone glue application. The bone glue pearls were placed in a container with cold water (a part of glue to 4 parts of water). They were left in place until the pearls had absorbed all the water becoming swollen and softened. Subsequently, the glue was heated with the use of an electric cooker, making sure that the temperature of the resin remained between 50-60°C and until it completely melts, with a density similar to that of honey. The resin was then poured into the transverse cut when still hot and allowed to stand for about 14 days (for solidification) before the tests were performed. Tensile tests were performed on bone glue specimens. However, most of the specimens experienced varying degree of curvature when removed form the mold. An average value of about 1000 MPa was recorded for the Young's modulus (E_r). Furthermore, this natural bone glue resin is largely characterized by a strong shrinkage, which could have compromised its ability to restore the continuity when used to seal crack in timber.

4.1.2. Rosin application (RRT series). The rosin, in their supplied state (liquid), was not suitable for beam repair. Therefore, they were mixed with the accompanying solvent (acetone) and left to rest in an open container. After about 24 hours, the solvent (acetone) was evaporated and the rosin had acquired a density similar to that of a myelose. The resulting product was then used to repair the damaged beams and tests were carried out after 14 days so as to allow the resin to set properly within the beam matrix. A typical Young's modulus (E_r) for this type of resin is 200 MPa.

(a) (b)

Figure 4. Natural resins used for repair: (a) Bone glue, (b) Rosin.

5. Analysis of tests results

The tests were identified by an alphanumeric code, in which the letters indicate the specimen condition and resin type i.e. control (CT), damaged-unrepaired (DUT), Bone glue repaired (BRT) and Rosin repaired (RRT), while beams within the same test series are differentiated by the addition of numerals. All the beams were subjected to a four point bending test during which the load applied, and the mid-span displacement were measured and recorded. In this way, it was possible to plot, for each beam, the load-displacement curve, up to the point of failure. Figure 6 shows the load-displacement curves associated with all the tested beams.

5.1. Control tests (CT series)

The failure mode recorded for undamaged (control) beams was characterized by the opening of a lesion at the beam mid-span, which then spread along the beam in the direction of the grain (figure 7a). The load-displacement curves for these beams are presented in figure 6. In addition, the maximum load (P_{max}) and the corresponding maximum (d_{max}) at mid-span were obtained (table 2). Stiffnesses obtained at the maximum load point (K) and at the point where only a third of the maximum load is reached (K'), which represents the slope of the first part of the load-displacement curve, were also computed. The "linearity index" (K'/K), which gives the level of deviation of the load-deflection curve from linearity, is then calculated. In fact, the closer the linearity index is to unity, the lower the deviation (figure 5).

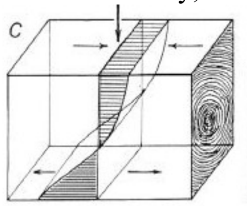


Figure 5. Typical normal stress distribution in a timber beam under bending: yielding may occur on the compressed side, while structural response is linear elastic for tensile stresses.

In the case of CT beams, the average value of 1.07 was obtained for the linearity index, which emphasizes the observed linear trend for this test series (figure 5). In addition, the maximum tension the timber beams are subjected to (σ_{tl}) was calculated in the most stressed section (mid-section) using equation (1):

$$\sigma_{tl} = \frac{M_{\max}}{W} \quad (1)$$

where M_{max} is the maximum moment obtained from

$$M_{\max} = \frac{P_{\max}}{2} \times l_1 \quad (2)$$

l_1 is the distance between the end-supports and the loading point (=302 mm) and W is the section modulus of the timber beam.

Table 2. Maximum values of load, displacement and moment from experimental results.

Test No.	Maximum Load P_{max} (kN)	Maximum Displacement d_{max} (mm)	Maximum moment M_{max} (kNm)
CT-1	12.45	23.47	1.88
CT-2	16.73	24.59	2.53
CT-3	15.32	20.41	2.31
DUT-1	4.23	9.46	6.39
DUT-2	4.68	10.42	7.07
DUT-3	5.12	7.96	7.73
DUT-4*	-	-	-
BRT-1	3.96	11.07	5.98
BRT-2	6.01	11.92	9.08
BRT-3	5.90	11.46	8.91
BRT-4	4.67	14.29	0.71
RRT-1	3.59	8.88	0.54
RRT-2	4.07	6.82	0.61
RRT-3	5.01	11.15	0.76
RRT-4	3.10	8.27	0.47

*Results discarded as not representative.

In addition, tensile stresses at the stretched edge of the timber beam (σ_{tl}), the lower edge (σ_r) and the upper edge (σ'_r) of the resin in the composite resin-wood section were computed using the method of transformed sections with the modular ratio $n=E_w/E_r$ and presented in table 3.

Table 3. Strength and stiffness indexes obtained from test results.

Test No.	Tensile stress σ_{tl} (MPa)	Tensile stress resin σ_r (MPa)	Tensile stress resin σ'_r (MPa)	Stiffness K (N/mm)	Stiffness K' (N/mm)	K'/K (-)
CT-1	41.07	-	-	530.5	573.2	1.08
CT-2	55.19	-	-	680.4	730.4	1.07
CT-3	50.54	-	-	750.6	812.4	1.08
DUT-1	29.12	-	-	447.1	590.0	1.32
DUT-2	32.21	-	-	449.1	523.5	1.17
DUT-3	35.24	-	-	643.20	850.7	1.32
DUT-4*	-	-	-	-	-	-
BRT-1	19.60	4.16	2.13	357.7	464.8	1.30
BRT-2	29.72	6.31	3.23	504.2	555.6	1.10
BRT-3	29.16	6.20	3.17	514.8	625.4	1.21
BRT-4	23.09	4.91	2.51	326.8	483.0	1.48
RRT-1	23.00	0.95	0.50	404.3	571.4	1.41
RRT-2	26.22	1.08	0.57	596.8	727.3	1.22
RRT-3	32.20	1.32	0.70	449.3	605.1	1.35
RRT-4	19.78	0.82	0.43	374.8	474.7	1.27

*Results discarded as not representative.

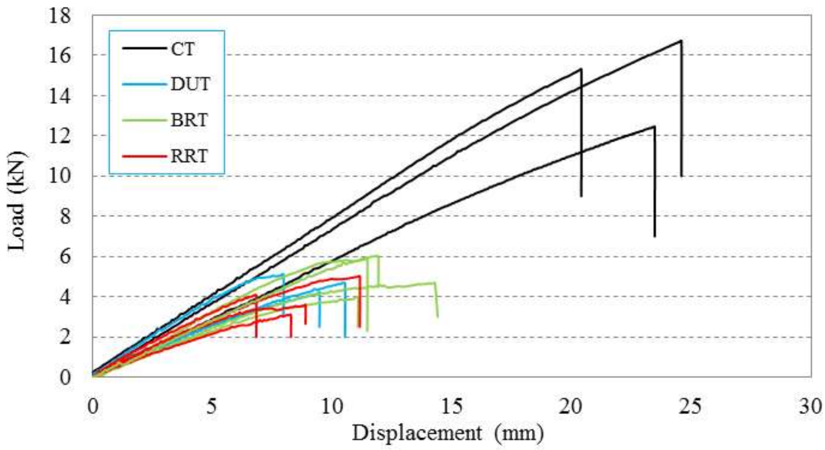


Figure 6. Load-displacement curves: CT (Control tests), DUT (Damaged and unrepaired beam tests), BRT (Bone glue repaired beam tests), RRT (Rosin repaired beam tests).

5.2. Damaged unrepaired beam tests (DUT series)

The beams' bending capacity decreased dramatically after the beams were artificially damaged with the transversal cut at mid-span. The average bending load (P_{max}) at failure decreased from 14.8 kN to 4.68 kN, with a reduction of 68.4%.

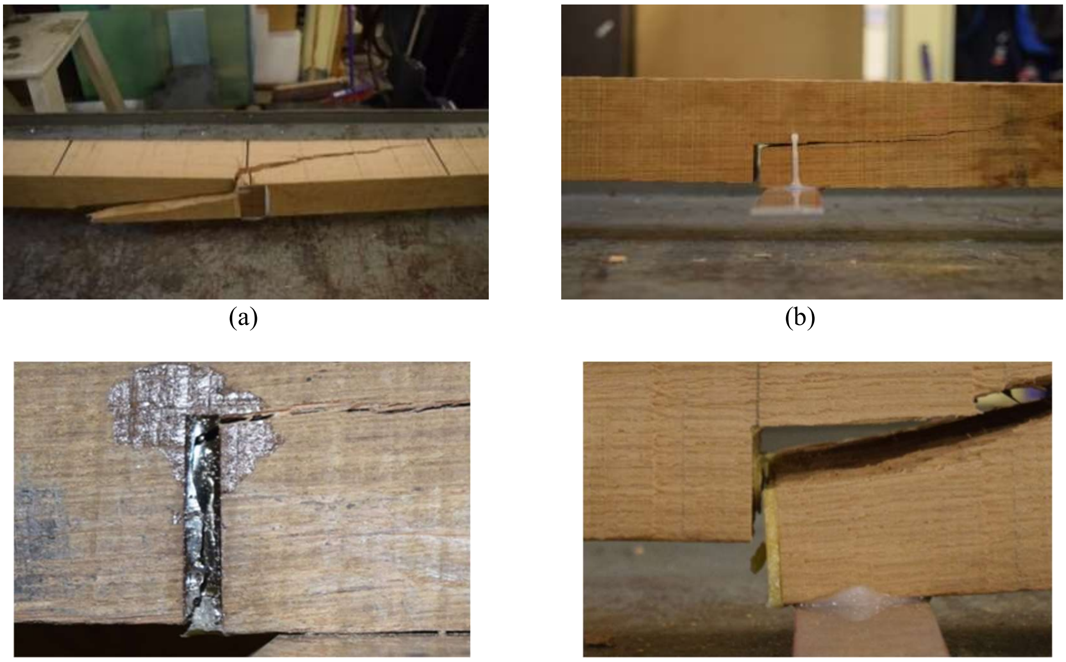
The most common failure mode was the opening of a crack starting from the top corner of the cut, which was then propagated in the direction of the grain (figure 7b). An average linearity index of 1.3 was recorded showing significant reduction in the load – deflection slope as the load increases. This is probably due to the plasticization of the wood fibers in the compressed area of the beams.

5.3. Repaired beam tests (BRT and RRT series)

The repair was done by filling the artificial cut with the natural resin, with the aim of restoring the continuity between the edges of the cut and the original pre-damage bending capacity. Unfortunately, test results demonstrated that it was not possible to achieve this objective.

Similart to the damaged un-repaired beams (DUT series), the beams repaired with natural resins, i.e. bone glue (BRT series) and rosin (RRT series), failed by the tensile rupture of the wood starting from the corner of the cut with consequent breaking of the resin present inside the cut (figures 7c and 7d). Same indices previously defined were also obtained and presented in table 2 for the BRT and RRT beams. It can be observed in table 2 that the use of bone glue results in higher load carrying capacity for the repaired beams when compared with rosin repaired beams. Results were unsatisfactory both in terms of bending capacity and stiffness: the application of the natural resins was unable to restore the continuity in the area of the cut. Failure occurred in the timber material on tension side inside the cut. At failure, natural resins only deformed (no failure) or detached from the timber. The main problem was the extremely low Young's modulus of the natural resins used.

In addition, there was a significant change in the initial slope as the beam was loaded, irrespective of the resin type. It should also be noted that the most stressed section was at the resin-wood interface for most of the repaired beams.



(a) (b) (c) (d)

Figure 7. Specimens' failure modes: (a) CT series (control undamaged beams); (b) DUT series (damaged and unrepaired beams); (c) BRT series (damaged and bone glue repaired); (d) RRT series (damaged and rosin repaired).

The load versus mid-span displacement curves for each test series is presented in figure 7. Average values for the maximum load (P_{max}), maximum displacement (d_{max}), stiffnesses (K and K') and of the linearity index (K'/K) for each test series are also presented in Table 4.

Table 4. Test results (average values).

	CT series	DUT series	BRT series	% change for BRT series*	RRT series	% change for RRT series*
$\mathbf{P_{max}}$ (kN)	14.8	4.68	5.14	9.8	3.94	-15.81
$\mathbf{d_{max}}$ (mm)	22.8	9.28	12.2	31.47	8.78	-5.39
K (N/mm)	653.8	513.1	425.9	-16.99	456.3	-11.07
K' (N/mm)	705.3	654.7	532.2	-18.71	594.6	-9.18
K'/K (-)	1.08	1.3	1.3	-	1.3	-

* % changes are calculated based on the damaged beams (DUT series).

Significant reduction in load bearing capacity in the damaged beams compared to the control beams should be noted (both in terms of maximum load and stiffness). This is probably due to the fact that the cut was made at the most critical point for a beam symmetrically loaded and subjected to flexure, i.e. mid span. Although the use of bone glue (BRT series) resulted in slight improvement, in terms of enhanced maximum load (about 10% average increase) compared to the damaged but unreinforced beams (DUT series), there were generally no significant improvement from natural resin repair, there was a significant increase in the maximum displacement (over 30% on average). The increase in the maximum displacement can, in a way, undermine the increaded load carrying capacity. For rosin repaired beams (RRT series), the opposite ensures. About 16% average decrease in load carrying capacity with a corresponding 5% average decrease in maximum displacement was recorded.

In the case of rosin, even though it has high tensile strength, its excessively low Young's modulus E_r (about 200 MPa, compared to the timber Young's modulus E_w of 6,000-9,000 MPa) makes it highly deformable and therefore unable to contribute significantly to the resistance and stiffness of the repaired timber beams, given the high value of the modular ratio $n=E_w/E_r$. In fact, the beams' bending capacity was not limited by the rosin's tensile strength, but by the wood tensile strength, with consequent tensile failure of the wood. Furthermore, during the preparation of the specimens, bone glue presented a high volume shrinkage, which could have made it unsuitable to restore the timber continuity in the cut (although the resin was injected several times to minimize this effect).

6. Conclusions

A non-invasive, reversible repair technique, using natural resins (bone glue and rosin) was studied in this work. This repair method is in accordance with the principles for the "analysis, conservation and structural restoration of architectural heritage" set by ICOMOS in 2003 [17]: "Where possible, any measures adopted should be "reversible" so that they can be removed and replaced with more suitable measures when new knowledge is acquired. Where they are not completely reversible, interventions should not limit further interventions".

The natural resins were applied directly to an artificially-damaged part of the beam, thus making the intervention minimal and without significantly altering the element being repaired. The bending stiffness of the beams has not been restored and the contribution of the resins in tension has been practically negligible. The long-term behavior of the resin needs also to be investigated and should be the focus of future research. More tests are actually ongoing using different natural resins with the aim at restoring the original, pre-damage bending capacity, but many difficulties have been highlighted when natural resins are used for this purpose, given their limited mechanical properties.

The use of natural resins showed limited improvements in the load carrying capacity of damaged beam, however there non-toxicity and environmentally friendliness should be enough motivation to further study how to effective use these and other natural resin to repair damaged timber beams. This could involve the use of more effective techniques with the same materials (bone glue and rosin) or a total change of both the technique and the material altogether. In conclusion, the ever-growing campaign for respect for the environment and use of materials with low toxicity, necessitates further research on the use of natural products for repair and reinforcement of structural wooden beams.

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