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FLEXURAL REINFORCEMENT OF TIMBER ELEMENTS ON-SITE WITH PRF ADHESIVE AND WOOD-BASED PRODUCTS

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ABSTRACT: In this study, the potential application of a two-component phenol-resorcinol-formaldehyde adhesive for on-site reinforcement of glued laminated timber (GLT) and a recovered spruce beam was investigated. Different spread rates (500 – 2000 g/m^2), means of pressurization of the bond lines (clamps, screws and the reinforcements own mass) were applied to establish bond lines between the substrate to be reinforced and the reinforcements, GLT and plywood (PLW). The surface conditions (not planed, partly coated/ sanded, varying surface moisture content) were chosen to resemble situations that might be encountered during on-site reinforcement. The bond lines of two of the 11 different combinations fulfilled the required shear strength according to EN 14080. The investigations show that thicker bond lines and low pressure on the bond lines result in lower bond strength. Coating and partial removal of the coating by sanding are expected to have amplified the effect of the chemically weak boundary layer. Bond lines between materials with similar surfaces yield higher shear strength compared to bond lines between materials with differing surfaces.

KEYWORDS: Flexural reinforcement, phenol-resorcinol-formaldehyde, glulam, plywood, shear strength

1 INTRODUCTION

1.1 BACKGROUND

There are several different motivations to reinforce timber elements. The first one, reinforcement of glulam beams during production serves the purpose of increasing the span of that beam by replacing the outer lamellae with lamellae of hardwood or engineered wood products [1, 2], steel or aluminium [3, 4 5], natural fibres (hemp, flax, basalt, bamboo etc.) [6] or glass fibre reinforced polymers [7]

The second motivation might be to reinforce elements of load-bearing structures after mechanical or biological damage [8] as well as after boring of holes for ventilation and sewage pipes [9]. To avoid the reinforcement of regular glulam beams with holes, [10] propose the use of GLT-LVL composite beams which they proved to make reinforcement of one or multiple large rectangular multiple holes obsolete.

As the term circular economy finds its way into the building industry, the third scenario, reinforcing existing wooden structures to upgrade them for change of use or after changes in regulatory specifications for instance an increase in snow or wind loads as reaction to climate change, comes into play. To increase the lifetime of structural timber elements such as trusses or floor beams by on-site flexural reinforcement, the following approaches are described in the literature:

1) Application of self-tapping screws to avoid splitting of glulam along the grain [11, 12, 13].

2) Inserting of glued-in rods in the wooden element, a technique that has been successfully used for almost 40 years, a comprehensive state of the art report has been presented by [14]. The geometry of the timber, the adhesive area and the rod area, the size of the anchoring zone, the material stiffness and strength, fracture mechanical properties of timber and adhesive, variability of all properties and loading conditions as well as other parameters like wood species and manufacturing practices are defined as key parameters for the load bearing capacity of glued-in rod connections [15]. The rods must be fixed with an adhesive system that provides a continuous bond between the reinforcement and the timber, fills voids and cavities and is able to transfer and sustain loads. Epoxy resins are identified as specifically suitable as structural adhesives in repair [16], acrylic, polyurethane and phenol-resorcinol-formaldehyde adhesive types showed cohesive adhesive failures of adhesion failures [8]. However, the development of adhesive systems is ongoing, and it is obvious that these findings do not represent the state of the art within adhesive technology.

3) Addition of fibre reinforced polymers as described by [17] who tested intentionally damaged timber beams from a 32-year-old storage building reinforced by two types of carbon fibre reinforced polymer (CFRP). The reinforcement yielded an improvement in load-carrying by up to 184% compared to the controls without reinforcement. [18] studied the effect of combining basalt and carbon fibres as reinforcement of timber beams. They compared different grammages of basalt fibres and

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unidirectional and bidirectional carbon composites. The results showed better effect of bidirectional fabrics compared to unidirectional fabrics and an increase of the beam stiffness with increasing grammage of basalt fibres. Besides grammage and orientation of the components of a CFRP, prestressing of the sheets was found to increase the bending strength of the reinforced beams significantly compared to those beams that were reinforced with non-prestressed CFRP was found [19].
4) Addition of wood-based panels [20].

1.2 FOCUS OF THIS STUDY

Generally, the reinforcing elements can be attached to the structural element by mechanical fixings, structural adhesives, or a combination of both to hold the reinforcing element in place and apply pressure during the curing phase of the adhesive.

When reinforcing on-site, engineers normally only consider load transfer due to mechanical fasteners. Adhesives are not considered due to uncertainty linked to the application process and whether the quality of the bond line is sufficient to enable the transfer of the load from the substrate to the reinforcement. There is a need for a better understanding on how on-site reinforcement using adhesives can be performed, and to identify the limitations. Currently only EN 17481 [21] covers adhesives explicitly for on-site repair of timber structures. Two-component epoxy and polyurethane adhesives which fulfil the requirements given in the standard are approved for the repair of cracked timber structures. However, two-component phenol-resorcinol-formaldehyde (PRF) adhesive systems which are widely used in the production of block glued glulam according to EN 14080 [22] might be suitable alternatives due to the ease of their application and the gap filling properties.

The aim of this study was to characterize the shear strength of the bond line between solid wood substrates of various qualities and selected wood based reinforcing elements.

2 MATERIALS AND METHODS

2.1 PREPARATION OF THE SHEAR SAMPLES

Pieces of recently produced commercial spruce glulam (GLT) and parts of a recovered spruce beam from an old barn were reinforced with GLT or plywood plates (PLW). A total of 18 sample blocks were prepared.

2.1.1 Materials to be reinforced

Two of the 11 GLT pieces (48 x 250 x 10400 mm) (b x h x l) were conditioned to 9-10 % (L) and 23 % (H) superficial moisture content. The remaining GLT samples were stored at 20 ˚C and 65 % relative humidity (M), one half of the surface of two of those samples was coated with a wall paint (C). The coated surface of one of the pieces was partly sanded (C+S).

Five pieces from a recovered spruce beam (RSB) (92 x180 x 152 mm) (b x h x l) were recovered from an old barn and stored at 20˚C and 65 % relative humidity prior to production of the sample blocks. Three of those pieces were sanded prior to the reinforcement.

2.1.2 Reinforcement

The GLT (36 x 250 x 10400 mm) and the pine plywood (PLW) (9 ply, 12 mm thickness) were stored at 20˚C and 65 % RH.

2.1.3 Assembly of sample blocks

The reinforcing element was bonded to the material to be reinforced with the PRF-adhesive Prefere 4094 and the hardener Prefere 5827, both supplied by Dynea AS. Adhesive and hardener were mixed at a ratio of 100:20, the application rate was varied between 500 g/m^2 to 2000 g/m^2. The adhesive was applied one-sided. Screws (5.0 x 50 mm) (SCR) (Figure 1), clamps tightened by hand (CLA) or the reinforcing elements` own weight (OW) provided pressure during curing of the adhesive.

Figure 1: *Sample blocks of two pieces of split GLT pressurized with screws.*

2.2 SHEAR TESTS OF BOND LINES

The samples were cut from the sample blocks at least 20 mm from the edges (Figure 2). Compressive shear strength (CSS) was tested according EN 14080 [2], Annex D (Figure 3). The shear area for the bond line was approximately 50 x 50 mm.

The Tukey-Kramer test and t-test in JMP 10 (JMP Statistical Discovery LLC) was used for respectively overall or pairwise statistical analysis of the data.

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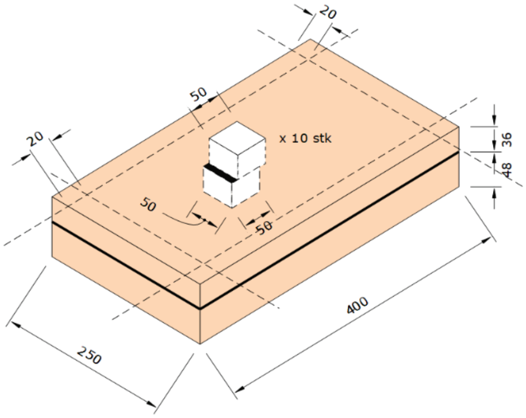

Figure 2: *Production of samples to test compressive shear strength.*

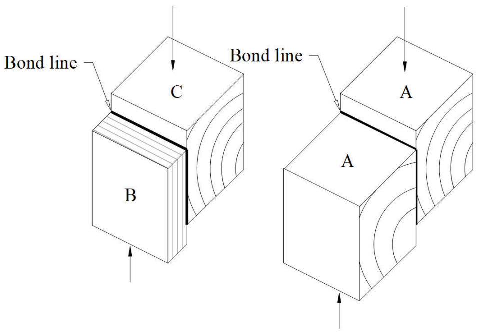

Figure 3: *Samples for compressive shear test of bond lines*

3 RESULTS AND DISCUSSION

3.1 REINFORCEMENT OF GLULAM

The average CSS of the bond lines between the material to be reinforced and the reinforcement was 7.1 N/mm^2 with significant difference between reinforcement GLT (7.6 N/mm^2) and PLY (5.5 N/mm^2), (Table 1). This can be explained by the combination of different surfaces in the samples reinforced with PLW compared to the similar surfaces of the reinforcement with GLT. Treatments 7 and 10 fulfilled the requirements for CSS in timber structures according to EN 14080. Detailed results are presented in Table 2.

Pressurizing the bond line with screws or clamps compared to the reinforcements` own weight increased the CSS of the bond lines significantly (Figure 4). The same applies for the wood failure percentage. This is most likely due to the higher pressure applied on the adhesive joint during curing by screws and clamps compared to the mass of the plywood panel. Thus, the latter results in lower penetration of the adhesive into the wood surface compared to the first, yielding a stronger bond and higher wood failure percentage.

Table 1: *Average compressive shear strength (CCS) of the bond lines between the recovered spruce beam and plywood (PLW) as reinforcement, S: sanded, OW: own weight.*

Treatment		Samples	CSS [N/mm^2]	
#	Name		$\bar{x}$	σ_x
1	GLT(C)_GLT_1000_OW	10	4.3	2.2
2	GLT(C+S)_GLT_1000_OW	10	4.6	2.3
3	GLT(H)_GLT_1000_OW	10	4.3	1.1
4	GLT(H)_GLT_2000_OW	10	6.2	0.7
5	GLT(L)_GLT_1000_OW	9	6.3	1.1
6	GLT(L)_GLT_2000_OW	10	5.7	1.1
7	GLT_GLT_1000_CLA	10	7.4	0.6
8	GLT_GLT_1000_SCR	10	7.5	0.5
9	GLT_GLT_500_CLA	10	7.4	0.9
10	GLT_GLT_500_SCR	10	7.9	1.0
11	GLT_PLW_500_SCR	14	5.5	1.3

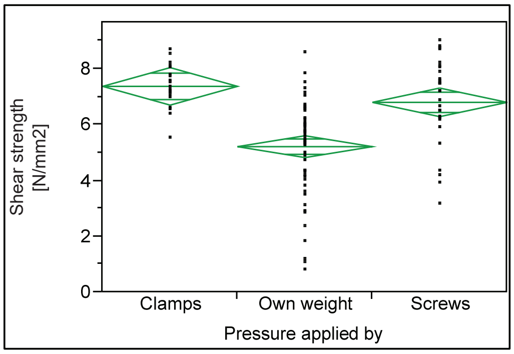

Figure 4: *Compressive shear strength of bond lines between GLT and reinforcement as result of pressurizing method*

A spread rate of 500 g/m^2 resulted in significantly higher CCS than a spread rate of 1000 g/m^2 (6.8 N/mm^2 versus 5.8 N/mm^2) (Figure 5), the same applies for the wood failure percentage. The reason for that is the supposedly thicker bond line resulting from the higher application rate. The lower shear strength of thicker bond lines compared to thinner bond lines is a known fact which is accounted for by the lower requirements for tensile shear strength of thick bond lines compared to close contact bond lines in EN 301 [23].

Table 2: *Average compressive shear strength (CCS) of the bond lines between GLT and reinforcements, C: coated, C+S: coated and sanded, H: high surface moisture content, L: low surface moisture content, PLW: plywood, OW: own weight, CLA: clamps, SCR: screws.*

Treatment		Samples	CSS [N/mm^2]		Wood failure [%]		Adhesive failure [%]		Invalid samples
#	Name		$\bar{x}$	σ_x	$\bar{x}$	Min	$\bar{x}$	Min	
1	GLT(C)_GLT_1000_OW	10	4.3	2.2	58	10	42	0	7/10
2	GLT(C+S)_GLT_1000_OW	10	4.6	2.3	61	10	39	0	7/10
3	GLT(H)_GLT_1000_OW	10	4.3	1.1	13	0	87	40	10/10
4	GLT(H)_GLT_2000_OW	10	6.2	0.7	100	100	0	0	0/10
5	GLT(L)_GLT_1000_OW	9	6.3	1.1	88	70	13	0	3/10
6	GLT(L)_GLT_2000_OW	10	5.7	1.1	99	90	2	0	1/10
7	GLT_GLT_1000_CLA	10	7.4	0.6	89	10	2	0	1/10
8	GLT_GLT_1000_SCR	10	7.5	0.5	100	100	0	0	0/10
9	GLT_GLT_500_CLA	10	7.4	0.9	97	90	3	0	1/10
10	GLT_GLT_500_SCR	10	7.9	1.0	100	100	0	0	0/10
11	GLT_PLW_500_SCR	14	5.5	1.3	91	30	0	0	6/14
12	RSB_PLW_1000_OW	4	2.9	1.3	58	40	43	10	4/4
13	RSB_PLW_2000_OW	4	3.4	1.1	78	50	23	10	4/4
14	RSB(S)_PLW_500_OW	4	3.9	1.7	30	100	0	70	3/4
15	RSB(S)_PLW_1000_OW	4	4.1	1.8	90	100	0	10	3/4
16	RSB(S)_PLW_2000_OW	4	5.6	1.9	98	90	3	0	1/4

An influence of the superficial moisture content of the GLT on the CSS was not found. High superficial moisture content, however, resulted in significantly lower wood failure percentage compared to medium and low surface moisture content. This might be due to water saturation of the fibres on the surface of the wetted sample hindering the penetration of the adhesive followed and the subsequent anchoring in the superficial fibres.

Coating of the GLT and sanding of the coated surface resulted in significantly lower CSS of the bond lines compared to the bond lines between untreated GLT and reinforcement (Figure 6). This result can be ascribed to the coating/ coating and sanding of the surface which intensifies the effect of the chemically weak boundary layer on the wooden surfaces that were not machined [24]. [25] did not find significant differences between the tensile shear strength of bond lines between substrates that were prepared by sanding on a professional sander and substrates prepared by planing. Sanding in the current study, however, was conducted manually, lacking the homogeneity of machine sanding.

Our findings underpin the importance of clean surfaces, often accomplished by machining of the material, as prerequisite for good bonding results. This is an issue especially when it comes to the reinforcement of aged wood structures with surfaces that are not accessible for machining.

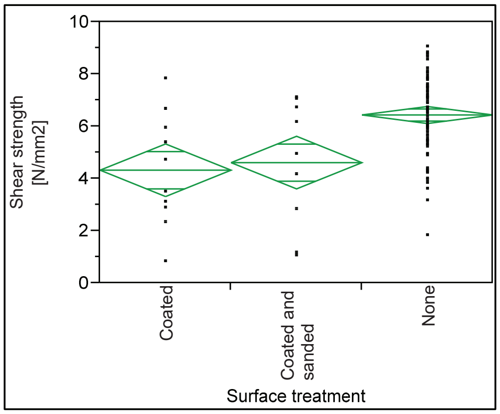

Figure 6: *Influence of surface treatment on the compressive shear strength of the bond lines between GLT and reinforcement*

3.2 REINFORCEMENT OF RECOVERED WOOD

The average CSS of the bond line between the recovered spruce beam and PLW was 3.0 N/mm^2, see Table 3 for average results per treatment. Neither spread rate nor sanding of the surface influenced the CSS or the wood failure percentage. None of the treatments fulfilled the requirements for CSS given in EN 14080. This is most likely due to the neglected machining of the recovered spruce beam with the resulting chemically weak boundary layer [25]. Ageing of the bulk wood material [26] may contribute, too.

Table 3: *Average compressive shear strength (CCS) of the bond lines between the recovered spruce beam and plywood (PLW) as reinforcement, S: sanded, OW: own weight.*

Treatment		Samples	CSS [N/mm^2]	
#	Name		$\bar{x}$	σ_x
12	RSB_PLW_1000_OW	4	2.9	1.3
13	RSB_PLW_2000_OW	4	3.4	1.1
14	RSB(S)_PLW_500_OW	4	3.9	1.7
15	RSB(S)_PLW_1000_OW	4	4.1	1.8
16	RSB(S)_PLW_2000_OW	4	5.6	1.9

3.3 COMPARISON OF REINFORCEMENTS

This comparison covers exclusively samples from blocks consisting of GLT reinforced with GLT or PLW with a spread rate of 500g/m^2 and bond lines pressurised by screws. Reinforcement with GLT resulted in bond lines with significantly higher CCS compared to reinforcement with PLW (Figure 7). This finding is in line with the significant difference between the CSS of the bond lines of all samples reinforced with GLT compared to PLW.

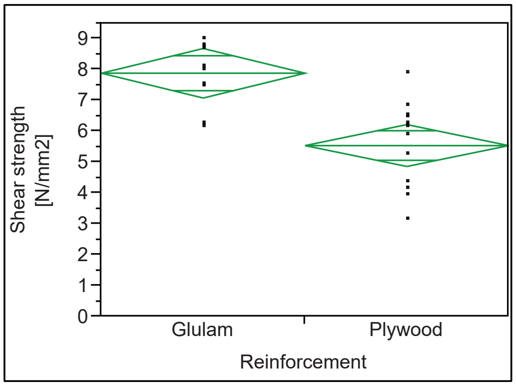

Figure 7: *Compressive shear strength of reinforcement with GLT compared to PLW*

4 CONCLUSIONS

The results suggest the potential of a combination of PRF adhesive and wood-based products as solution for on-site structural reinforcement of glued laminated timber and recovered wood. This application, however, implies neglecting generally accepted principles for wood bonding such as machining of surfaces and controlled application of pressure. These deficits were resembled by the design of the samples and explain the deficient bond strengths of most of the samples compared to the requirements defined in EN 14080. Further investigations should include higher numbers of replicates and reference samples prepared according to current practice of wood bonding.

Another aspect of reinforcing wooden structures on-site, especially in countries with extended periods of low air temperature, is the influence of these low temperatures on the curing of an adhesive and the definition of thresholds for reasonable use of the adhesives. This parameter should also be included in future research.

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