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Comparison of different techniques for the shear strengthening of glulam members

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ABSTRACT: The work presented in this paper is part of an ongoing Swiss federal research project that deals with the assessment and strengthening of glulam members. In the course of the tests some of these methods are not only used to repair delaminated glulam beams subjected to tension perpendicular to grain and shear but also to reinforce weak parts of the members, e.g. at the supports and the loading points. Two different strengthening methods, one based of self-tapping screws and one on base of CFRP-meshes are compared to each other regarding their potential for strengthening glulam members that show delaminations.

With the help of short-span 3-point bending tests of missglued glulam beams, the shear strength and stiffness of the original and reinforced beams were evaluated. It was shown that the applied strengthening techniques helped to restore the required shear strength and to increase the shear stiffness of delaminated beams significantly but without reaching the level of the original beams.

1 INTRODUCTION

There are several reasons for strengthening timber members made out of glulam. Besides ageing and delamination, issues that are linked to a certain stage of reduced strength and/or stiffness due to existing failures, there are also needs for strengthening intact glulam members, e.g. in the course of a change of use with planned higher structural loadings.

The work presented in this paper is part of an ongoing Swiss federal research project that deals with the assessment and strengthening of timber structures. This paper focuses on the strengthening part and in particular on shear reinforcements of delaminated glulam members. The strengthening techniques include self-tapping screws, glued-in rods, injection of adhesives in delaminations and Carbon-Fiber-Reinforced-Polymers (CFRP) tissues glued externally, where only the first and last mentioned will be discussed here.

Self-tapping screws have been used in a strongly increasing number for timber constructions over the past years (Trautz 2008, 2009). They are available in different diameters of up to 13 mm and in lengths of up to more than 1 m. The main applications are connections and reinforcements. The application of the screws is relatively easy as a predrilling of holes is not necessary. Therefore they replaced more and more other pin-shaped connectors like glued-in threaded rods. In a study (Dietsch 2012) it is shown that self-tapping screws along with injection of adhesives into laminations is the most used technique of strengthening glulam members.

FRP materials are commonly applied as flexural reinforcement, as e.g. shown by Borri et al (2004). There is also knowledge about the application of CFRP-sheets (or meshes) for the reinforcement of timber (Thanasis et al 1997). FRP meshes are very flexible and can be easily cut with scissors. They are available in many different thicknesses (most often defined as mass per m^2) and widths. The application is possible in one or more layers and the meshes can be oriented uni-, bi- or multidirectionally. This allows the installation of FRP meshes in such way, that they are ideally adapted to the direction of existing forces or stresses on/in (timber) members. In addition they can be wrapped around member edges.

All these properties lead to the idea to compare the shear strengthening potential of such meshes with the one of an already widely used product, the above mentioned self-tapping screws. This will be presented in the following.

2 MATERIAL AND METHODS

2.1 Glulam beams

The material consisted of eight timber beams made out of glulam from Swiss grown Norway Spruce. The length of the beams was l = 2,500 mm with a cross section of width w = 140 mm and depth h = 600 mm (Figure 1). Following a grading including the determination of density and dynamic MOE as well as knots, the lamellas were sorted in order to build up beams with homogenized material properties. With a characteristic density ρ_k = 370 kg/m^3 the lamellas were in the range of glulam GL24h according to EN 1194.

The middle lamella was glued along its center only on one third of its width, reducing the shear strength and stiffness respectively (Figures 1 – 3). In order to prevent early bending failures the outer lamellas of all beams where made of high strength ash timber. The support- and loading point areas of the beams were reinforced with self-tapping screws with dimensions of 8.2 mm x 140 mm and 13 mm x 250 mm respectively. This was necessary because of the high loads would otherwise lead to compression stresses perpendicular to the grain that exceeded the characteristic strength values of the timber.

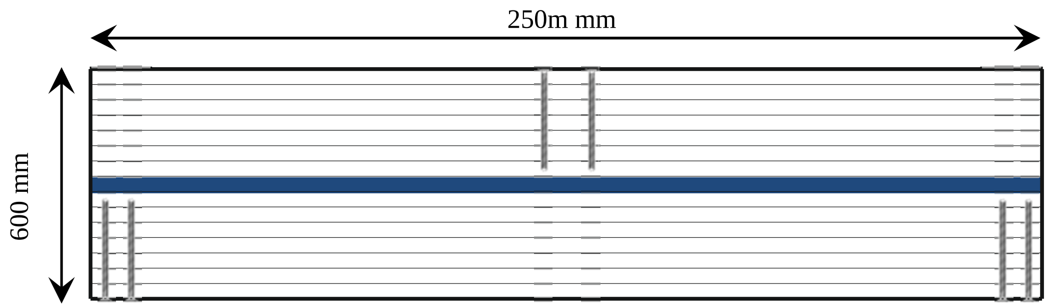


Figure 1. Basic view of the unreinforced specimens. The middle lamella is indicated in dark blue. Both gluelines of this lamella – the upper and lower one – were missglued over the entire length in such way, that only one third of the glueline cross-section was available for load transfer. The screws at the supports and the loading point served as reinforcement for the introduction of high loads into the beam.

Figure 2. Production of missglued middle lamella at n'H Lungern AG in Switzerland. The surface of the lamella was protected by tape in order to prevent proper wood-wood gluing.

Figure 3. Cross section of missglued middle lamella

2.2 *Reinforcements*

Two different reinforcement methods were used: self-tapping screws and CFRP meshes. The screws of the type SFS WT 13 x 800 were provided by Swiss company SFS unimarket AG and the CFRP meshes SikaWrap®-230 C/45 by Sika AG, also a company based in Switzerland. The reinforcements were applied by technicians of the two companies and/or under their supervision in order to guarantee optimal quality. For the application it was assumed the beams are installed in an existing structure and that their top edge is inaccessible. In consequence the reinforcement was applied from underneath and/or from the horizontal faces of the beam.

The self-tapping screws were applied from the tension edge under an angle of 45° (Figure 4). The number of screws applied per side was varied from one to two to four. Two beams each were reinforced with these configurations and the remaining two of the total eight beams were reinforced using the unidirectional CFRP sheets in one or two layers (Fig. 2). These sheets with a width of 30 cm were glued using an epoxy under an angle of 45° to the beams longitudinal axis (Figure 5).

Figure 4. Beam reinforced with screws (demonstration).

Figure 5. Beam reinforced with unidirectional CFRP sheets

2.3 Test methods

All beams were tested under a 3 – point bending set-up with 5 loading cycles. The effective span of the beams resulted in l_{eff} = 2300 mm. Initially the beams were tested without reinforcement until one side failed due to shear stresses. As intented, all failures of the unreinforced beam ends occurred at one of the two gluelines of the middle lamella. Following the failure, each beam was loaded again in order to determine their reduced shear stiffness. After strengthening the end of the beam, where the failure occurred, the beam was again subjected to 3 - point bending until failure occurred on the other side. With another load cycle the residual shear stiffness was determined. After the reinforcement of the second side the beams underwent a fifth testing cycle in order to determine the strength of the completely reinforced beams. For all tests the loads were recorded as well as the global bending deformation and deformations along the missglued lamellas.

3 RESULTS AND DISCUSSION

3.1 Strength

The results of the tests with the beams containing the missglued middle lamella are summarized in the following table 1.

Apart from the failure load and the respective bending stress σ_b at midspan, the nominal shear stress at failure τ^* and the nominal compression stress perpendicular to the grain at failure $\sigma^*_{c,90}$ are indicated in order to highlight the level of the loading. Both nominal stresses are referred to the full cross section and the support area respectively without taking into account the shear- and compression reinforcements and represent the most important stress values within this study.

The main focus was on the shear strength as it was the aim of the study to show the potential of the applied methods for shear reinforcement. As reference value the characteristic value for glulam GL 24h as given in EN 1194 with $f_{v,g,k}$ = 2.7 kN/m^2 was taken. Because the short span bending tests were designed to provoke shear failure, bending and compression strength perpendicular to the grain are only of secondary importance. However, the respective failure modes can occur at this test set-up and did so. As reference values the same standard indicates a characteristic bending strength $f_{m,g,k}$ = 24.0 N/mm^2 and a characteristic compression strength $f_{c,90,g,,k}$ = 2.7 N/mm^2 respectively.

The relevant stresses were calculated as follows:

$$\tau^* = 1.5 \cdot 0.5 \cdot F_{max}/(b \cdot h) \tag{1}$$

$$\sigma_b = M_{max}/W \tag{2}$$

$$\sigma^*_{c,90} = 0.5 \cdot F_{max}/(a \cdot b) \tag{3}$$

Three data sets per beam are indicated in Table 1. The first one refers to the completely unreinforced beam. After shear failure at one side - followed by its reinforcement - the beam was tested a second time and shear failure occurred at the opposite beams end which was not yet reinforced. This stage is indicated by the second data set. After reinforcement also of the other side the beam underwent the final loading cycle which the third data set is referred to.

Table 1. Results from tests with missglued and reinforced glulam beams. The bold numbers highlight strength values, all other values represent relevant stresses at the moment of failure.

Beam No.	Reinforcement	Failure Mode	F_{max} kN	τ^* N/mm^2	σ_b N/mm^2	$\sigma^*_{c,90}$ N/mm^2
	None	shear	160	**1.43**	10.8	3.57
1a	1 x 1 CFRP	shear	218	**1.95**	14.7	4.87
	2 x 1 CFRP	compr. perp.	303	2.71	20.5	**6.76**
	None	shear	240	**2.14**	16.2	5.36
1b	1 x 2 CFRP	shear	251	**2.24**	20.0	5.60
	2 x 2 CFRP	compr. perp.	436	3.89	29.5	**9.73**
	None	(delaminated)	0	0	0	0
2a	1 x 4 SFS 13	shear	220	**1.96**	14.9	4.91
	2 x 4 SFS 13	compr. perp.	361	3.22	24.4	**8.06**
	None	shear	180	**1.61**	12.2	4.02
2b	1 x 4 SFS 13	shear	244	**2.18**	16.5	5.45
	2 x 4 SFS 13	compr. perp.	290	2.59	19.6	**6.47**
	None	shear	200	**1.79**	13.5	4.46
3a	1 x 2 SFS 13	shear	240	**2.14**	16.2	5.36
	2 x 2 SFS 13	bending	372	3.32	**25.1**	8.30
	None	shear	235	**2.10**	15.9	5.25
3b	1 x 2 SFS 13	shear	329	**2.94**	22.2	7.34
	2 x 2 SFS 13	shear	398	**3.55**	26.9	8.88
	None	shear	208	**1.86**	14.1	4.64
4a	1 x 1 SFS 13	shear	290	**2.59**	19.6	6.47
	2 x 1 SFS 13	shear	376	**3.36**	25.4	8.39
	None	shear	196	**1.75**	13.2	4.38
4b	1 x 1 SFS 13	shear	245	**2.19**	16.6	5.47
	2 x 1 SFS 13	bending	360	3.21	**24.3**	8.04

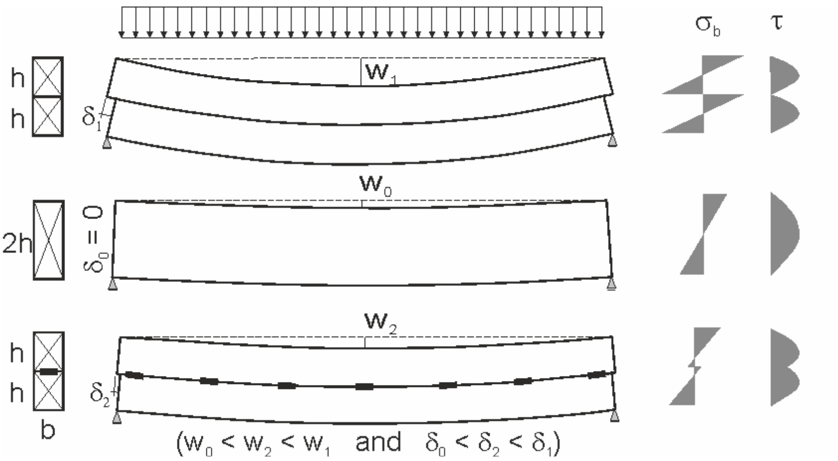
From the table it can be seen that missglueing the middle lamella had the desired effect in reducing the nominal shear strength τ^* of the unreinforced beams. The shear strength $f_{v.g}$ (here = τ^*) was well below the characteristic value of $f_{v,g,k}$ = 2.7 kN/m^2. Every applied strengthening technique led to a significant increase of the shear strength (compare first and second with third data set). However, the ultimate shear strength capacity of the reinforcements could not be determined discretely as most beams after having been reinforced at both ends showed a failure mode different from shear failure. Only two out of eight completely reinforced specimens failed due to shear. On the other hand, all beams with the exception of specimen 1a showed a shear stress superior to the characteristic strength value $f_{v,k}$ = 2.7 kN/m^2 at failure. As beam 1a did not show a shear failure, it can be expected that its shear strength also is similar or superior to the characteristic value. Therefore it can be stated, that all strengthening set-ups lead to a restoration of the shear strength to a level higher than the (required) characteristic shear strength.

As a side effect it can be observed, that the screw-reinforcements at the supports and loading point of the beams lead to a significantly increased compression strength perpendicular to the grain. The highest loadings of the beams resulted in respective stresses that were 2.5 to 3 times higher than the given characteristic value of $f_{c,90,g,,k}$ = 2.7 N/mm^2.

The results also show that the used short span 3-point bending setup only partly allows determining the shear strength of reinforced glulam beams. Apart from evaluating different strengthening techniques the future work should therefore also concentrate on finding test set-ups that permit a higher shear loading.

3.2 Stiffness

As could be shown in the previous section the necessary shear strength could be restored to the required level by the reinforcements. In addition to strength requirements there are also stiffness requirements. A glulam beam that is (partly) delaminated shows a similar bending behavior to that of dowelled beams with an elastic connection. One model to describe the load bearing behavior of such beams is the γ procedure as shown in Figure 6.



$$I_{eff} = \frac{bh^3}{6} \quad (\gamma = 0) \tag{4}$$

$$I = 4\,\frac{bh^3}{6} \quad (\gamma = 1) \tag{5}$$

$$I_{eff} = \frac{bh^3}{6} + \gamma\,\frac{bh^3}{2} \quad (0 < \gamma < 1) \tag{6}$$

Figure 6. Load bearing behavior of dowelled beams.

The factor γ depends on the stiffness of the connection. No stiffness at all, like a completely delaminated beam leads (if friction is neglected) to γ = 0, the different cross sections act independently. On the other hand, γ = 1 refers to one complete cross section that is capable to counteract the existing bending moment. The reinforced beams will act in between these two extremes and the γ value will depend on the stiffness of the reinforcement.

In table 2, the longitudinal lamella slip modulus based on the deformation δ at the end of the beams are compared for three different stages and in Figure 7 an example is shown. The first value corresponds to the original stiffness of the layer between the missglued lamellas before failure. It can be estimated to be 1/3 of the value that could have been expected, if the glueline would have been complete. The second value shows the modulus for the same layer after failure while the third value corresponds to the reinforced layer.

Table 2. Longitudinal lamella slip modulus $L_S = 0.5 \times F / \delta$ in kN/mm

Beam	Reinforce-ment	Original	Failed	Reinforced	Factor	Horizontal lamella slip δ
1a	1 x CFRP	406	95	223	2.35	
1b	2 x CFRP	426	28	108	3.86	
2a	4 x SFS	--	24	59	2.49	
2b		550	29	86	2.95	
3a	2 x SFS	244	26	55	2.10	
3b		492	25	60	2.38	
4a	1 x SFS	253	22	40	1.80	
4b		334	30	47	1.57	

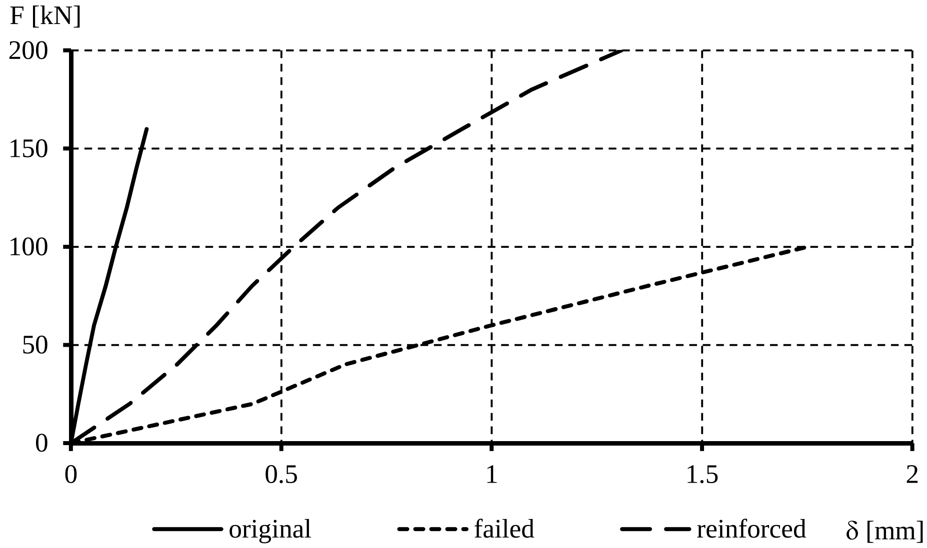


Figure 7. Example for Lamella slip δ versus Force *F*. The curves show the stiffness obtained for specimen 1b.

It can be observed that the stiffness expressed as the lamella slip modulus drops dramatically (80% to 90%) after failure as could be expected. With the different reinforcements it was possible to increase the stiffness as it is indicated by the factor in Table 2. The number of tests does not allow a statistical analysis, however the effect of an increased number of screws can be verified globally as they led to increased stiffness. The same is true for the number of CFRP sheets. Regarding the stiffness the CFRP meshes showed a good potential. However, as for the screws independent from their number, the stiffness of the reinforced did not reach the level of the original beams without failure. This means that for reinforcements of this kind the consequences regarding the bending performance as indicated further up have to be considered, even if the shear strength of the beam is completely restored.

4 CONCLUSIONS

In a test series several glulam beams with a missglued middle lamella were loaded up to failure and then reinforced with the help of different techniques. It could be shown that the reinforcements are effectively increasing the (nominal) shear strength to the required level. The high loading of the reinforced beams often lead to failures other than shear failures, so that the shear strength of the reinforcements cannot be stated discretely in most cases. Apart from evaluating different strengthening techniques the future work will therefore also concentrate on finding test set-ups that permit a higher shear loading.

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