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BEHAVIOUR OF TIMBER-GLUED PANELS STRENGTHENED WITH BFRP UNDER TENSILE LOADING

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ABSTRACT

Wood is a complex material which exhibits wide range of variation of its material properties. Adding to this variations, often found defects such as knots significantly affect the properties and performance of timber structures. Studies have been conducted focusing on strengthening of timber structures against defects such as knots. One such strengthening option for glued laminated timber beams is the fibre reinforced polymer (FRP) strengthening. This paper presents a study aimed at investigating the behaviour of timber-glued panels with Basalt FRP (BFRP) under tensile loading. The results from an experimental program using both, timber without knots and with knots are presented. A finite element model aimed at further understanding the experimental results is also presented. It was found that, BFRP can effectively enhance the load carrying capacity of damaged timber specimens. Effectiveness of BFRP increased with the BFRP cross sectional area and damage percentage of timber. It was also found that, after the failure initiation of timber, BFRP can still carry further loading, therefore resulting in more ductile behaviour compared to pure timber specimens.

KEYWORDS

Glued laminated timber, basalt fibre reinforced polymer, strengthening, tensile loading.

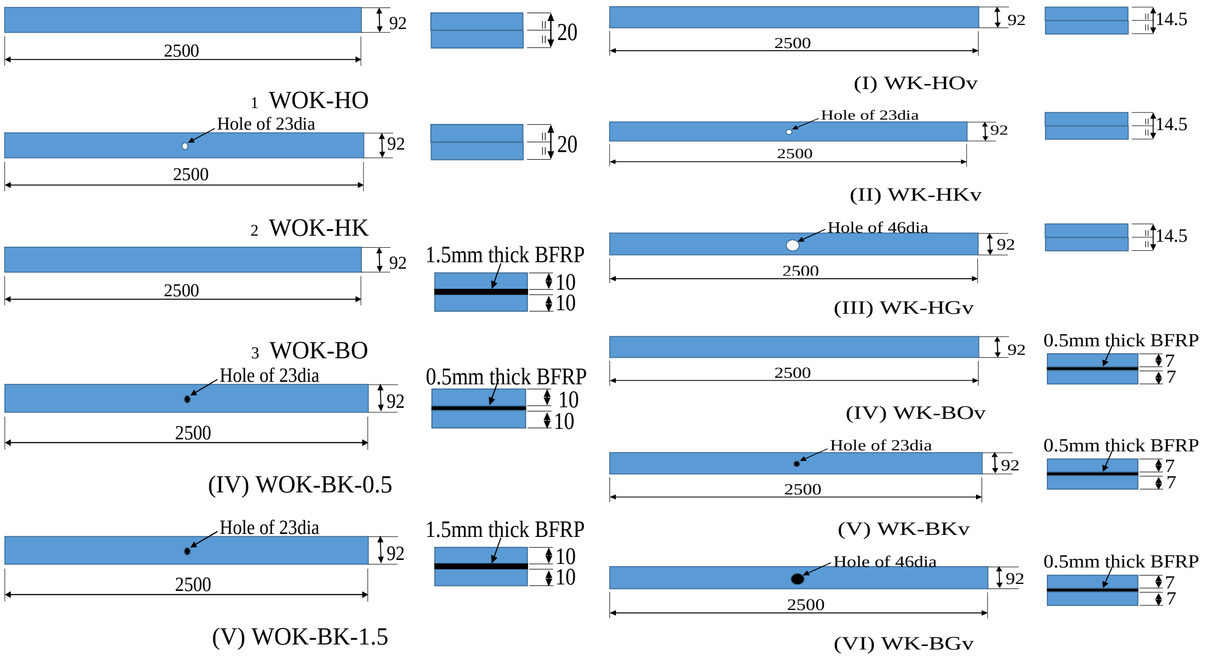
INTRODUCTION

Wood is a complex material which exhibits wide range of variation of its material properties. Adding to this variations, often found defects such as knots are probably the most critical wood anatomical feature effecting the properties and performance of timber structures. Studies have been conducted focusing on strengthening of timber structures against defects such as knots (Bulleit 1984). One branch of these studies has been focused on strengthening of the glued laminated timber beams (glulam beams) (Theakston 1965; Bulleit 1984; Moulin et al. 1990), including fibre reinforced polymer (FRP) strengthening of glulam beams (Theakston 1965; Moulin et al. 1990; Tingley 1996; Fiorelli and Dias 2003; Gentry 2011; Raftery and Harte 2011). Many studies have been carried out on the use of FRP on strengthening concrete and steel structures (Teng et al. 2002; Teng et al. 2012). However, the studies on strengthening timber structures using FRP have been rather limited. In strengthening of glulam beams FRP can be applied externally or within the laminates. The latter is more advantageous especially in terms of fire performance as the wood acts as a protective layer while in the former FRP layer will be debonded due to weak fire performance of the bonded interface. The existing studies mainly used glass FRP (GFRP) and carbon FRP (CFRP) in combination with timber. These studies have shown that both strength (Moulin 1990; Raftery and Harte 2011) and stiffness (Moulin 1990; Raftery and Harte 2011) could be greatly enhanced by using FRP in glulam beams especially where weak sections are present at the tensile laminates. In addition, commonly observed debonding failures in FRP strengthened concrete and steel structures (Teng et al. 2002, Teng et al. 2012) were not observed in the FRP strengthened glulam beams. However, the use of expensive FRPs such as CFRP or GFRP (not as much as CFRP) hinders the benefit that could be gained by using FRP in glulam beams. More economical FRPs such as basalt FRP (BFRP) may provide economically feasible solutions. This paper presents a study investigating the behaviour of timber-glued panels strengthened with BFRP under tensile loading.

EXPERIMENTAL PROGRAM

Specimen Details

The experimental program was carried out in two series. In series-I, timber plates without any knots were used to construct the test specimens (called WOK here after). Series-I aimed to investigate the effect of BFRP strengthening of WOK timber specimens. Tested specimens include WOK timber specimens (a) without BFRP and without holes (WOK-HO); (b) without BFRP and with a 23mm diameter hole (WOK-HK); (c) with a 1.5mm thick BFRP layer and without holes (WOK-BO); (d) with a 0.5mm thick BFRP layer and a 23mm diameter hole (WOK-BK-0.5); and (e) with a 1.5mm thick BFRP layer and a 23mm diameter hole (WOK-BK-1.5). All the specimens include two 10mm thick WOK timber plates and BFRP strengthened specimens included an additional BFRP layer in between the timber plates. The holes were made only in the timber plates, and the BFRP was continuous through the length. The configuration of the specimens used in Series-I is given in Figure 1a. Series-II used timber plates with knots for constructing the test specimens (called WK hereafter). Tested specimens include WK timber specimens (a) without BFRP and without holes (WK-HOv); (b) without BFRP and with a 23mm diameter hole (WK-HKv); (c) without BFRP and with a 46mm diameter hole (WK-HGv); (d) with BFRP and without holes (WK-BOv); (e) with BFRP and with a 23mm diameter hole (WK-BKv); and (f) with BFRP and with a 46mm diameter hole (WK-BGv). Specimens without BFRP had a total thickness of 14.5mm and the specimens with BFRP consist of two 7mm thick timber plates and a 0.5mm thick BFRP layer in-between the two WK timber plates. The configuration of the specimens in Series-II are given in Figure 1b.



(a) Series I

(b) Series II

Figure 1. Specimen details

Testing and Instrumentation

The experiments were carried out using a GEHZU 850 testing machine. This machine was specifically developed for tensile testing of timber lamellas and beams. The load was applied at a constant displacement rate between 0.01 and 0.02 mm/s. Strain at different locations of the specimen was measured during the testing using the attached strain gauges. Total displacement and the applied load were taken from the machine reading at continuous intervals.

EXPERIMENTAL RESULTS

Failure Mode

The failure modes of the WOK timber specimens are shown in 2(i), while the typical failure modes of WK timber specimens are shown in Figure 2(ii). The following observations were made:

- WOK-HO and WOK-BO specimens: failure initiated in the mid-span predominantly due to longitudinal tensile stresses, and soon followed by longitudinal cracks due to discontinuity of the fibre at the tensile cracked locations (Figure 2(i) a and b).
- WOK-HK, WOK-BK-0.5, and WOK-BK-1.5 specimens: failure initiated at the holes (Figure 2(i)c-e). Soon after the failure initiation, longitudinal cracks started to propagate away from the hole. After some propagation in the longitudinal direction, these cracks started moving diagonally towards the outer edge and soon were followed by the complete failure.
- WK-HOv and WK-BOv specimens: failure initiated at the knot locations, and soon followed by diagonal or longitudinal-diagonal crack resulting in complete failure (Figure 2(ii)a and b).
- WK-HKv, WK-HGv, WK-BKv, and WK-BGv specimens: similar to WK-HOv and WK-BOv specimens, failure initiated at the holes (Figure 2(ii)c-f). However, different to the WK-HOv and WK-BOv specimens, longitudinal cracks propagated towards the knots and complete failure occurred in a brittle manner when the crack reached a knot.

- All the specimens without BFRP: complete failure occurred when section is fully cracked, i.e. discontinuity of the longitudinal fibres, thus inability to further transfer the load in longitudinal direction.
- WOK-BO and WOK-BK-1.5 specimens: testing was stopped after the timber sections were fully cracked. However, at this time complete failure of the composite section was not yet reached.

(a) WOK-HO (b) WOK-BO (a) WK-HOv (b) WK-BOv

(c) WOK-HK (d) WOK-BK-0.5 (c) WK-HGv (d) WK-BGv

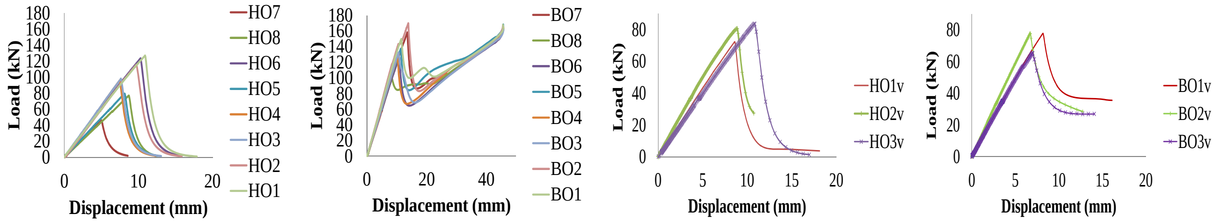
(e) WOK-BK-1.5 (e) WK-HKv (f) WK-BKv

(i) Series-I (ii) Series-II

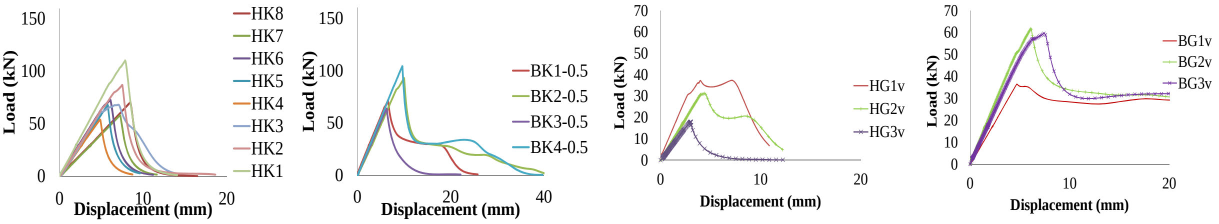
Figure 2. Typical failed specimens

Load Displacement Behaviour

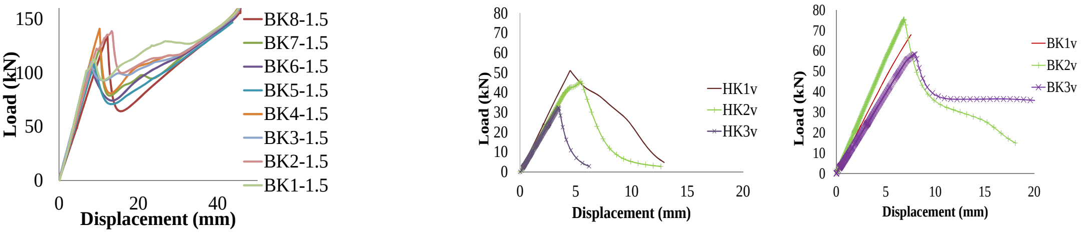
The load displacement curves of the test specimens in Series-I are given in Figure 3(i) while those of the specimens in Series-II are given in Figure 3(ii). These results are discussed in the following sections in terms of the: (a) equivalent elastic modulus, (b) ultimate load, and (c) post ultimate load behaviour.



(a) WOK-HO (b) WOK-BO (a) WK-HOv (b) WK-BOv



(c) WOK-HK (d) WOK-BK-0.5 (c) WK-HGv (d) WK-BGv



(e) WOK-BK-1.5 (e) WK-HKv (f) WK-BKv

(i) Series I (ii) Series II

Figure 3. Load displacement curves

Table 1. Experimental results

Series	Specimen type	Timber elastic modulus E_t [GPa]			Equivalent elastic modulus $E_{eq,NH}$ [GPa]			*average* E_{eq}/E_t	$\Delta E_{eq}/\Delta E_t$	Ultimate load [kN]
		Low	High	Average	Low	High	Average			
I (WOK)	HO	10.43	17.82	13.37						95.18
	HK	9.98	18.73	14.24						73.52
	BO	10.08	13.42	11.79	12.59	15.69	14.18	1.20	0.93	137.64
	BK-0.5	9.08	11.94	10.33	9.98	12.77	11.20	1.08	0.98	83.02
	BK-1.5	9.66	13.96	12.05	12.20	16.20	14.42	1.20	0.93	121.64
II (WK)	HOv	12.65	16.59	13.97						78.80
	HGv	10.08	18.17	13.48						28.79
	HKv	14.12	16.92	15.36						43.00
	BOv	11.47	17.67	14.50	12.66	18.65	15.59	1.07	0.97	73.65
	BGv	10.56	17.21	14.21	11.78	18.20	15.31	1.08	0.97	52.60
	BKv	11.91	13.53	12.55	13.08	14.65	13.70	1.09	0.97	67.19

(a) Equivalent elastic modulus

The elastic modulus of the timber as well as the equivalent elastic modulus of the BFRP-timber hybrid specimens are given in Table 1. The results shown in Table 1 are the average of the results in each specimen type. Equivalent elastic modulus were always higher than the timber elastic modulus. This is however, no surprise as BFRP has a much higher elastic modulus than timber. Significant variations in the timber elastic modulus of each specimen type was observed. For the BFRP-timber composite specimens the variation of the equivalent elastic modulus was lower than the variation of timber elastic modulus. For WOK specimens, when a 1.5mm thick BFRP layer was used the reduction of the variation was about 7% while when a 0.5mm BFRP layer was used the reduction was about 2.6%. For WK specimens, with the 0.5mm BFRP layer the reduction in the variation was about 3.4%. This increase in the efficiency of the WK specimens compared to the WOK timber specimens is believed to be mainly due to the smaller thickness of the timber plates, thus increasing the BFRP/timber area ratio.

(b) Ultimate load

The average ultimate loads of the Series-I and Series II specimens are given in Table 1. For both WOK-BO and WOK-BK-1.5 specimens, the first peak load was taken as the ultimate load (Figure 3(i)). The second peak load of these specimens are purely due to the strength of the BFRP layer, and full failure of the timber can be expected after the first load drop. Therefore, the ultimate load of the composite section is considered to be the first peak load. The ultimate load increase of the BFRP strengthened specimens compared to their pure timber specimens were:

- 45% for WOK-BO specimens and -7% for WK-BOv specimens. The reduction in the latter is believed due to lower strength timber in those specimens,
- 13% for WOK-BK-0.5 specimens and 56% for WK-BKv specimens. This indicates that effectiveness of BFRP increased when timber specimens with knots were used.
- 65% for WOK-BK-1.5 specimens. This indicates that effectiveness of BFRP strengthening increased with the thickness of the BFRP sheet.
- 83% for WK-BGv specimens. This indicates that effectiveness of the BFRP increased when the diameter of the hole becomes larger (compared to 56% increase in WK-BKv specimens).

(c) Post ultimate load behaviour

Significant differences were observed in the post ultimate behaviour between the BFRP strengthened and pure timber specimens (Figure 3). The key differences are listed below:

- All the pure timber specimens showed rapid loss in load carrying capacity, showing the brittle nature of the tensile failure in timber.
- All the BFRP-timber composite specimens, some load retention was observed in the post ultimate load curve.
- Specimens with a 1.5mm BFRP layer (i.e. WOK-BO and WOK-BK-1.5) resulted in a sudden load drop soon after the ultimate load, and then continued to increase until the experiments were stopped (Figure 3(i)b and e). The stiffness of the secondary curve was much smaller than the initial stiffness. This is due to the loss of timber section, and load increase is only due to the residual capacity of BFRP.
- In WK specimens with BFRP (i.e. WK-BOv, WK-BGv and WK-BKv), after the first load drop no further increase in load resulted, but a long ductile plateau was observed. Inability to further increase the load is

believed due to the lower percentage of BFRP volume in the cross section. Nevertheless, due to relatively weaker timber specimens with many knots and a hole, BFRP is believed to become more active in resisting the load after the first failure.

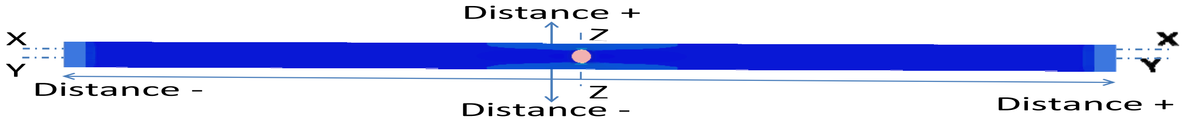
FINITE ELEMENT ANALYSIS

Finite Element Model

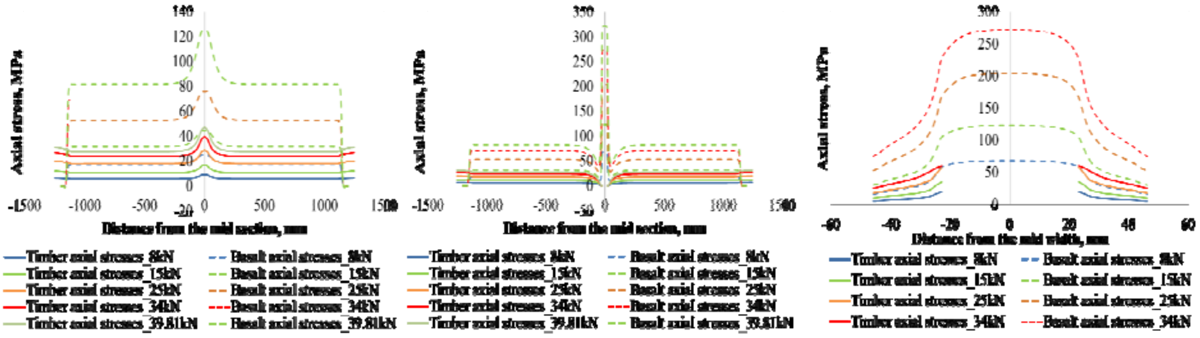
In order to better understand the behaviour of BFRP strengthened timber specimens, 3D finite element modelling was carried out. The elastic modulus of the timber in the fibre direction was taken from the average experimental measurements of the specific specimen category. The elastic modulus of the transverse direction (i.e. tangential direction) and the through thickness direction (i.e. radial direction) was calculated according to the specifications given in EN 338:2010. Hill failure criterion was used in modelling the damage initiation of timber (Hill 1948). The damage evolution of the timber was modelled assuming that damage is characterized by the progressive degradation of the material stiffness, leading to material failure. Damage evolution was defined using fracture energy criterion available in Abaqus (Abaqus 2011) to avoid the mesh dependencies. The material behaviour of the BFRP was assumed to be elastic until failure. BFRP was modelled as an orthotropic material.

Results

Due to space limitation, only the axial stress distributions will be discussed in this section. The axial stress distributions along different sections of the BFRP strengthened timber specimens with holes are given in Figure 4. As the stress distributions vary at different sections, the variations along three different sections as shown in Figure 4a, i.e. longitudinal section through solid timber region (section X-X), longitudinal section through the centre of the hole (section Y-Y) and transverse section through the centre of the hole (section Z-Z), were compared.



(a) Nomenclature



(b) Axial stress distributions on section X-X
(c) Axial stress distributions on section X-X
(d) Axial stress distributions on section X-X

Figure 4. Axial stress distribution along different sections

From the axial stress distributions obtained from the FE model, following can be observed:

- Comparing the stress distributions through solid timber (i.e. section X-X) and stress distributions through solid timber and hole (i.e. section Y-Y), it is clear that the BFRP was significantly more active through the hole region in transferring the load. The BFRP stresses in the solid timber regions were not so high.
- Looking at the stress variations near the hole region (i.e. section Z-Z), it can be seen that even though BFRP in the hole region carried a higher stress than the solid timber region, at the time of failure initiation in timber, the BFRP stress was only 23% of its strength.

DISCUSSION

From the experimental results of WOK-HO and WOK-BO, latter resulted in 45% load increase. However, when WK-HOv and WK-BKv specimens were compared, BFRP strengthening resulted in a 7% load reduction. This reduction is obvious due to the lower strength of the timber. However, it also indicates that due to high strength variation of timber, pure comparison of the experimental results may not give correct measurements of the efficiency of BFRP strengthening. FE results, with more well behaved material properties of timber showed that, BFRP contribution (with 0.5 BFRP thickness) in solid timber sections are minimal. However, with the increase in BFRP cross sectional area to timber cross sectional area ratio, increase in the BFRP contribution can be expected.

Comparing the results of specimens with holes, clear increase in the load carrying capacity was observed. The percentage increase became large when the area of the hole increased. Effectiveness of BFRP strengthening in terms of load carrying capacity also increased when knots were present in timber. From the FE results, it could be clearly seen that, BFRP in the hole region carried significantly high stresses, thus contributing towards increasing the load carrying capacity of such strengthened specimens.

It was also seen that the BFRP stress, at the time of failure initiation in timber, was well below its strength. Therefore, even after the failure of timber BFRP is capable of resisting the load. The higher the thickness of the BFRP layer, the higher will be the load resistance. This explains the post ultimate load increase behaviour we observed in the experiments. The sudden load drop is due to the sudden energy release as a result of the brittle failure of timber.

CONCLUSIONS

This paper presents a study aimed at investigating the behaviour of timber-glued panels strengthened with BFRP. Experimental results from specimens made using timber panels without any knots as well as from specimens made using timber panels with knots are presented. Results from a finite element model to further investigate the behaviour of such timber-glued panels with BFRP, are also presented.

It was seen that, when the BFRP cross sectional area is small, BFRP strengthening of solid timber sections may not have a significant effect on increasing the load carrying capacity. However, the contribution of BFRP increases with the increasing BFRP cross sectional area. In addition, BFRP strengthening could significantly enhance the load carrying capacity of timber with damaged cross sections, such as holes. At the time of timber failure, BFRP still possesses high residual capacity, thus may resist further loading.

This work was carried out as the first step towards investigating the behaviour of BFRP strengthened glulam beams. Further research is needed in understanding and modelling the behaviour of BFRP strengthened glulam beams. Such a study is currently underway at ETHZ.

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