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Behaviour of basalt fibre reinforced polymer strengthened timber laminates under tensile loading

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ABSTRACT

Timber has been widely used all over the world as a structural material. The defects such as knots could significantly reduce the mechanical properties of timber, thus significantly affecting the performance of timber structures. Existing studies have demonstrated the ability to use fibre reinforced polymer (FRP) composites to increase the strength, stiffness and the ductility of glulam beams. Such strengthening however, often becomes uneconomical due to higher FRP material volume and the use of expensive FRPs such as carbon FRP and glass FRP. Oppose to current approaches of strengthening glulam beams using FRPs, use of minimal amount of FRPs to reinforce weaker sections, thus reducing the variability and resulting in a higher load carrying capacity, may provide better economical solutions. In addition, the use of cost effective FRPs such as basalt FRP could further reduce the costs.

This paper presents an experimental and theoretical investigation aimed at understanding the behaviour of BFRP-strengthened timber sections. The experimental component of the study presented consists of 54 tensile specimens with and without BFRP. In some of the specimens, holes were cut in the mid span to simulate a defect. The experimental study showed that BFRP increases both the strength and stiffness of the timber specimens. Findings of an FE study of BFRP-strengthened timber specimens are also presented. Stress and strain distributions of the specimens, obtained from the FE study are presented and discussed. Based on the findings of the FE study, and idealized strain distribution is presented. This idealized strain distribution was then used to develop analytical models for an equivalent elastic modulus of the regions with defects. In addition, analytical models are also presented to predict the ultimate load carrying capacity of the pure timber and BFRP-strengthened timber specimens. The predictions agreed well with the experimental results.

The analytical models were then used in Monte Carlo simulations to demonstrate the effectiveness of the BFRP strengthening. It was found that BFRP could yield significant benefits in terms of increasing the strength and stiffness for the timber sections with defects.

1. Introduction

Wood is a complex material which exhibits a 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. Many attempts had been made to study the effect of such defects in the behaviour of timber structures under different load applications [1–3]. Preliminary models have also been developed to estimate the strength and elastic modulus of the timber sections with defects [1]. Numerical modelling of the clear wood itself is challenging due to the highly anisotropic nature of wood material. Adding to this, the existence of the defects has made numerical modelling of the timber structures quite complex. Even though the understanding of the behaviour of timber together with defects is still a challenge faced by the researchers and moreover practitioners, timber has been used in the construction industry for many years. While research is underway on understanding the effects of defects, studies have been conducted focusing on strengthening of timber structures against defects [4]. One branch of these studies has been focused on strengthening of the glued laminated timber beams (glulam beams) [4–6].

Fibre reinforced polymer (FRP) materials have been used extensively in strengthening concrete, masonry and steel structures [7–11], and to a lesser extent in strengthening timber structures [12–17]. The use of FRPs in strengthening of the structures have been mainly due to its superior mechanical properties compared

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to little weight. In addition, comparatively low installation costs are also a major factor driving the choice of FRP strengthening systems over the other conventional strengthening systems such as use of steel plates. Flexural strengthening of beams has been done for both concrete beams and steel beams using externally bonded FRP plates [7–10].

The use of FRPs in strengthening of glulam beams as well as solid timber beams have been explored [5,6,18–25]. The application of FRP externally as well as the application of FRP within the laminates of glulam beams have been studied. 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 [6,18,20,25] and stiffness [6,18,25] could be greatly enhanced by using FRP in glulam beams especially where weak sections are present at the tensile laminates. Additionally, large strain capacities before failure were observed [6,21]. Tingley [18] showed that use of FRP in tension zones could also bring additional benefits such as the ability to use low-grade timber in place of high-grade timber and reduction of variability.

The use of expensive FRPs such as CFRP may hinder the benefit that could be gained by using FRP in glulam beams. More economical FRPs such as basalt FRP (BFRP) [26] may provide economically feasible solutions. However, the work on the use of BFRP in glulam beams have been very limited [27,28]. In addition, most of the existing studies have focused on demonstrating the effectiveness of FRPs in increasing the strength, stiffness and the ductility of the glulam beams. Therefore, such studies often resulted in having to use high volumes of FRP materials (typically thicknesses of 6 mm or above), thus often found to be costly [29]. Localized effects of FRP strengthening on weak sections such as sections with defects have not been paid much attention to. The ability of FRP to reinforce weaker sections, thus reducing the variability and resulting in a higher load carrying capacity may provide more economical solutions than relying on FRP to carry significant loads as expected in typical flexural strengthening of glulam beams. In addition, analytical models for ultimate load carrying capacity of FRP-strengthened timber members, that are capable of capturing the material and geometric property variations of timber, are necessary to adequately quantify the effectiveness of FRP strengthening. Addressing these needs and exploring the use of BFRP in glulam beams, this paper presents an experimental and theoretical investigation on the behaviour of timber-glued panels strengthened with BFRP under tensile loading.

2. Experimental program

2.1. 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. For the ease of reference, hereafter these timber specimens without knots are referred to as control timber specimens. Series-I aimed to investigate the effect of BFRP strengthening of control timber specimens. Tested specimens include control timber specimens (a) without BFRP and without a hole (i.e. an artificial defect) (HO); (b) without BFRP and with a 23 mm diameter hole (HK); (c) with a 1.5 mm thick BFRP layer and without a hole (BO); (d) with a 0.5 mm thick BFRP layer and a 23 mm diameter hole (BK-0.5); and (e) with a 1.5 mm thick BFRP layer and a 23 mm diameter hole (BK-1.5). All the specimens include two 10 mm thick timber plates and BFRP strengthened specimens included an additional BFRP layer in between the timber plates. The holes, created to represent weak sections, 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 Fig. 1a and Table 1.

Series-II used timber plates with knots for constructing the test specimens. For ease of reference, hereafter the specimens with knots are referred to as defected timber specimens. Tested specimens include defected timber specimens (a) without BFRP and without a hole (HOv); (b) without BFRP and with a 23 mm diameter hole (HKv); (c) without BFRP and with a 46 mm diameter hole (HGv); (d) with BFRP and without a hole (BOv); (e) with BFRP and with a 23 mm diameter hole (BKv); and (f) with BFRP and with a 46 mm diameter hole (BGv). Specimens without BFRP had a total thickness of 14.5 mm and the specimens with BFRP consist of two 7 mm thick timber plates and a 0.5 mm thick BFRP layer in-between the two timber plates. The configuration of the specimens in Series-II is given in Fig. 1b and Table 1. The BFRP used in the current study had an elastic modulus of 46 GPa and ultimate strength of 1200 MPa (according to manufacturer data) parallel to the fibre direction. Elastic modulus of timber was measured on all specimens during the testing while the strength of timber was measured on pure timber specimens.

2.2. Testing and instrumentation

The experiments were carried out at the structures laboratory of the Swiss Federal Institute of Technology, Zurich (ETHZ) using a testing machine (GEHZU 850) 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. These strain gauge locations are given in Fig. 2. Total displacement and the applied load were taken from the machine reading at every 0.5 s intervals.

2.3. Interpretation of the experimental results

As the timber specimens are expected to have large variation of the material properties from one specimen to another, direct comparisons may not accurately reflect the effects of strengthening. Therefore, following procedure was used to calculate the elastic modulus and the equivalent elastic modulus of the specimens for comparison purposes.

2.3.1. Calculating the elastic modulus of the timber

The strain readings were taken from the strain gauges attached to the top and bottom of the timber plates. When there is no BFRP used, then the calculation of the timber elastic modulus in the specimens without holes is straightforward, i.e. load divided by the product of the cross sectional area of timber (A_t) and measured strain (ε). When basalt fibre is used, assuming uniform strain distribution of the cross section, the elastic modulus of timber can be calculated as:

$$E_t = \frac{P - E_f \varepsilon A_f}{\varepsilon A_t} \tag{1}$$

where A_f is the cross sectional area of BFRP, A_t is the cross sectional area of timber, E_f is the elastic modulus of BFRP, E_t is the elastic modulus of timber, P is the applied load, and ε is the measured strain.

For the timber specimens with a hole, given the strain gauges are attached a reasonable distance away from the mid span, Eq. (1) can still be used to calculate the timber elastic modulus.