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Flexural strengthening of LVL beam using CFRP

Mahbube Subhani [a,*], Anastasia Globa [b], Riyadh Al-Ameri [a], Jules Moloney [b]

[a] School of Engineering, Deakin University, Waurn Ponds, Victoria 3217, Australia
[b] School of Architecture and Built Environment, Deakin University, Geelong, Victoria 3220, Australia

HIGHLIGHTS

- Bending tests on LVL beams using two configuration of externally bonded CFRP.
- Effectiveness of CFRP is limited by the fibrous failure of LVL under tension.
- Analytical model considering non-linearity of wood under compression.

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ABSTRACT

Laminated veneer lumber (LVL) is one of the major construction material in Australia as well as other parts of the world. To increase its load carrying capacity, various internal and external methods of applying fibre reinforced polymer (FRP) can be found in the literature. In this article, carbon FRP (CFRP) is used externally on the tension side of LVL beams to enhance its flexural capacity. Two types of bonding arrangements are considered in this study, and the improvement in terms of ductility, stiffness and ultimate load carrying capacity against control beams are investigated. In addition, the experimental data is verified using two analytical models. One of the analytical models considers elastic-plastic behaviour of timber in compression while the other contemplates the non-linear behaviour. The advantages and accuracy of both models are assessed for the application in the design of a CFRP-LVL composite beam.

1. Introduction

Structural application of timber materials dated back centuries and have also been increasing due to easy handling and economical and sustainable way of producing structural components. In recent decades, glue laminated timber (glulam) and laminated veneer lumber (LVL) have gained popularity because of their improved engineering properties. Even though these products are better compared to conventional timber beams in terms of the flexural or shear strength, further improvements may be required to make these products eligible for multi-storey or large span construction. In recent years, fibre reinforced polymer (FRP) was found to be an effective tool for strengthening of timber beams, which resulted in reduce cross-section of the structural component, making it useful for large span construction. On the other hand, a number of old and/or historical timber structures can be found all over the world which require different retrofitting technique in order to enhance one or more properties of a timber beam. Accordingly, FRP-timber composite beams are accepted as a solution for both strengthening and rehabilitation of timber beams. Different FRPs are used in order to achieve this goal. This includes glass fibre reinforced polymer or GFRP [1–3], carbon fibre reinforced polymer or CFRP [4–7] and basalt fibre reinforced polymer or BFRP [2,8–10].

Along with various FRPs, different ways of implementing FRPs on timber beams can also be found in literature. Such as, externally bonded FRP strip in one or more layers [4,6,7,11,12], internally embedded rods [2,13,14], embedded FRP plates [3,15], externally bonded FRP sheet as U-wrap [8,9], horizontally near surface mounted (HNSM) FRP cords in one or more layers [5,7,16], vertically near surface mounted (VNSM) FRP cords/plates [16–18], L-wrap at two corners of the beam [19], FRP pins [20] and combination of HNSM and VNSM [1]. In addition, these studies focuses on different properties of the beams which includes flexural stiffness, ultimate bending moment capacity, ultimate load, shear strength, bearing strength, etc. in order to evaluate the improvement on these properties of a FRP-timber composite beam. While various FRP and different strengthening scheme have their own advantages and limitations, the easiest and quickest way to strengthen a timber beam in tension is by applying the FRP plates

* Corresponding author at: Building KE, School of Engineering, 75 Pigdons Road, Waurn Ponds, Victoria 3216, Australia.
E-mail address: mahbube.subhani@deakin.edu.au (M. Subhani).

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or sheets externally. It can be noted here that these investigation are conducted mainly on glulam beams and not on the LVL ones.

The analytical model to predict the ultimate load or moment carrying capacity of a CFRP-timber composite beam depends on the failure mode of the composite beam [21]. One of the most common mode of failure is initiated by the cross-grain tensile rupture of timber beams. To model this type of failure mode, both analytical and numerical works have been reported. One of the effective approach is the cohesive zone model adapted in [4,6,22]. However, the cohesive zone modelling is only solved numerically due to its complexity. Classical strength of materials approach is found to be another appropriate method which is used by numerous researchers for analytical and numerical validation. In these models, the stress strain relationship of the composite beams are taken into account. It is well established that the FRPs behaves linearly elastic till failure. However, there are different stress-strain relationships available in relation to the tensile and compressive behaviour of timber materials. Most of the literature reported the stress-strain relationship of timber under tension in the direction parallel to the grain as linearly elastic till failure [8,12,17,23]. Nevertheless, linear softening [24] and exponential softening [25] after reaching the maximum tensile strength (parallel to the grain) are also suggested and solved numerically. However, the strain difference at the maximum tensile strength and ultimate strain (in tension) is negligible and therefore, can be ignored in the design.

In contrast, various constitutive models adopted different approaches to deal with the non-linear stress-strain relationship of timber under compression in the direction parallel to the grain. A bi-linear model suggested [23] a linear elastic behaviour until yield compressive strength followed by a linear softening behaviour or negative slope until failure. This model was adopted and verified experimentally by a number of researchers [13,26,27]. Nonetheless, a more simplified linearly elastic followed by perfectly plastic model is also employed in numerous studies [8,11,17,18,28] which was found to be effective as well. A linear elastic until yield strength followed by a quadratic curve is proposed in [12]. However, the parameters related to the quadratic equation is determined empirically and may not be representative of all the timber beams. A segmented (three segments) non-linear compressive stress-stress diagram was recommended in [29]. Although these models are successfully implemented, they require two or three different equations corresponding to the elastic and post-elastic behaviour. Therefore, a single non-linear equation that combines both the state of timber (under compression) can be useful for designing a CFRP-timber composite beam. Glos [30] developed a single equation to represent the stress-strain relation of timber in compression which is further simplified in [24]. The latter study also compared the proposed equation against the former one with satisfactory outcome.

In this article, two types of externally bonded CFRP are applied on LVL beams, and their efficiencies are compared in terms of maximum load carrying capacity, flexural stiffness and ductility. These two types include the application of CFRP sheet on the soffit of the beam and as a U-wrap on the tension side of the beam. Three samples are tested for each group and compared against three control beams without any reinforcement. In addition, the experimental values are verified theoretically concerning ultimate moment carrying capacity. Again, two analytical models are used to verify the experimental data, one of which is based on the commonly used elastic-plastic model while the other considers the non-linear relationship of timber in compression. The accuracy and merits of these two analytical models are pointed out for the design of a CFRP-LVL composite beam.

2. Experimental program

The experimental investigation was conducted in three groups, one of which is the control group while the other two belongs to two different strengthening schemes. There are three samples for each scheme. The detail of the experimental program is described in the following sections.

2.1. Materials

2.1.1. Timber

Laminated veneer lumber (LVL) beams are used in this study. The grade of the LVL beam is F17 [e-beam⁺]. According to Australian Standards (AS 1720.1), the material properties of this LVL, obtained from the manufacturer (Hyne Timber), is presented in Table 1. The cross-section of the LVL is 45 mm (width) x 240 mm (height). The average moisture content of this LVL is approximately 10%. The length of the beam is 2.4 m with a clear span of 2.1 m.

2.1.2. CFRP

Sika-Wrap 230 C unidirectional CFRP sheet is used for the tests. The thickness, average modulus of elasticity and mean tensile strength of the CFRP sheet obtained from manufacturer data sheet are 0.131 mm, 216,000 MPa and 3176 MPa, respectively. The rupture strain of the CFRP is 1.8%. A 1.5 m long CFRP is attached along the length of the beam (Fig. 1).

2.1.3. Adhesive

Two parts Sikadur 330 epoxy, mixed with 3:1 ratio, was used to apply on the beam specimens in order to attach the CFRP. The tensile strength, flexural and tensile modulus of elasticity of Sikadur 330, obtained from the manufacturer data sheet, are 30, 3800 and 4500 MPa, respectively.

2.2. Fabrication of test specimen

A total of nine LVL beams are used. The first three beams are the control ones (denoted as LVL_C) where the flexural capacity of the LVL beam is investigated. The CFRP is applied on the LVL beams by two techniques. The first strengthening scheme comprises of CFRP strip (denoted as LVL_S) applied on the soffit of the beam with an equal width of the LVL beam (Fig. 1(a)), while in the second strengthening technique, CFRP is wrapped (denoted as LVL_U) around the tension side of the LVL beam's cross-section (Fig. 1(b)). The leg of the U-wrap in the latter technique is extended up to the mid-height of the LVL beam. Three samples were prepared for each of the strengthening technique. The samples preparations are depicted in Fig. 2(a) and (b).

The surface of the timber was prepared prior to bonding by using a hand held disc sander using 120 grit sandpaper on high speed. Sanding was undertaken in a prescribed and repetitive approach for 20 seconds on each timber sample. Wet lay-up procedure is used to apply the CFRP to the pre prepared LVL surfaces.

Table 1
Material properties of F17 LVL.

Characteristic strength (MPa)				Modulus of elasticity (MPa)	Density (kg/m^3)
Bending	Shear	Tension	Compression		
62	5.3	34	47	14000	650