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# DETERMINING OPTIMUM CFRP LAMINATE THICKNESS FOR A MOBILE FOREST BRIDGE GIRDER

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The objective of this study was to determine the optimum thickness of carbon fibre reinforced polymer (CFRP) laminate needed to reinforce a 10 m span of girder in a modular and mobile forest bridge. Finite element analysis was carried out using the Autodesk Mechanical Simulation program. The simulation was carried out by varying CFRP laminate thickness and recording the resulting stress, strain, deflection and safety factor values. The CFRP of 6 mm thickness was selected to reinforce the 10 m timber beam due to stronger and stiffer behaviour of the material under applied loading. Intersection point of stress values trend between the top and the bottom side of timber beam indicated that 6 mm was the optimum thickness for the specimen. Reinforced 2 m timber beams recorded decreased stress on the top and displacement at the bottom side of specimens by up to 33.43 and 61.56% respectively. Knowing the optimum thickness of CFRP laminate for its intended purpose would allow the structure to be designed and fabricated at its lightest weight without compromising the capability of the structure during applied loading. The proposed modular and mobile forest bridge is expected to solve accessibility problems for post-harvesting research activities.

Keywords: Finite element analysis, static stress, flexural bending, displacement, safety factor

## INTRODUCTION

Timber extraction, particularly with the construction of logging roads, significantly damages the forest environment (Hasmadi et al. 2010). Careful planning and construction of these forest roads, including stream crossings is very important in reducing their environmental impact (Brinker & Taylor 1997). Conventionally, bridges and culverts have been built to cross streams, but these permanent structures are costly and negatively impact water quality through erosion and sedimentation. Portable bridges are increasingly utilised as temporary stream crossing structures due to their relatively low construction and maintenance costs, ease of installation and transportation, and reduced effects on water quality and the environment (Gangarao & Zelina 1989, Hafizah et al. 2014). Modular prefabricated bridges may be manufactured as a composite of materials comprising timber, aluminium and fibre reinforced polymer (FRP), and are designed to be light and portable, yet strong and durable (Tugilimana et al. 2017). Carbon FRP (CFRP) and glass FRP (GFRP) are commonly used reinforcement materials, with CFRP reinforced timber shown to have flexural strength up to eight times that of steel reinforced timber. In analysing the properties of these composites, timbers are modelled as an orthotropic material with cylindrical or rhombic symmetry, following the assumption that composite properties are almost the same in any direction perpendicular to fibres following the assumption that composite properties are almost the same in any direction perpendicular to fibres (Davalos et al. 1991).

The present study analysed the flexural behaviour, under different point loading intensities, of timber beams wrapped with CFRP of different thicknesses. The objective of the study was to predict the optimum thickness of CFRP for a 10 m modular girder that would meet weight bearing requirements while being as light as possible. Finite element analysis (FEA), which is a widespread technique in structural analysis, e.g. modelling interfacial stresses in FRP-reinforced concrete hybrid beans and predicting performance of FRP-to-timber bonded interfaces, was used in the present study to calculate stress, strain, displacement and safety factor values (Yang et al. 2004, Wan et al. 2014).

## MATERIALS AND METHODS

A CFRP-wrapped timber beam girder with aluminium connector was subjected to a bending test to validate pre-processing for the simulation. The three-point bending test was set up with two support points and one load point, and four linear variable differential transducers (LVDTs) installed to measure deflection (Figure 1). The bending test was carried out at a loading rate of 2.81kN min$^{-1}$.

Maximum deflection (104.817 mm) was recorded by LVDT 4 at the mid-span load point and also predicted by FEA (101.366 mm). The results showed that FEA of the girder could predict the deflections of that structure with acceptable accuracy (error less than 5% for both methods), when applying the given boundary conditions and material properties.

Modelling and assembly of the timber beam and connector 3D models was performed in AutoCAD®. Both timber and aluminium were assigned as brick elements in the simulation program (Kim & Andrawes 2017). Material properties previously established for Western white pine, aluminium and CFRP (Table 1) were used as input in the FEA simulation.

A 3D model of two 2 m long timber beams and one connector was assembled (Mamat 2018, Figure 2a). The CFRP laminate was first bonded to the bottom flange of the beams and then the aluminium connector was applied to join the two beams together (Figure 2b). During bending, CFRP is assumed to react as a linear elastic while Young's modulus, tensile

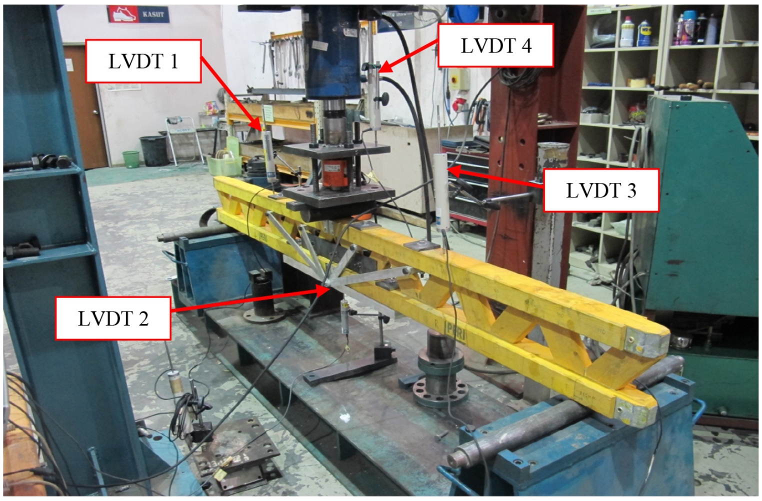

**Figure 1** Specimen with LVDTs ready for bending test

**Table 1** Material properties for timber, aluminum and CFRP

| Material properties | Orthotropic | | Isotropic | |
|---|---|---|---|---|
| | Timber | | Aluminium | CFRP |
| Mass density (kg m$^{-3}$) | 425.338 | | 2700 | 1900 |
| Modulus of elasticity (MPa) | Local axis 1 | 11100.559 | 68900 | 181000 |
| | Local axis 2 | 868.739 | | |
| | Local axis 3 | 420.580 | | |
| Shear modulus of elasticity (MPa) | Local plane 12 | 577.091 | 26000 | Nil |
| | Local plane 13 | 532.965 | | |
| | Local plane 23 | 55.848 | | |
| Poisson's ratio | Local plane 12 | 0.329 | 0.33 | 0.28 |
| | Local plane 13 | 0.344 | | |
| | Local plane 23 | 0.410 | | |

Timber (Forest Product Laboratory 1999), Aluminium (Dey et al. 2017), CFRP (Nor et al. 2010) failure strain and the stress-strain relationship for timber is assumed to be uniaxial (Plevris & Triantafillou 1993).

All parts of the specimen were set as surface type contact, i.e., the components in the model were separated and allowed to slide. However, the CFRP laminate was set as bonded to the timber beam for reinforcement following Selvaraj et al. (2016). In the FEA, a downward maximum nodal force of 29.43 kN (3000 kg) was assigned. This specified load was based on gross vehicle weight of a four-wheel-drive, with a maximum payload of 1060 kg. Five load values were inserted into the simulation: 5.89, 11.77, 17.66, 23.54 and 29.43 kN. The applied load was placed at the beam mid-point (Figure 2c).

Meshing of the beam model was carried out after all boundary conditions were defined. The meshing process generated nodes and elements needed by the simulation program to compute the reactions to applied loading. The nodes were assigned according to the two-point bending test setup. A complete meshed specimen of the two 2 m CFRP-reinforced timber beam joined with the aluminium connector is shown in Figure 3.

The bending simulation was then carried out in Autodesk® Mechanical Simulation on 3D models with CFRP thicknesses of 2, 4, 6 and 8 mm. The 3D models developed were assumed to be geometrically linear and respond to the system with linear elasticity (Minalu 2010). The reinforcement between timber and CFRP

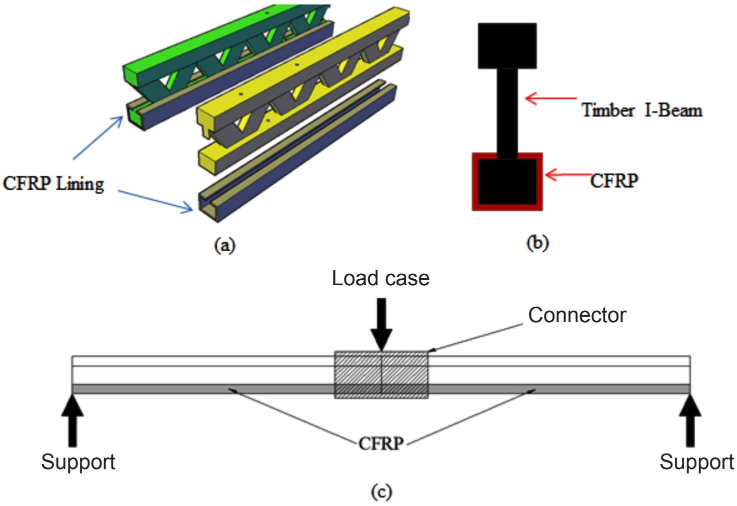

**Figure 2** CFRP-wrapped timber beams and connector (a) 3D model, (b) cross section and (c) midspan load application

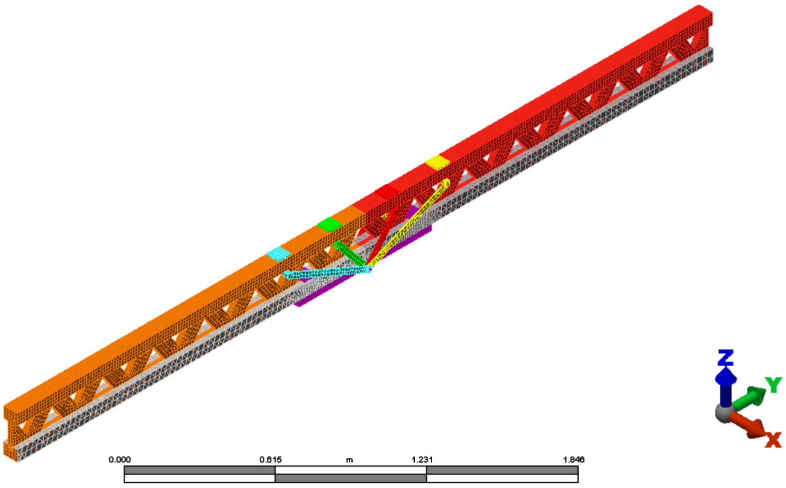

**Figure 3** Specimen completed pre processing

laminates was assumed to be perfectly bonded (Almusallam et al. 2015). The results generated by the static stress analysis were assumed to be not sensitively dependant on the selected mesh size (Park et al. 2010). The resulting stress, strain, displacement and safety factor values under different load cases were recorded and analysed to determine the optimum CFRP thickness for the girder. Maximum stress and strain values were plotted for the CFRP-wrapped specimens and resilience values were calculated from the area under the stress-strain line. The modulus of resilience is the greatest amount of strain energy per unit volume that can be stored in a member without exceeding the limit of proportionality up to the elastic limit of the member (Megson 2005). Safety factor analysis was carried out only on the aluminium connector because its isotropic and homogeneous material characteristic could be defined.

Additionally, compression and tension stress, i.e. stress at the top and bottom sides respectively, was recorded using the manual probe provided in the simulation program and compared to that of the control (no CFRP reinforcement). The aluminium connector was set as invisible to allow the probe to reach the desired nodes on the CFRP surface. On top side, stress was recorded at the specimen mid-span.

## RESULTS AND DISCUSSION

### Stress, strain, resilience and safety factor values of the reinforced specimens

From the simulation, it was observed that the locations of maximum and minimum stress and strain varied in the specimens as a result of reinforcement with different thicknesses of CFRP laminate. Figure 4 shows that the maximum stress was highest in the 6 mm-wrapped specimen and the graph slope closer to the Y-axis exhibited stronger and stiffer behaviour, followed by the 2, 8 and 4 mm-wrapped specimens (Schorer et al. 2008). The 6 mm-wrapped specimen also had the highest resilience value (3.7), showing that the material can absorb energy without suffering any damage followed by the 2, 8 and 4 mm-wrapped specimens (3.2, 2.5 and 2.4 respectively) (Roylance 2001). Similarly, safety levels in descending order were 6, 2, 8 and 4 mm-wrapped specimens, which recorded safety factor values of 39, 41, 61 and 65 respectively. In normal practice, a higher safety factor value indicates a higher capability of the specimen to react to the applied loading. However, in the modular bridge system, lower safety factor values recorded for the aluminium connector indicated that the stress was successfully transferred to the supports. The safety factor value of the 6 mm-wrapped specimen was 617.14% higher than that of the plain specimen. A surface area of 0.2224 m$^2$ (80%) of the beam wrapped with CFRP in the study doubled the coverage reported in a study by Almulsallam et al. (2015).

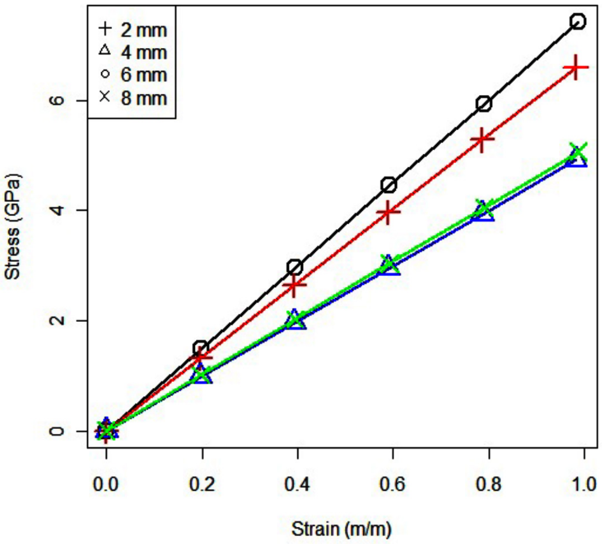

**Figure 4** Stress-strain plot for different thickness of CFRP reinforcement

### Stress at top and bottom side of reinforced and plain specimens

Compression stress positively correlated with the thickness of CFRP reinforcement at the bottom flange of the timber I-beam (Figure 5). The beam became increasingly rigid and less elastic as CFRP thickness increased. Conversely, tension stress decreased as CFRP thickness increased because loading stress was successfully transferred to the supports. Tension stress in the CFRP-wrapped beam was 33.43% lower than that recorded for the plain beam. This was better than the 25% higher maximum ultimate load reported by Selvaraj et al. (2016) for a CFRP-wrapped beam with two uni- and one bi-directional wrap layers in a closed configuration. The curves for compression and tension stress intersect at 6 mm CFRP thickness, where stress at the bottom and

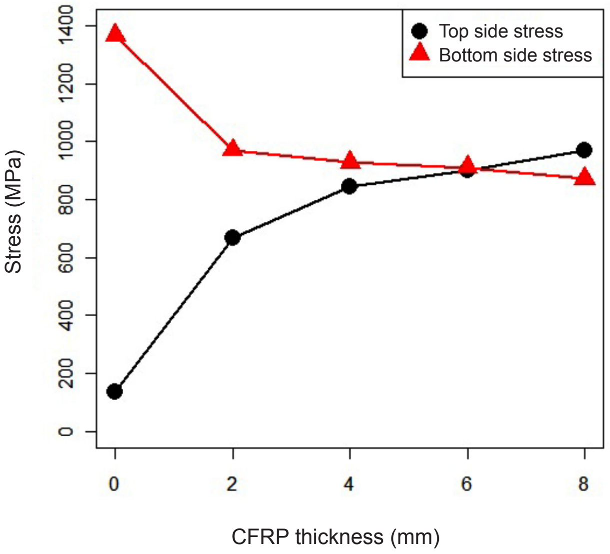

**Figure 5** Stress at top and bottom sides of plain and reinforced specimens

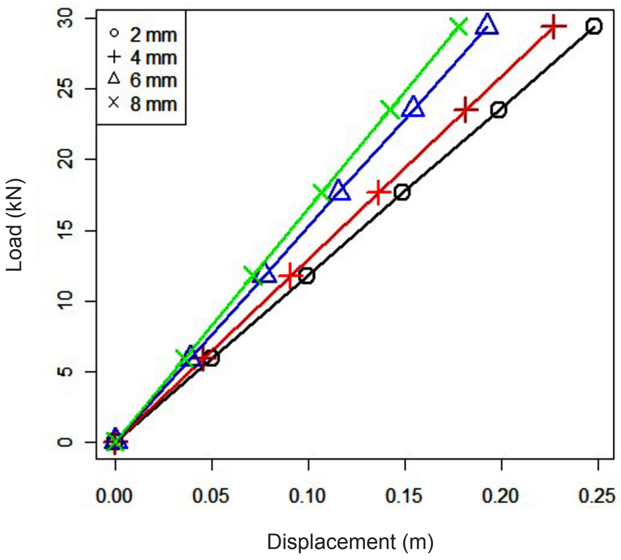

**Figure 6** Midspan displacement in timber beams wrapped with CFRP of different thicknesses

top were equally distributed at 910 MPa each side (Figure 6). This intersection point represents the optimum value for the structure within the specified boundary conditions.

## Load displacement response of reinforced specimens

Figure 6 presents the displacement response at midspan for the specimens reinforced with CFRP of different thicknesses, under five load cases. A linear displacement response to load was observed for all specimens, with 2 mm CFRP showing the greatest degree of displacement and the 8 mm CFRP-wrapped specimen showing the least displacement. The results could be attributed to the increased ductility of the specimen in the presence of CFRP reinforcement and is in agreement with results of a previous study that showed deflection upon loading decreasing with greater FRP thickness (Plevris & Triantafillou 1993). In that previous study, CFRP reinforcement increased stiffness by 60% while this study showed an increase in stiffness of 61.56%.

## CONCLUSION

Bonding CFRP laminate to the bottom flange of timber I-beam significantly enhanced the strength of timber structure. Based on the analysis, 6 mm thick CFRP laminate was determined to be the optimal thickness to reinforce a 4 m timber beam span. CFRP reinforcement increased the rigidity of timber by reducing elasticity of the timber structure, while ductility increased with increasing CFRP reinforcement. Stress from the applied loading was successfully transferred to the supports. Knowing the optimum CFRP thickness for reinforcing the timber girders will facilitate efficient fabrication of the planned modular and mobile forest bridge.

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