Numerical flexural strengthening investigation of timber-CFRP composite beams

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Abstract. Timber is among the most important construction materials with unique characteristics in comparison with other materials for instance steel and concrete. It is one of the first sustainable materials and continues to be a favoured selection in the current infrastructure. In the last decade, to refine the mechanical properties of timber, structural elements reinforcing fiber polymers have developed. In this study, to improve the flexural properties of timber beams, carbon fiber-reinforced polymer (CFRP) laminates are attached externally and internally between timber layers. For numerical simulations, first finite element model was validated according to the data obtained from experimental tests, then a series of simulations with different parameters were executed to investigate the flexural behaviour. The considered parameters include CFRP laminates’ existence and position. The linear elastic orthotropic material model was used to represent linear behaviour while the 3D anisotropic Hill material model was assumed to define the nonlinear behaviour of the material. Finite element simulations are executed by commercial software ABAQUS.

1. Introduction
The use of timber as a building material has greatly expanded in recent centuries, with wood being widely used in architecture, even for the construction of bridges and buildings. Mainly, it is characterized by its easily formed and its good mechanical properties. In addition to its aesthetic characteristics, its low density contributes to the construction of lightweight structures. Wood will continue to be an important building material due to the spread of environmentally conscious thinking. Moreover, it is considered a truly renewable and biodegradable material with lower production and processing energy requirements than other structural materials.

Protecting the forests and reducing the disadvantages compared to reinforced concrete or steel requires the efficient use of wood in structural applications. In order to increase the load-bearing capacity of wood, several attempts have been made to reinforce glue laminated timber (GLT) beams [1], which can be done with steel, polymer fabric, fiberglass, or carbon fiber [2]. Placing the reinforcing layer in the case of a timber support on the pulled part is most effective. According to practical experiments, up to a two-fold increase in load capacity and a stiffness increase of approximately 20% can be achieved. [3] The expected failure of a laminated-glued beam reinforced in this way begins with the rupture of the cover lamella. This phenomenon can be explained by the high modulus of elasticity of the resin layer, as the tensile stresses that the resin, which is about 20 times stiffer than wood, can still withstand and easily exceed the tensile strength of the wood. A characteristic feature of the failure process is that the rupture of the cover lamella does not mean complete failure. The wood system can withstand even more load increases after a smaller load capacity drop, as shown by researchers Blaß and Romani. [4].

De Jesus et al. [5] investigated experimentally and numerically the effect of different lengths of carbon fiber-reinforced polymer (CFRP) laminates on the strengthening of GLT beams in bending. M. Khelifa et al. [6] and [7], Khennane et al. [8] and Kawecki and Podgórski [9] investigated flexural strengthening of timber beams with CFRP, using Abaqus software to numerically predict the performance of GLT beams in flexion after strengthening by use of CFRP sheets of distinct lengths,
externally attached to the soffit of timber beams. Researchers are using the method of gluing strips to the bottom of a girder on the entire cross-section, because fiber-reinforced polymer (FRP) is most efficient under tension. Fiorelli [3] carried out studies on beams reinforced with Glass Fiber Reinforced Polymer (GFRP) and CFRP while Kossakowski [10] used laminates made of glass, aramid and carbon.

This paper presents the results of an experimental program of 3-point bending tests of GLT beams reinforced with unidirectional CFRP laminates. In the experimental program, two different reinforcement vertical positions are investigated and obtained results are compared with a non-reinforced beam result.

Furthermore, a constitutive model based on timber plastic damage was developed and used to investigate the bending strength of GLT beams. In this study, a constitutive model based on timber plastic damage developed and used to investigate the bending strength of GLT beams. The novelty of the article is that it contains not only the usual external plane reinforcements, but also examines the effects of CFRP lamellas incorporated during the manufacture of wooden beams. Moreover, CFRP strips were applied to enhance the bending strength of GLT beams. All these parameters were considered and their effects were studied.

The present model considered the Hill mechanical model for orthotropic timber, isotropic adhesive and isotropic CFRP behaviours. Nowak et al. [11] used the same Hill model for the plasticity of wood defined by using the Hill yield criterion and the generalized Hill yield criterion, which take into account the differing yield stresses during compression and tension.

2. Behaviour of materials and constitutive modelling

2.1. Timber
The behaviour of GLT in compression parallel to grain shows some softening in general; it can be regarded as elastic perfectly plastic. The basic anisotropic yield criterion which can be applied in timber is the Hill yield criterion [10]. Generalization of this criterion for anisotropic materials with different plasticity limits during compression and tension, so defining the generalized Hill yield criterion.

The Hill yield criterion [12] is one of the criteria used in the numerical analysis of wooden elements. The theory results from a generalization of the Huber-Mises-Hencky hypothesis for anisotropic materials. It allows a connection between material strengths and anisotropic directions.

When this criterion is used with the isotropic hardening option, the yield function is given by:

\[ f(\sigma) = \frac{3}{2} (\sigma^T \cdot [M] \cdot (\sigma) - \sigma_0^{(p)}) \]

where:
- \( \sigma_0 \) reference yield stress;
- \( \varepsilon^p \) equivalent plastic strain;
- \([M]\) Mass matrix.

When it is used with the kinematic hardening option, the yield function takes the following form:

\[ f(\sigma) = \frac{3}{2} ((\sigma) - (\alpha))^T \cdot [M] \cdot ((\sigma) - (\alpha)) - \sigma_0 \]

where:
- \((\alpha)\) yield surface translation vector.

In a coordinate system that is aligned with the anisotropy coordinate system, the Hill yield stress potential can be expressed as follows:

\[ f(\sigma, \sigma_y) = F(\sigma_{22} - \sigma_{33}) + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2 - \sigma_y^2 = 0 \]

where:
- \( F, G, H, L, M, N \) are constants which are determined experimentally of the material in different orientations.
\[ F = \frac{1}{2} \left( \frac{1}{R_{22}} + \frac{1}{R_{33}} - \frac{1}{R_{11}} \right) \]  
(4)

\[ G = \frac{1}{2} \left( \frac{1}{R_{33}} + \frac{1}{R_{11}} - \frac{1}{R_{22}} \right) \]  
(5)

\[ H = \frac{1}{2} \left( \frac{1}{R_{11}} + \frac{1}{R_{22}} - \frac{1}{R_{33}} \right) \]  
(6)

\[ L = \frac{3}{2} \frac{1}{R_{23}} \]  
(7)

\[ M = \frac{3}{2} \frac{1}{R_{13}} \]  
(8)

\[ N = \frac{3}{2} \frac{1}{R_{12}} \]  
(9)

where: \( R_{ij} \) are anisotropic yield stress ratios.

This criterion can be applied in modelling wood and processed wood products, titanium alloys, zirconium alloys and fiber matrix composites.

2.2. CFRP

This material may be considered anisotropic with transverse isotropy. The CFRP material was considered as linear elastic isotropic until failure. The elastic modulus in the fiber direction of the unidirectional CFRP material used in the present study was specified by the manufacturer as \( E_{\text{CFRP}} = 170 \) GPa while \( \nu_{\text{CFRP}} = 0.3 \) was used for the isotropic model.

3. Materials and methods

3.1. Finite element modelling

Finite element analysis was carried out to model the nonlinear behavior of GLT beams. For modelling the laminated timber beams 8-node solid (C3D8) element was used. The 4-node (doubly curved shell) element (S4) was selected to stand for the CFRP. The contact between CFRP and timber is considered as surface to surface contact, and the glue contact is defined by using friction coefficient equals 0.1 which is available in the ABAQUS manual [13]. For gluing the timber lamellas together cohesive contact was used too. Steel bearing plates (length = 200 mm, width = 120 mm and thickness = 30 mm) were installed at points of loading to prevent local failure caused by crushing.

Figure 1 shows beam geometry and loading and supporting conditions where all beams were tested under monotonic loading up to failure, with one concentrated load on the center of the beams.

![Figure 1. Beams geometry and loading condition.](image_url)
To model the load distribution plates, the (C3D8) 8-node solid element is used. The boundary condition at the first support is a roller to produce rotation and horizontal movement and a pin set at the other support to produce rotation. The loading conditions were the same for all the models, a vertical concentrated load was considered at each plate which placed at the top of the beam and this load was distributed by the coupling effect. Moreover, a fine mesh was applied to obtain results of sufficient accuracy where the total elements number of the beams was approximately equal to 60000 elements. Figure 2 shows the numerical model used, while Table 1 shows the numerical specimens’ properties.

Table 1. Material properties for numerical modelling of timber.

| Elasticity properties | Plasticity properties |
|-----------------------|-----------------------|
| $E_1$= 11.5 GPa       | $\sigma_{yield}$=43.1 MPa |
| $E_2$= 1.2 GPa        | $Q$=130 MPa            |
| $E_3$= 1.2 GPa        | $b$=21                 |
| $G_{12}$=0.98 GPa     | $F$=0.5                |
| $G_{13}$=0.34 GPa     | $G$=0.5                |
| $G_{23}$=0.34 GPa     | $H$=0.5                |
| $v_{12}$=0.29         | $L$=1.5                |
| $v_{13}$=0.29         | $M$=1.5                |
| $v_{23}$= 0.29        | $N$=1.5                |

It can also be clearly seen in Figure 2 that an important aspect in the creation of the model was that the GLT beam was not taken as a homogeneous timber material, but the timber lamellas were modelled separately and then connected to each other by a cohesive connection.

3.2. Experimental program
In this research, we performed three-point bending tests following de Jesus [13]. According to this experimental work, nine beams of 2500 mm long GLT beams - with a cross-sectional area of 120x240 mm - were tested. Besides, reinforcement Sika CarboDur S-1012 CFRP laminates were used with a width of 100 mm, a thickness of 1.2 mm, and a length of 2000 mm which was glued using adhesives SIKA products. Adhesion tests of timber and CFRP were performed before the start of the tests. Based on this, it can be stated that the adhesive strength between the two materials is higher than the tensile strength of the timber perpendicular to grain, which was a condition of the buildability. Commercially available GLT beams were used, the properties of which were specified by the manufacturer. The experimental properties of the used materials are presented in Table 2.
Table 2. Material properties.

| Material     | Type     | Flexural strength [N/mm²] | Compression strength [N/mm²] | Tensile strength [N/mm²] | Shear strength [N/mm²] | Elastic modulus [N/mm²] |
|--------------|----------|---------------------------|-------------------------------|--------------------------|------------------------|------------------------|
| Timber       | GL24h    | $f_{m,k} = 24.0$          | $f_{c,0,k} = 21.5$            | $f_{c,90,k} = 2.5$       | $f_{i,k} = 3.5$        | $E_{0,mean} = 11.5$    |
|              |          |                           |                               |                          |                        | $E_{90,mean} = 0.30$   |
| CFRP         | Carbdur  | -                         | -                             | 3.100                    | -                      | 170.000                |
| Epoxy glue   | Sikadur-30| -                         | 85 - 95                       | 26 - 31                  | 16 - 19                | 9.600                  |

The first three test specimens were the normal GLT beam without strengthening (TYPE-0). The CFRP laminates were glued on the lower plane of the other three beams (TYPE – A while for the rest three beams, CFRP laminates were embedded between timber layers (TYPE-B), as shown in Figure 3.

Displacement transducers were used to measure the deflection of the beams along the girder, as shown in Figure 4. These measuring points can be used to define the deflection line of the beams under the loading. The beams were tested during the project GINOP-2.2.1-15-2016-00030.

4. Results and discussion
At the beginning of the simulation work, the aim was to validate the models (without reinforcement - TYPE-0, CFRP used at the bottom - TYPE-A and the strengthening built into the structure - TYPE-B). Then the parameters of the timber material model and the adhesive properties of the GLT beams were determined, and then the parameters of the CFRP and epoxy were set. By comparing the numerical results with the experimental test results, it was realized that the ultimate loads and stiffness properties for the three specimens’ types are almost similar.

The main measurement results are shown in Table 3.
Table 3. The numerical and experimental test results.

| Specimen | Experimental results | Numerical results |
|----------|----------------------|------------------|
|          | Deflection at 70 kN | Deflection at failure | Ultimate force | Deflection at 70 kN | Deflection at failure | Ultimate force |
|          | $\Delta$ [mm]      | $\Delta_u$ [mm]   | $P_u$ [kN]    | $\Delta$ [mm]      | $\Delta_u$ [mm]   | $P_u$ [kN]      |
| TYPE-0   | 12.85               | 25.79             | 121.08        | 12.99               | 27.43              | 116.14          |
| TYPE-A   | 12.30               | 35.01             | 133.00        | 11.01               | 36.06              | 136.54          |
| TYPE-B   | 12.36               | 30.03             | 119.50        | 12.47               | 33.12              | 124.89          |

Figures 5-7, show the deflections of the middle cross section of the validated models compared to the experimental tests. 0-1 to 0-3 means the three TYPE-0 beams, A-1 to A-3 means the three TYPE-A and B-1 to B-3 means the three TYPE-B beams that is used in the experimental tests.

Figure 5. Comparison of experimental and numerical results on TYPE-0.

Figure 6. Comparison of experimental and numerical results on TYPE-A.
Using the parameters of the fabricated models, additional models were constructed by changing the vertical position of the CFRP laminates along with the height of the beam in 10 mm steps. The process was repeated until the neutral axis of the strengthened beam was reached because by then the CFRP laminates would have worked in the compression zone. The measurement results show that the stiffness (resistance to deflection) of the beam increased continuously as the CFRP laminates were placed towards the bottom plane of the beam. Figure 8 shows the results of the numerical experiments, the different curves indicating the location of the CFRP from the bottom of the beam.

As can be seen, where the CFRP laminates in the lower position were applied, results in the greater strength of the GLT beam. The load capacity of the beams was not given in this case, the concentrated load was maximized at 120 kN, because it was only intended to study the extent to which the behaviour of the girder changes.
Figure 9: The stresses of the beam (2cm) under 110 kN load.

The stresses arising in the beam are also as expected, i.e. the highest tensile stress values occurred in the most bent zone of the girder under the loading. Figure 9 shows the beam, where the CFRP laminate was placed 2 cm from the bottom under 110 kN concentrated load.

We also investigated the effect of different CFRP positions on the neutral axis of bent beams where zero stress arises in the elastic range. Figure 10 shows how the position of the neutral axis moved due to the different CFRP positions.

Figure 10: The neutral axis position displacement due to the use of CFRP.

5. Conclusion
Comparing between numerical and experimental results it is noted that the existence of carbon fiber reinforced polymer laminates causes an increment in the load capacity significantly and the rigidity of the glue laminated timber beams.

The experimental and the numerical results show that the use of CFRP laminates for bent GLT beams is most effective when applied in the lower, tensioned zone. However, there is a limit to this eccentricity beyond which the application of the CFRP no longer brings such benefits.

By using CFRP reinforcement, up to a 10% increase in load capacity and stiffness can be achieved for glue laminated timber beams during practical application.

Further testing of CFRP laminates used - as non-reinforcing after installation - at the production of wooden beams is necessary, because a more accurate understanding of the behaviour of these types of structures is needed.
6. References

[1] Kim Y J, Harries K A 2010 Modeling of timber beams strengthened with various CFRP composites Eng. Struc. 32 pp 3225–3234

[2] Lee Y, Park J, Hong S, Kim S 2015 A Study of Bond of Structural Timber and Carbon Fiber Reinforced Polymer Plate Mater. Sci. 21 pp 563–567

[3] Fiorelli J, Dias A A 2003 Analysis of the strength and stiffness of timber beams reinforced with carbon fiber and glass fiber Mater. Res. 6, pp 193–202

[4] Blaß H J, Romani M 2001 CIB Working Commission W18: Timber Structures Design Model for FRP Reinforced Glulam Beams.

[5] De Jesus AMP, Pinto José MT, Morais José JL 2012 Analysis of solid wood beams strengthened with CFRP laminates of distinct lengths Constr Build Mater. 35 pp 817–828

[6] Khelifa M, Auchet S, Méausoone P J, Celzard A 2015 Finite element analysis of flexural strengthening of timber beams with Carbon Fibre-Reinforced Polymers Eng. Struct. 101 pp 364–375

[7] Khelifa M, Celzard A 2014 Numerical analysis of flexural strengthening of timber beams reinforced with CFRP strips Composite Structures 111 pp 393–400

[8] Khennane A, Khelifa M, Bleron L, Viguier J 2014 Numerical modelling of ductile damage evolution in tensile and bending tests of timber structures Mechanics of Materials 68 pp 228–236

[9] Kawecki B, Podgórska J 2020 The Effect of Glue Cohesive Stiffness on the Elastic Performance of Bent Wood–CFRP Beams Materials 13 (22) 5075

[10] Kossakowski P G 2011 Load—Bearing Capacity of Wooden Beams Reinforced with Composite Sheets, Structure 3 pp 1–9

[11] Nowak T, Patalas F, Brol J 2018 The use of Hill anisotropic yield criterion timber elements reinforced with CFRP strips Annals of Warsaw University of Life Sciences - SGGW, Forestry and Wood Technology 104, pp.219-227.

[12] Hill R 1983 The Mathematical Theory of Plasticity. New York, Oxford University Press.

[13] Simulia D S 2018 ABAQUS User’s manual Dassault Systems, analysis user’s guide volume IV: Elements.