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# Finite element analysis of flexural strengthening of timber beams with Carbon Fibre-Reinforced Polymers

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ABSTRACT

This study focuses on the flexural behaviour of timber beams externally reinforced using Carbon Fibre-Reinforced Plastics (CFRP). A non-linear finite element analysis was proposed, and was validated with respect to experimental tests carried out on seven beams. All the beams had the same square cross-section geometry and were loaded under four-point bending, but had different numbers of CFRP layers. The Abaqus software was used, and different material models were evaluated with respect to their ability to describe the behaviour of the solid timber beams. Elasto-plastic behaviour with damage effect was assumed for the timber material, linear elastic isotropic model was used for the CFRP, and a cohesive model was used to represent the interaction between two adherent surfaces (CFRP and timber). These two surfaces were paired and, taking into account the presence of an adhesive layer, one of them was defined as the master surface whilst the other was the slave surface. Predicted and measured load–mid-span deflection responses and failure modes were compared. The increases of flexural strength for the two different reinforcement schemes with 2 and 3 layers of CFRP composite sheets were 41.82% and 60.24%, respectively, with respect to the unreinforced timber beams. The maximal difference between calculated and experimental ultimate load-bearing capacity for reinforced solid timber beams with 2-layers of CFRP was around 1.2%.



## 1. Introduction

The recent years have shown that technologies from the composite industry are becoming more and more utilised in civil engineering and in mechanical industries. The introduction of new construction materials and related technical know-how indeed allows achieving desired engineering properties. Timber and timber products are among the most important construction materials, and are also becoming more and more used in the form of composite materials with the introduction of the so called "highly engineered wood products". Timber is generally used in buildings, frames, truss bridges, and many other applications. Besides, wood is a renewable, environment-friendly and nontoxic material, available in large quantities almost all around the world. Additionally, it has a high thermal efficiency, is a net carbon absorber, and can be easily recycled.

Mechanical wood properties are often inappropriate for heavy loads in buildings. Improving the structural behaviour of building units by combining reinforcements with conventional building materials is already an old concept, extensively used in construction. For example, in the twentieth century, the combination of reinforcement steel and concrete has been the basis of a number of structural systems used in construction. Designers of products and material experts continue to develop new composite materials that might be used with conventional building materials like steel, concrete and timber, and which are expected to lead to the development of stronger, larger, more durable, energy-efficient and aesthetic structures.

Timber material has adequate strength both in tension and in compression. But this high strength is often accompanied with low stiffness, so that the design is controlled by deflection limitations. Strengthening timber beams aims at achieving higher stiffness. Increased stiffness without need of increasing the thickness of the beam may result in substantial space and material savings.

Timber presents damage and failure modes due to transversal tension. Besides, its natural origin gives timber a variable and heterogeneous character, and its mechanical behaviour is affected by the presence of defects such as knots, splits and slope of grain. These flaws are more detrimental in the tensile zone than in the compressive zone, since under tension they tend to develop into

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cracks. Deterioration can be stopped by reinforcing the exposed surfaces of the wood with composite materials, and the resultant strengthening is one way of improving the mechanical behaviour of timber. Recently, composite materials such as Carbon Fibre-Reinforced Plastics (CFRP) have been tested for structural strengthening and repair of timber elements, due to their attractive characteristics [1–21]. Repairing damaged timber members by CFRP is a viable alternative to the replacement of other conventional engineering materials (for example steel plates) due to its many advantages such as corrosion resistance, light weight and flexibility, ease of cutting, high elastic modulus and high strength to environmental aggressive factors. Usually, the behaviour of timber beams is governed by flexion, hence the need to strengthen them in bending. In addition, the load-bearing capacity of the timber beam specimens might be significantly improved with shorter lengths of CFRP.

Several experimental programs have investigated the performance of Reinforced Timber (RT) beams with CFRP, and have shown the effectiveness of using externally-bonded CFRP materials to improve the flexural capacity of RT members [1–14]. However, most of the previous studies were carried out using CFRP laminates externally attached to the soffit of solid wood beams along the full span length. To characterise the stiffness of timber beams in flexural, ductility and strength response of FRP-wood beams, an experimental programme based on a four-point bending test configuration was carried out by Borri et al. [1]. Experimental tests of the reinforced wood showed that external bonding of FRP materials may increase the flexural stiffness and the load-bearing capacity. The study presented by De la Rosa García et al. [7] showed that the strengthening systems of pine timber beams with basalt and carbon FRP gave rise to structures having higher stiffness and carrying capacity than the initial ones. The recent work carried out by Raftery et al. [14] also described an experimental test programme which examined the strengthening of glulam in flexion using bonded-in glass fibre reinforced polymer (GFRP) rods. It was found that the geometrical arrangement of the routed out grooves played an important role in the mechanical performance of the strengthened glulam. The effect of having shorter lengths of CFRP sheet did not receive much attention and the literature lacks information on the behaviour of RT beams strengthened with shorter lengths of CFRP sheets.

One of the few studies that considered the length of CFRP was realised by de Jesus et al. [8], who investigated experimentally, numerically and analytically the effect of distinct lengths of CFRP laminates on the strengthening of RT beams in flexion. It was concluded that the interfacial stress peaks decrease with the increase of strengthening length, and that the length of the strengthening does not influence significantly the stiffness of RT beams [8–10].

Several numerical works have investigated the performance of strengthened RT members using the Finite Element (FE) method [15–21]. Khelifa et al. [15] developed a numerical procedure to simulate the flexural behaviour of CFRP-strengthened timber beams wherein the kinematic continuity was assumed between adhesive and wood. This is justified by the fact that the shear modulus of wood is low, and failure modes do not occur between wood and adhesive. The obtained results showed that the proposed formulation can efficiently capture the load–displacement response with acceptable accuracy. Nowak et al. [19] developed a 3D nonlinear FE model that used shell and spatial elements to predict the mechanical behaviour of historic timber beams reinforced with CFRP strips. Shell elements were used to model the CFRP. Wood and adhesive were modelled using solid elements. In [19], the proposed FE model of wood was somewhat simplified by treating the latter as a homogenous orthotropic material. It was concluded that the use of simplified 3D FE model can accurately predict the response of the strengthened specimens.

In another study [20], a FE model was developed in order to analyse the flexural strengthening of timber beams reinforced with CFRP strips. The authors used cohesion elements to model the adhesive placed between wood and CFRP. It was found that the use of cohesive elements can accurately predict the response and the failure mode of the strengthened specimens. The work of Nowak et al. [19] was very interesting but neglected the interaction between elasto-plasticity and damage. It was therefore the aim of our previous study [20] to analyse the mechanical flexural behaviour in wood within the framework of continuum damage mechanics and plasticity.

The aim of the present work was to numerically predict the performance of RT beams in flexion after strengthening by use of CFRP sheets of distinct lengths, externally attached to the soffit of timber beams. Such a numerical study was carried out within the framework of continuum damage mechanics and plasticity, as none of these developments are yet to be used in the modelling of the flexural behaviour of RT beams with flexure damage. No studies dedicated to this topic, having many technological, economical and environmental advantages but whose modelling is very complex, have been offered so far in the literature. A 3D nonlinear FE model was thus developed here, using the Abaqus finite element simulation code [22]. The present model considered the different material constitutive laws for mechanical orthotropic timber, isotropic adhesive and isotropic CFRP behaviours. The model was validated by comparing the predicted load–displacement curves, the ultimate load capacity and the failure modes with the measured experimental data obtained by Borri et al. [1]. A parametric study was also designed and performed. The parametric study varied the size of the tension reinforcement as well as arrangements of the CFRP sheets, and the effect of the number of CFRP layers was investigated. The FE modelling of such a problem, if simulated correctly, might be used as a numerical tool for predicting the flexural behaviour of RT beams externally strengthened with distinct lengths of CFRP sheets and anchorage systems.

## 2. Experimental work

No experimental work was carried out in the present paper, which was only based on the experimental data reported in [1]. The present section therefore aims at presenting how the tests were performed, and what are the materials characteristics and the main assumptions used in our simulations.

### 2.1. Characteristics of materials

#### 2.1.1. Wood

The experimentation considered 7 beams classified in the second category according to the classification of wood reported in Ref. [1]. The moisture content was 10.88%, and the average timber density was 453.6 kg/m$^3$ as reported in [1].

#### 2.1.2. CFRP

Table 1 gives the main characteristics of the CFRP used to reinforce the timber beams, taken from the manufacturer's data sheets reported in [1], measured according to the ASTM D 3039 [23] standard. The knowledge of these mechanical properties is a precondition for the sustainable application of CFRP.

**Table 1**
Properties of CFRP (from [1]).

| | |
|---|---|
| Tensile strength | 3.388 GPa |
| Tensile modulus of elasticity | 41.76 GPa |
| Ultimate strain | 1.00% |
| Equivalent thickness | 0.165 mm |