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Structural efficiency of full-scale timber–concrete composite beams strengthened with fiberglass reinforced polymer

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ABSTRACT

The objective of this article was to experimentally evaluate timber–concrete composite beams in two different situations – with and without glass fiber reinforced polymer (GFRP). Four full-scale composite beams (5.4 m in length) were produced, two of which had reinforcement (nominal thickness of 10 mm) and two with no reinforcement. The fiberglass reinforcement was formed from the impregnation of unidirectional fiberglass cloth – effective thickness of 0.5 mm – with epoxy resin. The connection system consisted of steel hooks inclined at 45 degrees, bonded with epoxy adhesive to the holes previously drilled on the wood, whose apparent density at 12% moisture content was 0.79 g/cm^3. The reinforced timber–concrete composite beams tested had performance efficiency of 79% and average rupture strength of 142.5 kN. Finally, the reinforced timber–concrete composite beams were analytically evaluated using the proposed method in Eurocode5, showing reasonable agreement with the experimental results.

1. Introduction

One of the ideal precepts of structural building designs regards applying the appropriate material in the most appropriate location, considering its physical and mechanical characteristics. The timber–concrete composite (TCC) structures are clearly in line with this principle, because in the composite system the reinforced concrete slabs are usually fully compressed, while timber beams are predominantly solicited by normal tensile stresses [1]. Thus, the combination of these materials enables to achieve a structurally efficient, stiff yet lightweight cross-section.

Several studies are currently researching TCC structures [2–6], however its use dates back to the early twentieth century. There are reports that composite structures were used before the First World War in England [7]. In 1914, Redpath Brown and Company began a series of tests with steel–concrete composite structures. Between 1922 and 1939 several buildings and bridges were built using this system, especially due to the shortage of steel at that time [8].

Successive advances have been observed in this area in recent years. Yeoh et al. [9] present the state of the art concerning TCC structures, covering different aspects related to the connection system, the influence of concrete properties, short- and long-term behavior, design approaches, and numerical modeling. Recently, several Brazilian researchers have also investigated the subject [10–12]. However, it was in the 1970s that investigations into the structural behavior of TCC systems were initiated in Brazil [13], leading to the construction of various Brazilian bridges [14].

The convenient rationalization of timber used in buildings, as well as the necessary reduction of Portland cement, exemplifies strong arguments to enhance the development of TCC systems. In this context, this construction technique has been successfully used in the flooring systems of residential, industrial and sports buildings, with potential applications in structural repairs of historical works, as well as in the construction of new buildings. A concrete slab can be supported on a wooden deck [15], which facilitates the construction process. Fig. 1(a) and (b) illustrate the application of the system in the construction of a housing project located in São Paulo, Brazil.

Additionally, some advantages of TCC systems can be highlighted:

- Significant increased stiffness and strength compared with the independent use of the materials [9,15].
- Increased vibrational damping – which means that verifications of limit states due to vibrations are more easily met.
- Improved sound insulation – the increase in floor mass, compared with traditional wooden floor, is advantageous to reduce airborne sound transmission.

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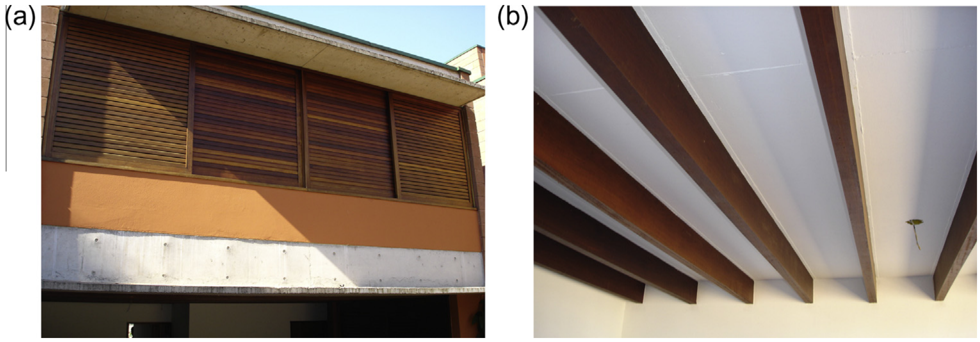

Fig. 1. Timber–concrete composite structure in residence: (a) External view; (b) Internal view.

- Advantageous under fire conditions – the top layer of concrete is an effective barrier against the spread of fire.
- Flexible under diaphragm actions, which can significantly alter the seismic response of a building [16].
- Construction agility, cost competitive and conducive to prefabrication [17].

There needs to be a bonding element between the materials for the composite system to perform properly, this ensures the transfer of horizontal shear efforts and also prevents vertical separation between the parts. The connection system can be obtained by means of nails, screws, metal plates, metal rings, HSB connectors [18], pins (or hooks) achieved from reinforcing steel bars, notches plus vertical dowels [19] or adhesives. The connectors are usually positioned along the beam, according to the shear stress distribution [9,20], and largely affect the behavior of the composite system. The proper spacing indication between the connectors is critical in order to maximize the load-carrying capacity of the composite system [21].

The slip between the concrete slab and the timber beams causes the partial composition effect of the cross-section [22,23]. Under bending, the Bernoulli hypothesis is not valid for the entire cross-section, however the sections can still be considered flat when the materials are analyzed separately. The shrinkage and creep of the materials involved are responsible for increasing the slip deformation, which is then responsible for increasing the vertical displacement of the composite system [24]. Another concern regards the behavior of TCC structures when exposed to fire [25].

An alternative to analyzing the behavior of TCC beams consists in the development of computational modeling, often based on the Finite Element Method (FEM). These models are subjected to calibration, comparing the responses with the values obtained experimentally. However, there is a lack of experimental results on full-scale composite floors to validate numerical methods and analytical formulas, especially when the analysis involves the time-dependent behavior of composite floors [1,26].

The structural performance of TCC structures is encouraging. Davids [27] points out that when compared to timber–concrete beams considering the materials separately, that is without any interaction effect, the timber–concrete interaction results in a bending strength increase of least 40% and stiffness increase of 200% or more. In practice, however, these gains can be quite different, because they depend on the behavior of the connection system utilized and they are also subordinate to the time-dependent behavior of materials that constitute the composite system, among other properties [4,20,21].

Nevertheless, adding fiber reinforced polymer (FRP) to the beams opens new perspectives for the design of timber structures [28,29]. Concrete and sawn timber composite beams reinforced with fiberglass (GFRP), and screw-based connection system, were tested and the results are in Brody et al. [30]. The results demonstrate that the actual stiffness of the composite beam is of approximately 67% of the theoretical stiffness of the beam (considering the total composition of materials, that is, no slip at the interface of the materials).

Weaver [31] evaluated the performance of fiberglass-reinforced glulam beams, considering the partial contribution of the associated reinforced concrete slab. In this study, the connectors were subjected to loads varying between 2,000,000 and 2,500,000 cycles. Yeoh et al. [23] also performed studies on TCC beams under cyclic loading to simulate fatigue on bridges.

Premrov and Dobrila [28] analyzed the behavior of four TCC beams reinforced with CFRP (Carbon Fiber Reinforced Polymer) strips of 1.2 mm in thickness and 150 mm in width. These specimens were subjected to three-point bending tests, with the load applied at the middle of the 4.5 m span. Based on the tests, it was shown that the composite beams reinforced with carbon fibers had the first failure in the tensile region of the wood, and its average value reached was 130.5 kN.

Due to the great potential of TCC structures as a sustainable and efficient solution, our paper presents the experimental evaluation results of TCC beams with and without fiberglass reinforcement, as a contribution to this state of the art construction technique.

High costs, long manufacturing time and other difficulties inherent in the handling of large structural components justify the production of only two specimens of each type of beam discussed in this paper. The need for a preliminary investigation of the behavior of materials and adhesives used during the tests also corroborates the number of repetitions in the methodological procedures adopted in this research.

2. Characterization of materials and the connection system

The production of the glued laminated timber beams included *Lyptus* wood – as known in Brazil – corresponding to the hybrids *Eucalyptus grandis* and *Eucalyptus urophylla*. For manufacturing of the glulam beams was acquired one lot containing 2.3 m^3 of *Lyptus* wood. Table 1 shows the mean values of the physical and mechanical properties of the material, corrected at 12% for moisture content, the number of tested specimens and the corresponding coefficients of variation (cov). All tests followed the requirements of ABNT NBR 7190 in Annex B [32], which determines the use of small size specimens and no defects.

The isocyanate adhesive – Wonderbond EPI EL 70 – was used to manufacture the glulam beams, with the catalyst EPI WS 742 – produced by *Hexion Química*. The timber-concrete composite beams were manufactured with ready-mixed concrete (normal-weight concrete – 2,400 kg/m^3). Enough material was extracted from this concrete to mould-six cylindrical specimens (15×30 cm), with the following average values: compressive strength at 28 days,