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Numerical and experimental evaluation of a double inverted trussed beam reinforced with steel cable

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HIGHLIGHTS

- It is an arrangement that generates a system lightweight, easy to handle, stronger and stiffer than a simple beam.
- Easy to be mounted and transported.
- Indicated to be used in formwork systems.
- If compared with simple beam, its resistance and stiffness increase 43% and 97%, respectively.

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ABSTRACT

A special type of queen-post truss was evaluated numerically and experimentally. The system consists of a main beam with a double rectangular cross section, into which are fitted two struts that are connected to steel cables anchored to transverse steel dowels embedded at the ends of the main beam. The system, which can be used as a support for concrete formwork, for structural rehabilitation and for numerous other applications, is lightweight, easy to handle, and stronger and stiffer than a simple beam. From experimental study, on average, beams are 97% stronger than ones without cable reinforcement, and the gain in stiffness was 43%. The numerical model was analyzed via the finite element method.

1. Introduction

It should be noted that wood is an important structural material, particularly due to its high strength-to-weight ratio in comparison with other materials. It is a natural renewable material with adequate mechanical properties, whose compressive strength parallel to the grain may exceed 60 MPa.

Timber trussed beams can be used as concrete formwork supports because timber beams are easy to transport and adjust to different conditions, thus preventing the overloading of shores.

The system called as inverted truss or queen (or king) post truss is little described in the literature. The little information that exists is fairly generic, and considers the structural model with classical connections – rigid or hinged, with a lattice arrangement composed of members. No reports of a system similar to the one presented here were found in the literature. Therefore, it is a unique system in terms of its assembly.

The use of steel in conjunction with wood has been successfully used due to appropriated interaction between these materials [1]. Herzog et al. [2] present several schemes for distributing members to form an inverted truss, which is characterized by the existence of upward thrust at the points where the struts are located, as shown in Fig. 1a and b. In this situation the structure is internally three-dimensional. Boresi et al. [3] offer general information about the system and present a numerical example of how to calculate this type of trussed beam. Pfeil [4] and Ritter and Fahert [5] offer the same information. The latter authors consider V-shaped struts tilted in relation to the vertical position – Fig. 1c – in a planar system. Rebello [6] offers a generic explanation of how to use this type of beam, indicating its advantages and efficiency. Pletz and Mello [7] studied another alternative involving V-shaped struts, as illustrated in Fig. 1d, considering it an easy way to prestress this type of structure.

Feio et al. [8] consider this type of beam suitable for structural rehabilitation, enabling the recovery of existing beams by increasing their stiffness and strength by means of easy handling. The arrangement with wire rope used in this study it is an interesting way to treat this type of problem, once wire rope is flexible and adjustable to curve surface. This topic can be also included as a

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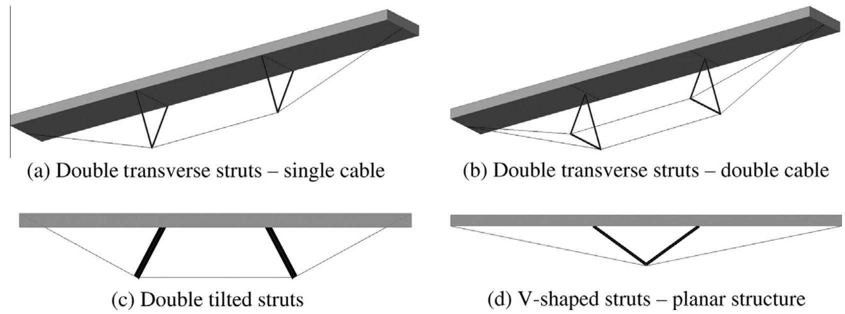

Fig. 1. Types of struts described in the literature.

structural rehabilitation category for solving problems in the same range as presented by Augelli et al. [9], Borri et al. [10], Pantelides et al. [11] and Branco et al. [12].

A team of researchers associated with the authors has reported information about similar situations. Gesualdo and Lima [13,14] and Gesualdo and Cunha [15] describe different arrangements.

There are also three-dimensional systems for use in bridges, for example. This type of system consists of a model similar to the one presented here, but the strut has two inverted V-shaped pieces that increase the system's stability.

The purpose of this work was to evaluate the aforementioned type of beam based on a numerical and experimental analysis. The analysis involved the connections, joints and details of anchorage including the positioning and the elastic and geometric characteristics of all the components of the system.

2. Experimental description

Lightweight, strong, stiff systems that are easy to assembly are essential for applications as concrete formwork supports. Moreover, the structural repair and rehabilitation of buildings requires simple procedures for adding new elements to existing beam systems. Therefore, a system was developed consisting of a horizontal double cross section connected to two vertical elements – struts – with steel cables anchored at the ends to transverse steel dowels, as illustrated in Fig. 2. This type of system is known as an inverted truss or inverted queen post truss. However, the system devised here differs from the conventional system described generally in the literature, since it includes a continuous cable anchored to transverse steel dowel pins located close to each end of the beam. The ends of the cable are connected by a stretcher that makes it continuous, thus transforming it into a double cable with back and forth movement (see Fig. 3).

Fig. 2 shows the position of the cable anchored to the transverse struts. The cable, which distributes the stress, passes through a standard stainless steel thimble and the radius of curvature of the cable is compatible with its diameter. The size of the thimble is larger than the diameter of the cable in order to accommodate the cable properly, since its bidirectional location causes a differential in its vertical position, Fig. 3d.

Fig. 4 shows details of the cable in contact with the strut. A transverse pin was used to better distribute the stress caused by the cable in contact with the strut.

To analyze the gain in stiffness, a direct comparison can be made of the beams, since the experiment allows the same beam to be tested under two conditions, i.e., with and without the cable system.

However, an analysis of rupture loads requires a comparison of pairs of beams that are considered acceptable. Therefore, three simple beams without cables were tested in bending to compare their ultimate failure loads.

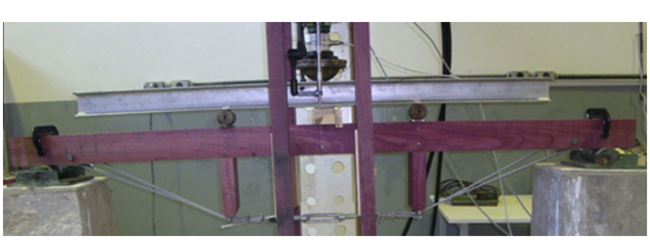

Fig. 2. Overall view of the beam under testing.

All the beams were tested with an unsupported span of 1800 mm, using 232.5 mm long struts, as illustrated in Fig. 5. The main beam was made of a Brazilian wood species known popularly as Roxinho (*Peltogyne cf. subsessilis*), which is readily available in the Brazilian market in the form of sawn timber. All the beams came from the same lot and had the same moisture content (10.4%), compressive strength parallel to the fibers (79.6 MPa) and density (877 kg/m^3) determined according to Brazilian standard ABNT NBR 7190:1997. These values are general for all the beams, but the main analysis involved a direct comparison of pairs of these beams.

Fig. 5 illustrates the loading scheme. Loads were applied on the beam at the points where the struts were located, i.e., at $\ell/3$ from the supports.

The vertical displacements were measured with two inductive displacement transducers positioned laterally at the midpoint of the beam, Fig. 6. The average value of two measurements was considered representative of the vertical displacement. The transducers were then fixed to the top of the beam to enable readings of displacements up to failure. To ensure the lateral stability of the system, a lateral bracing system was employed to prevent transverse movements, as illustrated in Fig. 6.

3. Experimental results

3.1. Procedures

The beams were tested in different configurations, as described in Table 1. The initial tests of the beams tested as inverted trusses were conducted without the cable (Case B), with loads below the elastic limit (Case A). This enabled a direct comparison of the modulus of elasticity of the simple beam and the cable-reinforced beam. To compare the ultimate load, three pairs of these beams – V1, V4 and V5 – were mounted as simple supported beams (Case A), which were cut from the same piece of timber and loaded up to failure. Each pair of beams, one a simple beam and the other an inverted truss, were loaded up to failure.

The diagrams shown here refer to "simple beams", i.e., beams without reinforcement cables (Case A), and "inverted trusses" (Case C), i.e., the complete system. The inverted trusses were also tested in two steps. The first test, to accommodate the cable and adjustments, involved loading to a level below the elastic limit. In the second test, the beam was unloaded and the cable stretched again to regain the deformation produced by the natural accommodation of the cable, after which the beam was loaded up to failure.

The cables used to reinforce the beams consisted of six wires of 6.4 mm diameter, each wire composed of 19 strands, according to information provided in a technical manual for steel cables. Fig. 7a shows a thimble deformed and undeformed. In order to prevent additional local deformation the thimbles were reinforced, based on previous experimental observations. To prevent crushing, the thimble's radius of curvature, a metallic element was welded to its internal surface, thus reducing the bending of the thimble, as illustrated in Fig. 7b.

Another option is to use solid steel thimbles, Fig. 7c. Although this is not a conventional product available in the market, it is undoubtedly a more rigid element. However, it is not