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Automated processing of dense points clouds to automatically determine deformations in highly irregular timber structures

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HIGHLIGHTS

- Timber beam frequently have irregular cross-sections along their length.
- Deformation of irregular beams can be automatically determined thanks to LiDAR data.
- The method was validated in an irregular timber beam under laboratory conditions.
- The results show that maximum error in the main body of the beam is less than 5%.

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ABSTRACT

Timber structures frequently present irregular cross-sections along their length, principally in old buildings. This irregularity may be a critical parameter to take into account during the deformation analysis of these structures. The aim of this paper is to propose and develop a new algorithm that automatically estimates the deformations of timber beams that have important geometric irregularities by using laser scanning technology. The proposed algorithm to determine deformations is based on Mohr's Theorems. The method is validated in a beam that is subjected to two different loadings. The results are compared with those obtained by contact methods and the differences are less than 5%. The results obtained demonstrate that the method proposed is suitable for the automatic analysis of deformation in irregular timber structures.

1. Introduction

Traditionally, wood has been one of the most frequently used building materials. This material can be found in the main structural body of small family houses, large buildings, bridges or cathedrals. Because of this, nowadays there are still countless historical timber buildings. Although wood is not the most used material nowadays, it is still used in large constructions such as sports facilities or shopping centres, and in smaller constructions as houses or bungalows. Furthermore, it is widely used as a structural element in buildings, mainly in the form of beams. The main advantages of using wood are: a) good thermal insulation, b) easy elaboration and execution, c) high versatility, allowing adaptation to different shapes and sizes, d) natural, biodegradable and ecologic character. The disadvantages are: a) less durability over other materials such as aluminium or stainless steel, b) instability against weather changes, mainly affecting humidity, so that it is necessary to apply an adequate protection, c) it is not an homogenous material so several uncertainties in its structural behaviour must be taken into account, d) the beam has often irregular shapes or lacks of material that affect the geometrical properties. The main defects of wood that affecting the geometrical properties of the cross-section are normally related to: the lack of material, which are mainly due to wanes (lack of material presented in the wood pieces when they are sawed), and the lack of material due to the human actions (Fig. 1). These variations of the geometric properties of the section have a direct effect on the results of the structural analysis.

For the structural analysis of a timber construction the ultimate limit state and serviceability limit state must be verified, as it happens with other types of constructions. The ultimate limit state verification indicates whether the material withstands the stress to which it is subjected or not, whilst the serviceability limit state verification indicates that deformations do not exceed the limits allowed by the building codes. Eurocode 5 [11] is used as a reference for the calculation of timber structures (particularly in Europe). The Eurocode 5 defines the recommended limiting values for deflections of beams and cantilevers with a wide range of

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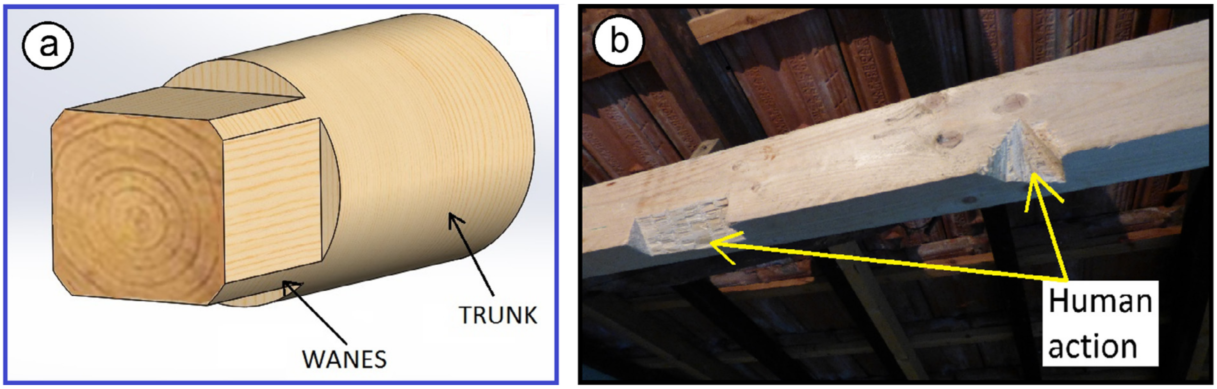

Fig. 1. Lack of material in timber beam. a) due to wanes b) due to human action.

values (Table 1). In the wooden pieces, the deformation mainly occurs due to bending, and in lesser degree due to the torsion. Due to the low modulus of elasticity of the wood, the deformation is a critical issue for a safe geometric design of sections, so its calculation is required. The calculation of deformation in timber beams has some differences with respect to other materials such as steel or aluminium. Among the main differences it should be noted the non-uniformity of the material or the creep deformation. Wood is a non-uniform material, so correction factors [11] are needed to correct the results given by the conventional analysis using the principles of mechanics of materials. Mainly for the calculation of the deformation, the creep deformation must take into account, which is affected by several factors: the moisture content and moisture variation, the type of load, the stresses state, or the temperature. For the determination of the final deformation of a timber piece (considering creep), the instantaneous deformation w_{inst} must be increased by the creep factor k_{def} (Table 2) [11]. This factor is dependent on the service class and load duration, and is only applied to permanent loads.

In order to accurately determine the deformation, it is necessary to know the geometry of the cross-sections of the beam all along its longitudinal axis. Currently these measures are usually collected manually, a task which is very laborious and often difficult to perform because the beams are normally located in hardly accessible places. In order to collected these measurements automatically and without having a direct contact with the beam, close range remote sensing technologies such as photogrammetry were used [24,25]. Photogrammetry results (measures and metric quality) highly depends on the color, light and texture of the beam surface to be measured; a bad lighting conditions can significantly difficult the measurement, which is an important disadvantage of the photogrammetry to this task.

Another suitable remote technology for this task is laser scanning. Laser scanning is a geomatic method that allows obtaining 3D geometry of objects' surface in an automatic way by using Light Detection and Ranging (LiDAR) technology [13]. There are a variety of research works dealing with the modelling of structures from laser scanning and its subsequent application to structural analysis, such as: modelling of historic buildings [1,2], modelling vaults and domes [3], modelling for civil engineering applications, architecture and construction [4–6], modelling of floor plans of buildings[7,8], modelling of deformation of beams [9] or modelling of metal frame connections [10].

However, very few research exists on the use of laser scanning data for the modelling of timber structures. Additionally, the existing works focus on the 3D modelling of the members but not in the subsequent structural analysis. Some relevant research papers found in the literature are: Balletti et al. [12], who study the shape and geometry of the articulated timber structures in the vaults of the traditional architecture of Venice. Oreni et al. [14] show the usefulness of conversion of 3D models to a historic building information model (HBIM), with the aim of supporting the conservation and management of heritage buildings. Bertolini-Cestari et al. [15] show the modelling and conservations interventions made in the timber dome of the Valentino Castle in Torino. Also, Fregonese and Taffurelli [16] presented the analysis, representation and documentation of the vaulted timber structure of the Basilica of St. Mark in Venice. Van Goethem et al. [27] performed the reconstruction and modeled of timber boards with knots from LiDAR data. This works focus on the 3D modelling of the beams but do not deal with the structural analysis. Alessandri and Mallardo [26] address some structural analysis of the timber roof construction of the Church of the Nativity in Bethlehem. Although this work deal with the structural analysis of a building with timber beams from LIDAR data, it is focused on the structural analysis of the masonry; moreover, their method do not automatize the data processing.

Related to the 3D modelling of timber structures with structural analysis purposes, Cabaleiro et al. [17] presented relevant work about the suitability of laser scanning data for the structural analysis of timber beams. In their work an algorithm that automatically finds the geometrical properties of cross-sections of highly irregular beams from laser scanning data is proposed (Fig. 2). The algorithm was conceived for its use in the structural analysis of existing structures during the process of rehabilitation of historic buildings. The proposed methodology started with the acquisition of a very dense point cloud, and the manual selection of a region of interest that contains the beam to be studied. The point cloud obtained is automatically divided into slices along the longitudinal direction (X axis) of the beam, to obtain the contour of each section. Then, a projection of the point cloud is performed in the YZ plane (orthogonal) to the longitudinal axis of the beam. To reconstruct the contour of each beam cross-sections, algorithm [17] developed from alpha-shape [23] is used. From this reconstructed contour, the geometric properties of each section (area, coordinates of the centroid, moments of inertia, product of inertia and section modulus) are calculated. Later, with knowledge about the loadings and boundary conditions, the structural analysis of the beam is carried out. Thus, the stress distribution along the beam

Table 1
Examples of limiting values for deflections of beams [11].

	w_{inst}	$w_{net,fin}$	w_{fin}
Beam on two supports	l/300–l/500	l/250–l/350	l/150–l/300
Cantilevering beams	l/150–l/250	l/125–l/175	l/75–l/150