Engineering Structures 204 (2020) 110082

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

The influence of cross-section variation on bending stiffness assessment in existing timber structures

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ARTICLE INFO

Keywords:
Existing timber structures
Geometric variability
Non-destructive testing
Ultrasound
Stress wave
Vibration

ABSTRACT

The frequent highly irregular geometry of the elements in existing timber structures complicates the structural verification of members and influences the use of non-destructive testing (NDT), affecting the inspection time, cost and results obtained. This process therefore needs to be improved. The main aim of this paper is to analyse how to obtain a representative nominal cross-section (NCS) of members, and its influence on determination of the static modulus of elasticity (MOE_{sta}). 21 150 × 200 × 11,000 mm^3 Salzmann pine (*Pinus nigra* subsp. *salzmannii* (Dunal) Franco) timber rafters from the 18th century Royal Coliseum of Charles III theatre (in Aranjuez, Madrid, Spain) were acoustically tested (by ultrasound, stress wave and vibration). The MOE_{sta} was determined by mechanical testing, and different criteria for determining the NCS were analysed. Good correlation was obtained between the MOE_{sta} and NDT parameters, and the best criterion to assign NCS was proposed to improve the accuracy of the models obtained by reducing the number of NCS measurements.

1. Introduction

Most of the studies using non-destructive testing (NDT) on timber pieces to estimate their mechanical properties centre on new sawn timber or small specimens. In recent years, *in-situ* building assessments have been complemented with the use of NDT such as stress waves, ultrasound, vibration, probing, and visual strength grading (VSG) to determine the physical and mechanical properties of existing structural timber members [1–8]. NDT research has led to new portable devices and methodologies, which have given rise to very positive results and new research lines [9]. This makes it possible to accurately estimate relevant parameters such as density, modulus of elasticity (MOE), and strength values, using the models described in research works for various species. These models allow safe verification of members from existing structures to estimate their bearing capacity or to identify biotic and structural damage [10–15].

Some research work conclusions are presented below using the above-mentioned NDTs:

1.1. Visual strength grading

VSG of timber for structural use can be used to establish a strength class depending on species and their physical–mechanical properties. Arriaga et al. [2] showed that there are no significant differences between the mechanical properties of pieces with or without wanes due to the continuity of surface fibres in 84 test pieces from existing structures (52 Scots pine [*Pinus sylvestris* L.] and 32 maritime pine [*Pinus pinaster* Ait.] pieces). Arriaga et al. [16] carried out VSG of 395 sawn timber pieces of three species (Scots pine, Salzmann pine [*Pinus nigra* subsp. *salzmannii* (Dunal) Franco] and radiata pine [*Pinus radiata* D. Don]) according to the UNE 56544 [17] Spanish standard. 52% of pieces were rejected. The percentage of rejected pieces was reduced to 10% by only considering knots and grain slope, with no significant differences in mechanical properties. Esteban et al. [3] related the fissures on timber with shear strength, MOE and modulus of rupture (MOR) using mechanical tests, concluding that there is no significant relationship between fissures and mechanical properties.

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https://doi.org/10.1016/j.engstruct.2019.110082
Received 28 May 2019; Received in revised form 13 November 2019; Accepted 9 December 2019
Available online 14 December 2019
0141-0296/

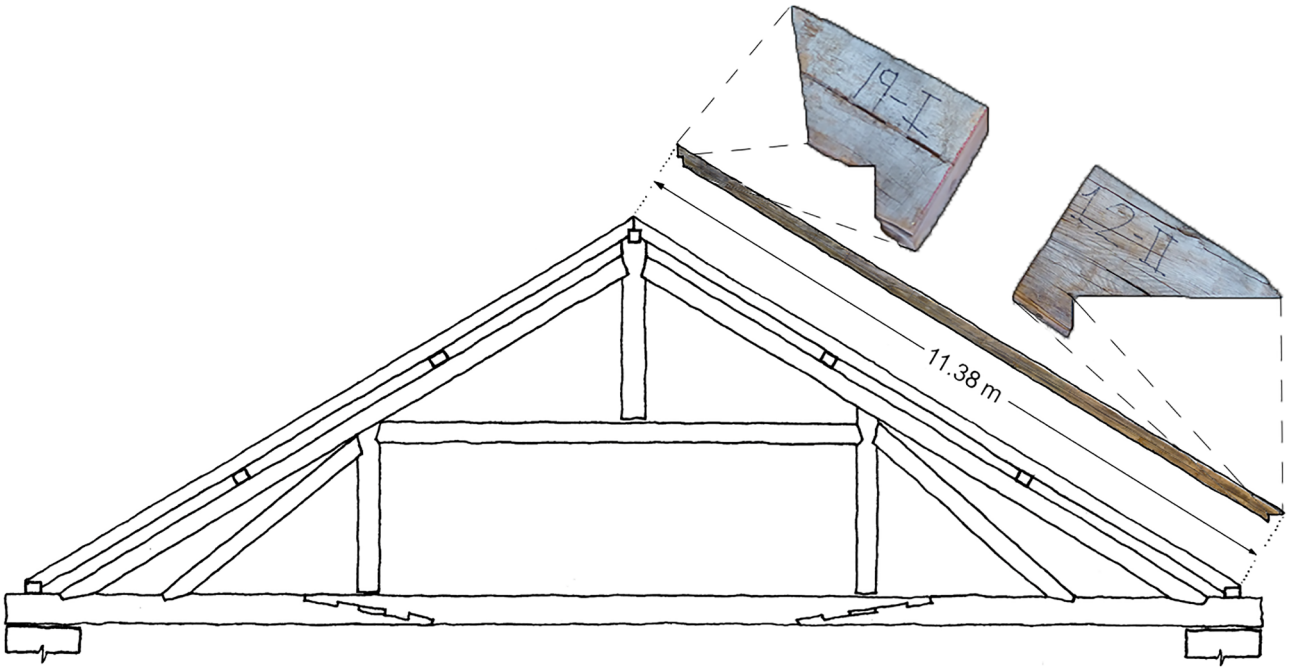

Fig. 1. Roof trusses and details of rafter ends.

1.2. Combining VSG and NDT

Other research works have combined VSG and NDT with positive results. Cavalli et al. [18] showed prediction values of the static modulus of elasticity (MOE_{sta}) through the dynamic modulus of elasticity (MOE_{dyn}) and wane parameter with $r^2 = 0.70$ and MOR with $r^2 = 0.43$ in 81 Norway spruce (*Picea abies* (L.) Karst.) and Silver fir (*Abies alba* Mill.) pieces from existing structures. In addition, two trusses from an existing building were tested by combining VSG and NDT to clearly identify their weak sections [19]. This simplified the use of structural reinforcements, which could be installed more accurately [20]. Riggio et al. [5] reported improvements in the estimation of physical–mechanical properties using NDT on Giotto's bell tower structure in Florence, Italy. The work of the COST Action IE0601 "Wood Science for Conservation of Cultural Heritage" (WoodCultHer) must also be mentioned. This was developed in 2007–2008 within the framework of the European Cooperation in Science and Technology (COST Actions). The Task Group "Assessment of Timber Structures" generated a document titled "Guidelines for On-Site Assessment of Historic Timber Structures" and gave rise to an interesting publication with the same title [21]. Guidelines are proposed for the evaluation of existing buildings by performing a highly structured analysis to provide enough data for proper structural safety analyses and planning interventions. This paper analyses timber pieces with emphasis on VSG. In addition, it gave rise to a pre-normative document prEN 17121 [22] and is currently being developed within the European Committee for Standardization, Technical Committee 346 "Conservation of Cultural Heritage" (CEN/TC 346) by its Working Group 10 "Historic Timber Structures" and has been launched for formal vote in 2019.

1.3. Cross-section variation

The study of timber members from existing buildings frequently reveals a highly variable cross-section (CS) along their length which is an important parameter for visual grading and mechanical behaviour [15,23,24]. This geometric variation can be caused by biotic degradation or irregularities in the sawing of the original pieces, and it may influence the estimation of mechanical properties [25,26]. The experimental procedure of geometric measurements may therefore have a relevant influence on the accuracy of the models obtained. Lourenço et al. [27] proposed a predictive model and a constant value for CS loss in softwood pieces from existing buildings. The proposed model was used to define deterioration curves over time, resulting in a predictive life-cycle time-dependent reliability index. Íñiguez-González et al. [28] observed that the coefficient of variation (CoV) of the cross section dimensions presented differences up to 4 or 5 times between old and new timber pieces. Sousa et al. [26] showed a 5% reduction in MOE_{dyn} and MOE_{sta} and a 30% reduction in compressive strength parallel to the grain between decayed and non-decayed parts in 20 old floor beams of *Castanea sativa* Mill. due to a variation in CS decay with NDT. However, the above research analyses the influence of CS from a different point of view from that of this paper. Nevado et al. [29] and the thesis by Nevado [30] use a more similar approach to that of the research works on structural reliability and its relationship with the variability of the section.

The aim of this work is to determine the influence of CS geometric variability in the estimation of bending stiffness using acoustic methods in the assessment of timber members from an 18th century building. Furthermore, several geometric measurement criteria were analysed in order to achieve a better prediction of MOE_{sta} based on NDT parameters.

2. Material and methods

2.1. Materials

The tested material comes from the Royal Coliseum of Charles III in Aranjuez, Madrid, Spain, designed by the French architect Jaime Marquet and built in 1768. This theatre was inaugurated in 1769 [31], one year before of theatre of the same name in San Lorenzo de El Escorial (1770). They are the two oldest roofed theatres in Spain still in use. The last restoration was undertaken in 1994, following the project of the architect Mariano Bayón Álvarez. The works were halted from 1996 to 2008. The structure of the roof was then disassembled and stored under cover, which made it possible to conserve many of its original pieces. The theatre reopened in 2014. The original main structure of the roof consisted of trusses with an approximate span of 18.40 m with a 32° slope. They were composed of 300 × 300 mm^2 CS