Construction and Building Materials 93 (2015) 798–805

Contents lists available at ScienceDirect

Construction and Building Materials

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

Applicability of the Hole-Drilling procedure for stresses quantification in timber bending elements in service

S. Sánchez-Beitia [a,*], M. Crespo de Antonio [a], L. Acuña [b]

[a] H.T.S. of Architecture, University of the Basque Country (UPV/EHU), Oñate square 2, 20018 Donostia-San Sebastián, Spain
[b] Dpt. of Agro-Forestry Ing., University of Valladolid, La Yutera Campus, 34071 Palencia, Spain

HIGHLIGHTS

- The Hole-Drilling procedure is applied for the first time in timber structures.
- The results are valid for a wood class and for big structural beam size.
- The orthotropic behavior of the wood has been considered.

ARTICLE INFO

Article history:
Received 15 February 2015
Received in revised form 9 May 2015
Accepted 11 May 2015
Available online 21 May 2015

Keywords:
Hole-Drilling
Timber structures
Orthotropic behavior
Bending beams
Pinus radiata D. Don

ABSTRACT

Hole-Drilling is a widely applied method for measuring residual stresses and stresses of in-site structural elements. The procedure can be considered as minor destructive testing because the inferred damage in the element is reduced and does not affect its structural strength. The relaxed strains by material extraction are related with the stresses state before making the drill through a compliance tensor. A general plane state of stresses near surface has been considered under an orthotropic behavior. The paper shows the procedure for the experimental deduction at laboratory of the nine constants of the elastic compliance tensor for the analyzed material (*Pinus radiata* D. Don) under the bending effects. Once the constants of compliance for the tested material are known, it is possible to go the opposite way for its application on real structures by drilling a hole with the same dimensions as those chosen at laboratory. It has been possible to approach the real stresses state in several timber beams by recording those strains.

1. Introduction

The development of nondestructive and semi-destructive testing methods is the main challenge for the assessment of structural elements in existing constructions. This paper deals with the application of the popular Hole-Drilling technique on wood, a natural and organic material. The Hole-Drilling method involves drilling a small hole and using a strain gage rosette to measure the relaxed strains. The damage caused to the wooden member is often localized, repairable and does not endanger its strength. For this reason it is considered to be a semi-destructive method [1]. This is an important feature considering the future of its application on real in-service structures. Current researches are gaining momentum in the area of in situ assessment of physical and mechanical properties of timber structures as it is mentioned in RILEM state of the art report on In Situ Assessment of Structural Timber [2]. The Hole-Drilling method is a widely used technique for measuring residual stresses since Mathar's foundational work in 1930s [3]. Since then, numerous researchers have contributed to the development and implementation of the method at both laboratory and real structures [4–8].

Wood has been often used building structures during centuries all around the world as it was an abundant, easy to come by and resistant material which did not need any sophisticated industrial processing. Between elements making up structures, horizontal members, such as beams or joists (smaller size beam), which work under bending efforts, are very frequent. In the restoration of historic buildings, wood appears frequently and needs to be regularly maintained and repaired. However, as wood is also a complex material because of its anisotropy, heterogeneity and variety, Hole-Drilling method had never been used on timber structures before. Furthermore, no alternative method for stress quantification in timber structures in service have been developed [9–11].

Regarding its mechanical behavior, wood shows three principal directions: axial, radial and tangential [11]. In Fig. 1 these three

* Corresponding author.
E-mail addresses: santiago.sanchez@ehu.es (S. Sánchez-Beitia), maite.crespo@ehu.es (M.C. de Antonio), luisacurello@gmail.com (L. Acuña).

http://dx.doi.org/10.1016/j.conbuildmat.2015.05.091
0950-0618/

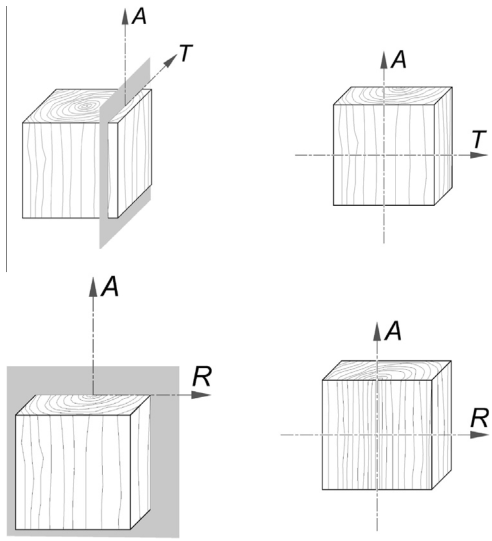

Fig. 1. View of the main planes of a block, according to a mechanical point of view. "A" means axial direction, "T" tangential direction and "R" radial direction.

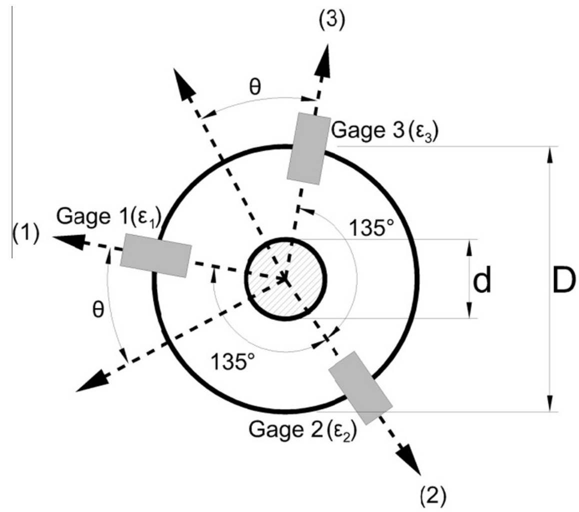

Fig. 2. Geometrical layout for Hole-Drilling technique; *D* is the diameter of the circumference of the strain gauges, while *d* is the diameter of the drill; symbols (1), (2), and (3) indicate the radial direction of the strain gauges *Gage 1*, *Gage 2* and *Gage 3*, respectively.

directions are shown by means of some perspectives according to the axial-tangential plane and the axial-radial plane. It is frequently referred to as axial (referring fiber direction) and transversal (perpendicular to fiber direction) directions with no specification as to whether transversal is radial or tangential. Wood's greatest strength is to be found along the fibers and further from that direction the lower strength. The method explained here has been developed for its application on bending horizontal elements in real structures. In existent constructions the only surface where the experimental procedure can be carried out is often on the maximum tensile side. This surface usually coincides with an axial–tangential plane. The whole experimental procedure will be located in axial–tangential planes where a plane state of the stresses near surface will be considered (see next sections).

2. Hole-Drilling method including the orthotropic behavior

Hole-Drilling method is technically established in ASTM E837 Standard (Test Method for Determining Residual Stresses by the Hole-Drilling Strain Gage Method) where the procedure is defined as a method which measures residual stress close to the surface of an isotropic material. The method involves attaching strain gages to the surface, drilling a hole in the vicinity of the gages, and measuring the relaxed strains thus originated. After drilling, the strain gages record the relaxed strains which are related by means of four parameters with the existent stress state. These parameters are dependent upon the mechanical constants of the material, the geometry of the rosette, the depth of drill and the strain gage size. Three strain gauges are enough to determine the state of the stresses in two-dimensional situations as follows:

$$\sigma_{\max} = \frac{\varepsilon_1 + \varepsilon_3}{A} - \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B}$$

$$\sigma_{\min} = \frac{\varepsilon_1 + \varepsilon_3}{A} + \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B} \quad (1)$$

$$\beta = \frac{1}{2}\arctan\left(\frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1}\right)$$

where ε_1, ε_2 y ε_3 are the relaxed strains recorded by gages 1, 2 and 3 (Fig. 2), respectively, $\sigma_{\max}$ and $\sigma_{\min}$ are the principal stresses and β is the angle (counterclockwise) between $\sigma_{\max}$ and the ε_1 direction. The constants "A" and "B" in Eq. (1) are obtained as follows:

$$A = -\frac{2a(1+\nu)}{E}$$

$$B = -\frac{2b}{E}$$

where "E" and "ν" are the mechanical constants of the isotropic material and "a" and "b" are dimensionless constants identified in the ASTM standard. The involved dimensions (the hole diameter, strain gages rosette and depth of drilling) are well established in the ASTM standard as shown in Fig. 2, where all the dimensions are lower than 3 mm. Consequently, they have to be adapted to the experimental situation due to wood boring standardized size (18 mm) and the strain gage length (12 mm). In this sense, the rosette has to be handmade and specifically set up for each measurement because standard rosettes for wood applications are not commercialized. However, the proportion between hole diameter, strain gage size, and the circumference diameter of the strain gages disposal have been maintained according to ASTM Standard, $D = 40$ mm, strain gage length 12 mm, $d = 18$ mm and 16 mm in drill depth. The authors have vast experience in the application of the Hole-Drilling method with other dimensions to obtain stresses in-service structural members and in other materials [12–15].

Initially, the conventional Hole-Drilling method was only useful on isotropic materials but in the early 70s, Bert et al. made an exploratory investigation concluding that the Hole-Drilling technique could be successfully used in rectangular orthotropic materials [16]. It was in 1994 when Schajer and Yang published a paper with a mathematical solution for orthotropic materials, industrial composites in their case [7]. In our field, an experimental approach has been adopted because the structure of wood as a natural material is not homogeneous from a sample to another, at both microscopic and macroscopic level. Due to this heterogeneity the research achieves empirical solutions from an experimental work.

Experimental tests have been carried out on *Pinus radiata* D. Don specimens, a widely used wood in several European regions in the building of structural systems. As said, the plane where tests are going to be carried out is defined by the axial–tangential directions. Within this plane the wood is defined by two principal