Construction and Building Materials xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

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

# Assessment of timber floors by means of non-destructive testing methods

Tiago Ilharco [a,*], Thomas Lechner [b,c], Tomasz Nowak [d]

[a] NCREP – Consultancy on Rehabilitation of Built Heritage, Ltd., Science and Technology Park of University of Porto (UPTEC), Praça Coronel Pacheco no. 2, 4050-453 Porto, Portugal
[b] NCC Construction Sverige AB, Division of NCC Technology & Sustainable Development, SE-405 14 Gothenburg, Sweden
[c] Chalmers University of Technology, Dept. of Civil and Environmental Engineering, SE-412 96 Gothenburg, Sweden
[d] Faculty of Civil Engineering, Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, Wrocław 50-370, Poland

ARTICLE INFO

*Article history:*
Received 25 May 2015
Accepted 29 May 2015
Available online xxxx

*Keywords:*
Timber floors
Structural assessment
Non-destructive tests

ABSTRACT

In the process of rehabilitation of built heritage, the preservation of timber floors is an essential issue. These structures have characteristics that are not entirely known, namely the connections between elements, the load distribution between beams, the importance of secondary elements, such as struts and floorboard, for the attenuation of vibrations and reduction of deformations of the floor, etc. If properly analysed and considered, these aspects can contribute to upcoming well-succeeded interventions, improving the global behaviour of the floors and, consequently, of the buildings. One of the focuses of the present paper is the assessment of the global behaviour of timber floors by means of dynamic analysis, which is one of the non destructive tests (NDT) used to evaluate the reference properties of the wood. In particular, this technique allows estimating the timber floors' stiffness and, consequently, assessing their efficiency and integrity. Furthermore, the paper focuses on the use of other NDT methods, namely involving stress-wave timing, X-ray and resistance drilling, which can provide very useful information about these characteristics. The information obtained with the combined NDT allows a better understanding of the timber floors behaviour and the implementation of more efficient rehabilitation and (or) strengthening techniques.



## 1. Assessment and assessment strategy of timber floors

Historical structures represent a part of the cultural heritage of every nation and societies pay considerable attention to their preservation and maintenance. The in-situ assessment of timber elements and their properties is essential in the continuous maintenance and preservation of historical timber structures. Much of the damage observed in historical timber structures can be attributed to biodegradation. The deterioration of structural members results in changes in geometry and load-bearing capacity. The replacement of members that have deteriorated may not be an acceptable option for structures of historical significance and re-design may be necessary to sustain the functionality of the structure. The structural strength assessment of timber structures, which uses various procedures and evaluation tools, is based on a multidisciplinary approach aimed at providing information about the mechanical properties and actual condition of timber members and the mechanical behaviour of joints. Abnormal structural behaviour can be suspected when the strength and stiffness of a structure is diminished due to deterioration, creep and the natural ageing of old timber [1,2] which implies changes in load-bearing capacity. Strategies for the analysis of structures of significant cultural value must therefore be established.

A structural investigation procedure should be based on adapting a general assessment methodology [3–6] to evaluate the structural condition and the mechanical performance of the floor structures in an efficient manner.

The methodology comprises the following steps:

(1) Diagnosis of the structure from previous repair work and action during service life.
(2) Preliminary assessment and visual inspection.
(3) Detailed assessment and investigation including material testing with non-destructive and quasi-non-destructive testing methods at critical sections.
(4) Evaluation of the results of the material tests.
(5) Structural analysis and evaluation of results.

* Corresponding author.
*E-mail addresses:* tiago.ilharco@ncrep.pt (T. Ilharco), thomas.lechner@ncc.se (T. Lechner), tomasz.nowak@pwr.edu.pl (T. Nowak).

http://dx.doi.org/10.1016/j.conbuildmat.2015.05.133
0950-0618/© 2015 Elsevier Ltd. All rights reserved.

This methodology shall include global and local non-destructive in-situ tests, namely with the use of seismographs, resistance drilling machines, pilodyn, stress-wave timing, X-rays, etc. The thorough interpretation of these in-situ tests' results and the estimation of timber floors' properties can only be achieved with a complete constructive/structural characterization, along with the analysis of the state of conservation of the structural elements. This characterization includes usually a visual inspection and an analysis of the geometric characteristics of the beams, struts and floorboards, the type of connection between these elements and between the beams and the walls, as well as a survey of the state of conservation of these elements, normally supported by the use of some of the referred NDT. The characterization of the wood species and of its density is also an important step to build a preliminary model of the mechanical behaviour of the floor.

## 2. Global assessment through dynamic response

The discussion about the global assessment of timber floors through dynamic response will be systematized in four main topics: (1) the dynamic behaviour of timber floors; (2) the techniques and instruments used to assess this behaviour; (3) the prediction of the wood reference properties; (4) the identification of the damaged areas based on the dynamic analysis. These topics will be analysed through an overview of this subject and making use of results from several NDT performed in timber floors of old buildings in Portugal included in structural survey campaigns.

### *2.1. The dynamic behaviour of timber floors*

In residential buildings, the design of timber floors taking into account the vibration limit state has in consideration the excitation caused by the movement of people, which produces vibration frequencies of about 2 Hz and 3.5 Hz for walking and running steps, respectively. The dynamic response of a floor is determined by several factors, such as its mass, stiffness, damping and geometrical and structural characteristics, namely the existence of struts, the thickness of the floorboard, the type of connection between beams and walls, etc. In most cases, the floor stiffness ensures a satisfactory dynamic behaviour. However, it also happens that floors designed to meet the criterion of deformation exhibit vibration problems. The traditional deflection criterion does not always guarantee satisfactory vibration behaviour [7].

The issue of vibration induced by people walking on timber floors is more complex than the static behaviour due to the resonance phenomena. Resonance occurs when the frequency of the impacts that forces the vibration coincides with the natural frequency of the floor, resulting in a progressive increase in the magnitude of vibration, leading to an eventual structural failure [8]. In an occupied building, with high permanent loads, the increased mass may decrease the floor natural frequencies to critical levels, since timber floors themselves have low mass (50–100 kg/$m^2$). This reinforces the idea that the application of heavy materials on timber floors, such as concrete slabs, can result in unsuitable dynamic behaviours.

Therefore, it is fundamental that the timber floors' design respect the vibration limit states to fulfil comfort and safety requirements. Ref. [9] concluded that two criteria for lightweight floors with fundamental frequencies above 8 Hz should be considered: one related to the deformation due to a concentrated load and other to the speed of the vertical vibration. These criteria were adopted by Ref. [10] in the design of timber floors to the vibration limit state, ensuring that the loads acting on a particular structure or structural element will not cause vibrations that may involve an improper functioning or level of discomfort unacceptable to the users.

According to Ref. [10], the vibration levels should be estimated by tests or calculations, taking into account the parameters that determine floors' dynamic behaviour, namely mass, stiffness and damping coefficient. The knowledge of all these characteristics allows the assessment of the natural vibration frequencies and vibration modes associated to each frequency, i.e. of the response of timber floors when subjected to known dynamic actions.

### *2.2. Description of the method and instruments*

#### *2.2.1. Dynamic tests*

Dynamic tests using ambient vibration are one of the most effective non-destructive in-situ testing techniques to identify the mechanical characteristics of structures. The existence of highly sensitive sensors allows testing without imposing a forced excitement on the structure and considering only environmental dynamic actions, such as wind, traffic, movement of persons etc., [11]. One of the advantages of the use of ambient vibration in relation to the forced vibration is that it's not necessary to know the characteristics of the excitation. Given the random and independent characteristics of the actions involved in an ambient vibration test, it's usual to admit that all the natural frequencies of the structure are equally excited. Still, some authors consider that, in the case of timber floors, the forced vibration allows a stronger response and may provide more consistent results [12].

#### *2.2.2. Instruments used and precautions to have during data acquisition*

For measurements of the ambient vibration of timber floors, seismographs that include tri-axial accelerometers (GeoSIG GSR-18bit), with an acquisition frequency of 250 Hz, have been used by the author [16] in the scope of the consultancy work developed by NCREP – Consultancy on Rehabilitation of Built Heritage, Ltd., [37]. It's a method that provides the temporal registries of the accelerations to which the structure is subjected, Figs. 1 and 2. The seismographs allow the transference of the information to a computer to be analysed. Nowadays, there are simple electronic devices, such as smart phones, which are equipped with accelerometers, Figs. 3 and 4, and provide reliable results if correctly calibrated with seismographs or accelerometers.

The registration of the dynamic response of a structure is a fundamental phase of the tests. If the acquisition is carried out with errors, it will be very difficult to correct them during the post-processing phase. Therefore, it is essential to perform a careful planning of the tests, defining the equipment to use, its location and the duration of the test. The positioning of the devices should

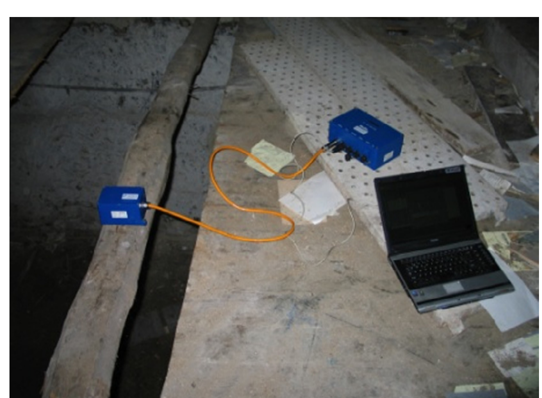

**Fig. 1.** Frequency measurement on a single timber beam.