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COMBINE USE OF NDT/SDT METHODS FOR ASSESSMENT OF STRUCTURAL TIMBER MEMBERS

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

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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, 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.

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 redesign 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

This methodology shall include global and local NDT, namely with seismographs, resistance drilling machines, pilodyn, stress-wave timing, X-rays, etc. The thorough interpretation of the tests' results and the estimation of timber floors' properties can only be achieved with an analysis of the state of conservation, along with a constructive/structural characterization. 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.

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.

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 2Hz and 3,5Hz 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, 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 an 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 "dangerous" levels, since timber floors themselves have low mass (50-100kg/m^2).

Therefore, it is fundamental that the timber floors' design respect the vibration limit states to fulfil comfort and safety requirements. [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 in [10] in the design of timber floors to the vibration limit state, stating that 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.

Description of the method and instruments

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]. 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].

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 250Hz, can be used, resulting in temporal registries of the accelerations to which the structure is subjected, Fig. 1. 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 and provide reliable results, Fig. 2.

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

Fig. 2. Calibration of smart phones accelerometers with seismographs.

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. It is, therefore, 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 be chosen so as to avoid areas of zero modal displacements and the data acquisition, in particular using ambient vibration, should be made by recording the dynamic response of the structure over a pre-defined time interval. Some other specific precautions should be considered during the tests, such as not disturbing the floor with the introduction of additional masses, such as those given by the test operators, and taking into account the presence of superimposed dead loads and its position.

Data processing and results achievement

After processing the collected data, the dynamic identification is done through the determination of the natural frequencies and the corresponding modes of vibration, which can consist on vertical, horizontal or coupled modes, depending on the main direction of vibration. One of the used methods is the Advanced Method of Frequency Domain Decomposition [13], currently implemented in the software ARTeMIS [14]. The fundamental frequencies of vibration of the floors are identified using the peaks observed in the records in the frequency domain (obtained via Fast Fourier Transforms, FFT). Fig. 6 show an example of the data obtained in the frequency domain, identifying the direction of higher vibrations associated. The value of the 1st frequency is 9.1Hz (z) and the 2nd is 10.0Hz (y).

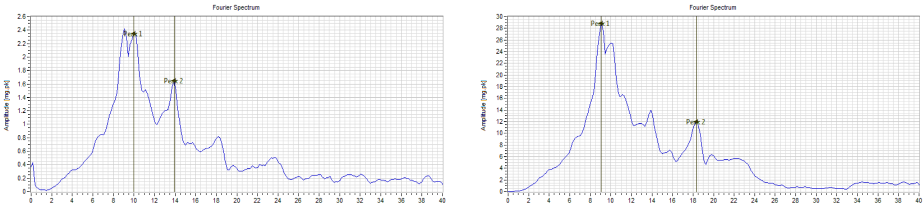

Fig. 6. Identification of the main frequencies of a timber floor (y and z).

Prediction of reference properties

The influence of the constructive elements of the floors

Timber floors are simple structures with a complex behaviour that depends on the performance of the whole system: the beams, the struts and the floorboard. In fact, the load distribution factor conferred by struts and floorboard, designated k_{sys} in [10], which accounts their stiffening effect, is essential to the estimation of the MOE when using the natural frequencies obtained in the dynamic tests. [15] determined that, in a common timber floor, the load distribution factor is 1,15, close to the one defined by [10] (1,1). Some in situ tests performed by [16] indicated that this factor can be even higher. The connections between different structural elements have also a strong influence in the vibrational behaviour of the floor.

Analysis of the results and prediction of the modulus of elasticity (MOE)

The dynamic tests performed with accelerometers positioned in different locations of a timber floor allow estimating some of the reference properties of the floor, namely the MOE. This approach can include simple calculations or more complex numerical models, which reproduce the in situ tests through numerical modal analysis. In this case, the numerical results are fitted to the results obtained experimentally by adjusting the mechanical properties through an iterative process. One must note that it's a very complex task to properly simulate the timber floors, namely due to their geometrical irregularities, types of connections between structural elements, etc. All these characteristics should be carefully integrated in the numerical structural analysis and, therefore, the calibration process should also be based on the data resulting from the visual inspection (geometrical, structural and conservation assessment) and other in situ tests.

If the estimation of MOE is developed through more simple calculations, rather than with numerical models, the need for understanding thoroughly the geometrical/structural characteristics of the timber floors is the same. For a simply supported beam, the fundamental frequency f_1 can be calculated using Eq. (2). Although the equation is defined for simply supported beams, [10] suggests its use for timber floors simply supported on the four sides. In this case, "$(EI)_{long}$" is the stiffness of the plate equivalent to the floor in the direction of the beams; "m" is the value of the mass per unit area and "L" is the span of the floor.

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_{long}}{m}} \quad (2) \qquad\qquad E = \frac{4 \times f_1^{\,2} \times L^4 \times m}{I_{long} \times \pi^2} \quad (3)$$

[8] states that the frequencies obtained in situ are typically up to 50% higher than the frequencies estimated using Eq. (2), thus suggesting its multiplication by a factor up to 1,5. This is due to the mentioned stiffness conferred, particularly, by the nailed floorboard and to the support conditions of the beams in the walls, which, in fact, don't correspond to simple supports. "$(EI)_{long}$" must account the increase of stiffness of the timber floor due to these conditions and should be obtained multiplying the stiffness of a simply supported beam (EI) by a stiffness factor (Sf) that, according to the frequency results obtained by [2], can go up to 2,25.
The MOE of the floor can be estimated following Eq. (3). Some experimental campaigns in a set of chestnut beams [16], including dynamic and bending tests [17] indicated a good approximation between the results of MOE obtained in both tests when multiplying the Eq. (2) by a value between 1,2 and 1,5 (equivalent to increase the stiffness of a simply supported beam with a factor (Sf) of 1,5 to 2,25).
This methodology is very useful to estimate the behaviour of timber floors in their present conditions and, in particular, in their future use, regarding, for instance, an increase of the live loads. The results can indicate the need to strengthen the timber floor in order to increase its stiffness and improve its dynamic behaviour.

Identification of damaged areas

Dynamic tests have the advantage, compared to other NDT methods, of allowing a global assessment of floors by measuring the frequencies and modes of vibration. However, they don't allow the separate analysis of the structural elements and may even lead to the occultation of some local damages. Therefore, the use of other NDT methods, such as X-ray, resistance drilling, stress-wave timing, etc. is fundamental to analyse thoroughly the state of conservation of timber floors. Still, since the dynamic response of the floor depends on the type of structural elements and connections, as well as on their level of degradation, these tests allow evaluating the global condition of a floor, helping in the detection of damaged areas.
The dynamic identification of other structural elements of a building, particularly walls, may also help to assess the behaviour of timber floors. In the particular case of a building in the city centre of Lisbon, whose in situ tests were conducted in collaboration with the National Laboratory of Civil Engineering (LNEC), the observation of two opposite facades responding in phase for lower modes indicated that the timber floors were effectively linking both walls [18]. This result, together with the observations made during the survey, confirmed the good condition of the timber floors. On the other hand, in a specific area of the main facade, an anoma-

lous behaviour was detected, with the identification of modes associated with a "free" vibration of this area. This result indicated that the connection between the timber floor and that area of the wall was deficient, probably due to the degradation of some timber beams, situation confirmed afterwards with a detailed survey.

Local assessment

As previously stated, the use of NDT, such as X-ray, resistance drilling, stress-wave timing, is fundamental in the local assessment to analyse thoroughly the state of conservation of timber floors and thereby the structural health of timber floor structures and their performance regarding the strength and stiffness values.
Once the critical sections are identified from a preliminary investigation, the corresponding actions on the floor structure can be quantified and therefore serve as a valuable input in the global analysis of the structure to achieve an as accurate response as possible.
Appropriate properties, such as density (ρ), the modulus of elasticity (MOE) and the cross-sectional properties, relating to the quality and health of single members need therefore to be determined using NDT.
The sequence of use for different assessment devices to detect and localise internal deterioration and damage, for example, is of great importance in an effective assessment procedure. It is therefore preferable initially to identify members requiring further investigation using global measurements, before applying methods such as resistance drilling and X-ray that require more effort and time.
The discussion about the local assessment of timber floors treats the techniques and instruments used to assess the structural soundness and performance. This also implies the prediction of local and semi-global material properties as well as the identification of damage and deterioration of structural timber members. Those aspects are integrated in the single method. These steps are presented in an overview and results from NDT investigations performed from a timber floor investigation of a historical structure in Sweden are roughly included in this survey.

NDT techniques for local assessment purposes

Among a number of different NDT tools to investigate timber structures, stress wave timing, X-ray measurements and Resistance drilling were studied to efficiently assess material properties and locally assess the performance of timber floor structures

Stress-wave timing

The transmission time is highly correlated with the modulus of elasticity (MOE), Eq. (4), which is of great importance for evaluation of the structural soundness of beams, purlins and columns in large timber structures [19]. Several commercial instruments, such as FAKOPP®, are available to measure and assess transmission-time in materials.

$$MOE_{dynamic} = \rho \cdot v^2 \qquad (4)$$

where ρ is the density and v the transmission time of the stress wave.
Stress wave measurements are a simple and efficient measurement technique to identify the internal soundness and condition of structural elements, but also to determine stiffness parameters for structural analysis. This technique requires an appropriate measurement strategy and approach to efficiently determine the structural performance of in-situ elements and to successfully detect internal damage, but also the extent of both external and internal damage. Such a stress-wave-based condition assessment strategy is simply illustrated in Fig. 11, where critical areas from the visual inspection where measured stepwise in different directions to identify decay and its extent of the structural element at different locations along the beam.

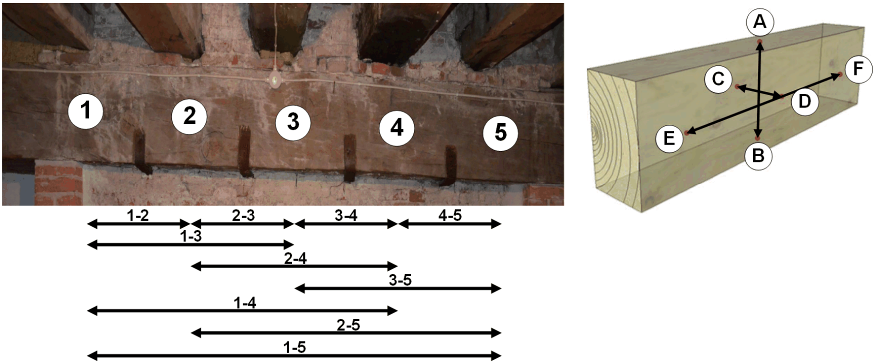

Fig. 11. (Right) Illustration of a stepwise (1-5) stress-wave-based assessment approach along a structural beam and (left) measurements in different directions to detect the extent of the damage/deterioration (A-B, C-D and E-F), adopted from [20].

Decayed and degraded wood show clear increases in stress wave transmission times, which also leads to a significant loss of strength [20]. An increase of the velocity sound by about 30% results in a loss of strength by about 50% [21, 22].
The longitudinal propagation of the stress waves vary from 4000 m/s to 5500 m/s depending on the wood species. Transverse propagation of the stress waves are about 25% of the value in the longitudinal direction and is mainly used as a qualitative parameter to assess the condition of structural elements and is the most efficient way to detect decay and its extent [23].
An appropriate measurement strategy to efficiently determine the structural performance as aforementioned is illustrated in Fig. 11.

Comprehensive longitudinal measurements on single element properties and the structural soundness were explored on a historical floor structure in Sweden [24]. The average velocity from the measurements throughout both of the timber floors was 4969 m/s (std. dev. 335 m/s), which is in the range of sound and good performing timber.

The principle to detect eventual deterioration as illustrated in Fig. 11 was performed on a historical floor structure in Sweden [24] in the upper and the lower floor, where the measurements for the upper floor showed rather constant velocities for all measurements with a slight decrease near the column, so no signs of degradation/deterioration were captured. In comparison to the upper floor, the lower floor, implied some signs of degradation/deterioration within the support region, where the velocity (3916 m/s) was about 20% lower than the velocity measured for sound members.

On-site X-ray investigations

The application of digital imaging processing and increasing resolution has made it possible to use quantitative assessments of components, such as the internal deformation of fasteners, the dimensions of hidden elements and strains [25]. Until recently, the opportunities for X-ray investigation have been used for the qualitative assessment of timber structures, but the opportunities to carry out quantitative evaluation are of great importance to evaluate the on-site structural behaviour.

The portability of available X-ray devices was a great step forward which especially facilitates the *in-situ* operation of e.g. timber structures. Portable units have shown to be promising, both with regard to quality and feasibility [26]. The ability to penetrate wood with lower-level energy X-rays and to record images with adequate quality, was evaluated in 1996 and further evaluations identified technical and logistical issues [27].

It is a well-known fact that timber density correlates well with other significant parameters such as MOE and bending strength (modulus of rupture, MOR), which makes it possible to provide indirect information about these properties by X-ray imaging, since real-time radiography (radioscopy) allows the study of component behaviour under moderate loads and is particularly suitable for timber structures due to the density differences. In order to obtain correct density data the X-ray equipment must be calibrated and an example of this is presented and thoroughly described by [26].

Mapping damage and deterioration of timber and mechanical connections is another powerful application for implementation of X-ray equipment on-site. As most of the portable X-ray equipment delivers images in a two-dimensional perspective, additional help using resistance drilling, for example, may be needed for the volumetric mapping of deterioration as a result of insect attacks. In many cases, a two-dimensional image is sufficient for determining the severity and progress of the invisible damage [28, 29], as decay due to rot and high moisture content can be seen and determined by measuring the area of the void.

In general, the qualitative radiographs from the investigation of a historical timber floor in Sweden [24] showed that the grain structure of the members was intact at critical sections. Radiographs of connections showed that the connection details were generally in good condition at the inspected locations except at one location where signs of deterioration close to the support structure was found, see Fig. 12, as verified by using resistance drilling.
The effect of local interior deterioration in structural elements needs to be taken into account in the general assessment and should be remedied.

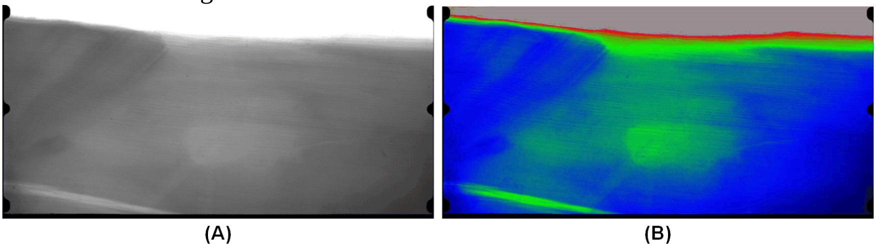

Fig. 12. A qualitative radiograph (A) & (B) of a beam in a floor structure indicates hidden deterioration (in the centre), as drilling resistance results verified.

Resistance drilling

Resistance drilling can be used to detect and quantify the internal condition and decomposition of the wood in timber structural elements. Although the drilling resistance causes tiny holes, it can be considered as a negligible influence on the structure, but should be preferably planned properly in the assessment in order to minimize the surgical intervention.
The use of that small diameter needle-like drill (1.5-3.0 mm at the tip) was introduced by Rinn [30]. Nowadays, there are some different commercial instruments available, e.g. IML RESIF400-S® (Fig. 13). The rate at which the wood is penetrated is constant. The torque needed to maintain a constant penetration rate corresponds to the drilling resistance and is graphically recorded versus drilling depth. Zones of lower drilling resistance can be identified as the ones with lower density. As a consequence those zones usually have lower strength and elasticity. Moreover, lower drilling resistance may indicate decayed zone, cavities, cracks and crevices. Peaks in the graph correspond to high resistance and high density. They also indicate the presence of knots in the cross section. Declines and low points correspond to low resistance and low density, including decayed zones, cavities or cracks (Fig. 13). Totally decayed wood shows no drilling resistance.
The drilling resistance is proportional to the relative variations in density, i.e. that decreasing drilling resistance is followed by decreased torque of the drill. A Resistance Measure (RM) parameter was implemented that allowed the comparison between the density of the drilling resistance and mechanical and physical properties of the timber. The RM parameter is though defined as the integral of the area of the drilling diagram divided by the length l of the drilled perforation [31], see Eq. (5).

$$RM = \frac{\int_0^l Area}{l} \qquad (5)$$

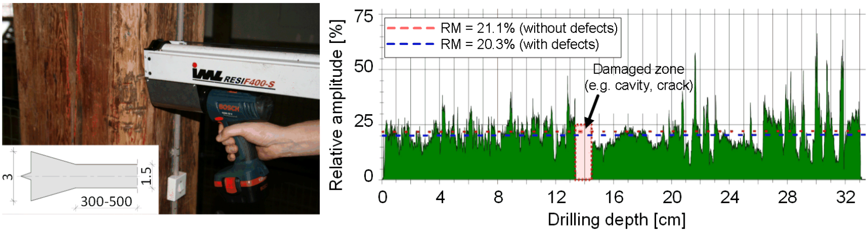

Fig. 13. (Left) IML RESIF400-S® and (right) density profile of drilling measurement. Drill shape and dimensions (mm) are shown in lower left corner.

This method is used to a great extent in the quantification of deteriorated timber. Resistance drilling enables to locate defects and structural discontinuities in timber members without affecting the performance, which is particularly important in the case of heritage structures [32, 33].
An investigation of a historical timber floor structure in Sweden showed that the coefficient of variation (CoV) of the obtained RM values is high [24], which increases the uncertainty when it comes to correlating the RM values with the wood parameters. In investigations of structural timber members in different historical structures carried out by the authors, partly reported by [34], the coefficient of variation reached values up to 37%.
Uncertainty about the potential for evaluating wood strength parameters using the drilling-resistance method was raised. It was found that many parameters, such as wood moisture content, drill-bit sharpness and drilling angle and direction, affect the drilling-resistance diagram [35]. The main purpose of the drilling-resistance method was therefore not the assessment of the mechanical properties of wood but simply the qualitative investigation of wood based on internal material defects. Due to its local measurement character, the parameter estimation requires several measurements.
Drilling resistance measurements can also serve as an input for determining effective cross-sectional areas of timber beams that affect the second moment of area and the load-carrying capacity of structural members in general.

Strength and Stiffness predictions from NDT

The densities from the radiographic measurements and the MOE calculations from the stress-wave measurements as mentioned previously might serve as an input in the analyses of the material resistances of the individual structural elements.

For this evaluation, the characteristic bending strength, $f_{m,k}$ (MOR), and shear strength, $f_{v,k}$, for example can be calculated according to [36] and [37] respectively, using the following expressions:

$$f_{m,k}\ [MPa] = 0.002065 \cdot MOE_{static} \quad (6)$$

$$f_{v,k}[MPa] = 0.2 \cdot f_{m,k}^{0,8} \quad (7)$$

The static MOE (MOE_{static}) is usually acquired from the dynamic MOE by a linear relationship equation according to Eq. 8 [38], but they can also be obtained directly from the density measurements, Eq. 9 according to [36].

$$MOE_{static} = 407.2 + 0.796 \cdot MOE_{dynamic} \quad (8)$$

$$MOE_{static} = 25.186 \cdot \mathbf{G^{0}.9454} \quad (9)$$

The quantitative evaluation of the mechanical properties and the density using stress-wave timing and radiographic measurements provided both good agreement and reasonable input for the structural analysis.
It is, however, important to remember that there may be some uncertainty about the correlations for timber between the output from the measured properties and the strength parameters using assessment techniques that might weaken the estimation of the actual capacity.

Conclusions

The focus of the present paper is the assessment of the behaviour of timber floors with the use of global and local NDT, namely involving dynamic behaviour analysis with seismographs, stress-wave timing, X-ray and resistance drilling.
The use of instruments to assess the dynamic behaviour of the floors, such as seismographs, has the advantage of allowing a comprehensive assessment of the timber floors' global behaviour, by measuring the characteristics associated with their dynamic performance, which allow estimating MOE. It can also evaluate the global state of conservation of the floors and detect damaged areas, which are usually associated to lower natural frequencies and, consequently, to lower MOE.
However, the use of seismographs does not allow the separate analysis of the structural elements that compose the floors and it may even lead to the occultation of damaged elements. For that reason, it should be used together with other NDT that can lead to the prediction of local properties, such as stress wave timing, resistance drilling and X-rays. To assess the general quality of the timber, it is sufficient to apply stress-wave measurements, in combination with resistance drilling and X-ray measurements. Reliable results can be obtained, thereby increasing the ability to minimise interventions and prolong the service life as a part of sustain-

able development. The extent of measurements should be adjusted to match the structural condition and existing information relating to the structure [24].
The combined use of these NDT allows a better understanding of the timber floors behaviour and the implementation of more efficient rehabilitation and (or) strengthening techniques.

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