Review on the Assessment and Repair of Cultural Heritage Timber Structures.

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Abstract. From the goal of maintaining the service life of a structure comes the need to determine the condition of the structure in situ and then plan an appropriate intervention. Especially when working with timber on historical buildings, all care must be taken in order to obtain proper data about its state, because the aim is not only the repair of the structure itself, but also the preservation of the history it carries with it. Having this in mind, this paper focuses on the literature review on how to assess the structures of ancient and historical buildings made out of timber, the most common methods for determining structural integrity in situ, focusing on non-destructive testing (NDT), interventions that could be useful and the importance of each method. There is a great variety of species of timber with different properties such as density, strength, water absorption, etc., which makes it important to determine them as well as the type of wood which requires testing beyond mere visual inspection. It is noted that the solution proposed in each case must consider aspects such as the load configuration and ductility of the original structure so the intervention doesn't change said aspects and, consequently, the global behaviour of the system. The substitution of members should always be avoided, and only considered in a situation that has no other solutions, since it compromises the aesthetics and historical values of the building.

Keywords. Assessment, Cultural Heritage, Historical Buildings, Intervention, Non-destructive Testing, Timber Structure.

1. Introduction

Cultural heritage buildings often use timber as a structural element, be it to support roofs, floors or the whole system. From past times, timber has been widely used and preferred over other materials due to the abundance of wood, its high mechanical properties and good workability [1] and until today is used in constructions. Lots of structures built with this material exist now and carry within themselves not only the building itself but also the history behind it as well as possible information about the technology of the society at the time based on the tools and techniques used, which are very difficult to retrieve once lost, as discussed in [2].

In order to maintain the integrity of these ancient constructions that are sometimes submitted to various conditions, including weathering, humidity, seismic loadings or even biological attacks by insects that affect the mechanical properties of the material, it is necessary to evaluate the state of the structure. Due to the sometimes delicate conditions of the elements to be evaluated, non-destructive testing (NDT) is often the best approach for these situations because they cause little to no damage to the structure, thus making the process safer than tests that require larger samples from a structure that is already damaged.

After gathering the data regarding the affected members, a restoration solution must be proposed. Interventions should always consider the principles of the Venice Charter [3], that provides a guideline for the preservation and restoration of historical monuments. Many different solutions are possible to implement nowadays, as shown in [4] in a way for the professional responsible for the intervention to be aware and choose the solution that best fits each situation.

2. Methodology

The first step taken in the elaboration of this literature review was searching for appropriate keywords to be used further in the research. Google Academics was the first database used to get a general overview of the articles, books and journals related to the main theme of this paper, thus being

possible to obtain more keywords and refine the search even more.

After that, the research was extended to other databases, such as Elsevier and Springer in order to find more specific materials related to timber structures of cultural heritage constructions. After relevant papers were found, the reference material of them were also checked hoping to obtain more information. Aspects such as number of citations, background of the journals that published the articles, and other works of the authors were also checked, mostly using the Scopus database, to guarantee the quality of the information.

3. Common inspection methods

The thorough inspection of the elements must be conducted to obtain precise information about the current state, properties and heterogeneity of the timber being analysed. As seen in [5] the importance of the detection of defects e.g knots, checks, splits and local grain deviation, is because they cause an alteration of the resistant section, thus generating a complex distribution of stresses.

To assess these types of structure present in cultural heritage buildings, non-destructive testing (NDT) are great approaches for not causing further damage to the element, since stressing even more an old structure with the presence of defects and that is sometimes submitted to harsh conditions could be critical.

Some of the most used methods on the inspection of said constructions are listed as follows.

3.1 Visual strength grading

One of the most common methods of assessment of timber structures, visual strength grading (VSG) consists in the visual inspections of the elements to locate possible macroscopic defects and based on them determine the elements mechanical properties. Standards such as UNI 11035-1 and UNI 11035-2 [6-7] respectively provide the guidelines for the measurements, terminology, rules and characteristic values for timber in Italy and can be used as reference for inspections of timber elements.

Even though it is the centre of some controversies due to being a method subjected to the grader's experience as stated in [8], and usually present results that are lower than the actual bearing capacity of the structure [9], VSG is a great method for obtaining the initial information about the condition of the elements.

When paired with NDT it is possible to obtain reliable information about the structure, since the visual grading method has some limitations. The detection of internal defects is for example not possible using only VSG. Also, as briefly discussed in [10] VSG lacks a general measurement protocol, which might cause doubts including which areas to sample, how many measurements should be made in each element and which of them to select to perform the inspections.

3.2 3D imaging

3D imaging methods are basically able to obtain a 3D model of the analysed object by an overlap of images, which can be obtained from sources such as digital cameras, satellites, scanners and even drones. As stated in [11], photogrammetry methods have the advantage of allowing a multi-temporal comparison of the object through the usage of its past images, and Bitelli et al. shows in [12] the construction of a 3D model using only historical images of the tower of Sant'Alberto, destructed in the year of 1944.

Aside from photogrammetry, information could be obtained from terrestrial laser scanning (TLS). It is a technique based on sending infrared laser beams and processing the reflected light of the objects, as better explained in [13], that also recommends to take care with aspects as angle of incidence of the beam, distance, visibility limitations and environmental conditions when performing the test, since it can affect the effectiveness of the results. [11] also make recommendations on how to obtain better images when using photogrammetry methods, such as constant and homogeneous lighting, avoiding flash light, optical stabilisation and digital zoom. [11, eq (1); eq (2)] provide ways of calculating the accuracy of the 3D result.

3.3 Wave methods

Wave methods involve the emission of waves and measuring its propagation speed, thus identifying internal defects and the material's characteristics such as modulus of elasticity. As described in [14] the equipment consists of an impact source to generate the wave stress and two sensors attached to the piece, which will sense the wave. The time required for the wave to propagate between the sensors is then determined and then it is possible to calculate its velocity.

Using this method, it is possible to determine the dynamic modulus of elasticity of the element, and [14, eq. (8); eq. (9)] shows respectively how to obtain the dynamic modulus of elasticity and its relation with the static modulus of elasticity.

The method is also important to assess old timber. A. Kandemir-Yucel et al. [15] used ultrasonic velocity methods (UVM) in combination with infrared thermography to examine Aslanhane Camii, a 13th century mosque, using a portable instrument to produce the ultrasonic velocity data and evaluate some of the pillars of the construction. They found that UVM has a sensitivity to changes in moisture content caused by microclimatic conditions, which should be determined so that the UVM results could have a better interpretation. [16] provides useful information regarding the end results of ultrasound and stress wave techniques and how the results by each method tend to equalise with the increase of timber size. They also showed that the

measurement of global velocity is not influenced if performed in the surface-edge or in the cross-faces if using the same device, thus giving the examiner less trouble when assessing elements with difficult access.

4. Structural interventions

Assessing the structure, although an important step, is only the first one towards solving the issues within the analysed timber elements, and proposing a solution that not only solves the structural problems but also preserve the historical traits of the construction proves to be a great challenge.

Even though sometimes each element can be evaluated separately during the inspection phase, it is important to understand the structure as whole when proposing the solution, since an inappropriate intervention could cause further problems, as changing the original ductility distribution among the elements, thus causing changes to the mode of collapse and structural behaviour [17].

In face of all the possible interventions, it is worth noting that the replacement of whole structural elements is not recommended by some authors [2,4,18] as it fails the objective of preserving the historical aspects of the structure, and should be used as a last option if no other solutions fit the case. [2] shows that there are some techniques available to copy the original piece's design and aesthetics that are used when substituting a whole structural element for a new one, which demands skillful carpenters to perform such tasks.

Strengthening the structure (elements and joints) is an important intervention to increase the capacity of the structure, prevent possible future defects and better distribute the stresses. Nonetheless, it is also important to be aware of other conditions present, such as humidity and the decay caused by insects, that could be prevented by other methods.

4.1 Measures against moisture

Moisture and moisture variation are big problems when dealing with timber due to the fact that it might lead to decay, volumetric variation and changes in strength.

Dealing with humidity can sometimes be a harder task than it looks. Rosina (2018) [19] suggests that the best intervention against moisture is monitoring the elements for a prolonged time. The author also mentions the importance of rain canalization in historic buildings to prevent the presence of water.

Preventing contact with soil when possible is a great measure. In [20] for example, the columns of the examined structure had serious rotting problems caused by moisture, and the chosen solution by the authors was to add pedestals and elevate the elements to prevent direct contact with the ground and thus the intrusion of water by capillary forces. Humidity plays a significant role in the strength of timber, as well as causing problems related to shrinkage, which makes its prevention critical.

4.2 Strengthening of the structural members

Many are the possible solutions that fit the reinforcement of the structural members made of timber. The first one to be discussed is the strengthening of beams by the usage of pre tensioned cables centering the bottom of the element and connected to the end of the pieces as shown in [4]. The authors also recommend using coupled cables for better stability, and warn about the drawbacks of this particular solution because it occupies a considerable amount of height and the strength added is not that outstanding.

Strengthening using plates made of steel or fiber-reinforced polymers are a viable option. They do not require the amount of height necessary for the centering cable solution given the dimensions of the plate, are not aggressive towards the aesthetics of the timber structure and could also provide a great increase in stiffness and strength as seen in [21] where the authors analysed the performance of steel plates and carbon fiber-reinforced polymer (CFRP) in glulam. [22] shows that CFRP reinforcements using strips proved to be effective in reducing the deflection of elements by tests made in prestressed beams.

Steel reinforcements, although really effective from the strength gain point of view, need attention when it comes to exposure, since it can generate problems related to corrosion and condensation of water, causing moisture related issues in the structure [2].

4.3 Strengthening of the joints

Strengthening the joints of the structural members is also crucial when treating historic timber structures. The malfunctioning of a joint could change the distribution of stresses along the structure, causing overloading on some pieces and possible changes in the rupture mode.

Branco and Descamps (2015) [23] provide detailed information for appropriate types of reinforcement for each kind of connection. When dealing with tenon joints for example, the authors propose solutions utilising wooden wedges to assure better contact between the pieces or fashioning it with a dovetail tenon to increase strength. For notched joints it is recommended to use bolts, stirrups and binding strips, and as for scarf joints the best solutions include adding fasteners such as bolts or screws.

Branco et al (2011) [24] also studied the efficiency of stirrups, tension ties, internal bolts and binding strip connections in a series of cyclic and monotonic tests compared to unstrengthened joints. The results showed that all the strengthening techniques analysed improved ductility, strength and viscous damping ratio, although some with their drawbacks, such as how the binding strips could be very difficult to implement in situ. The

authors concluded that insertion of a bolt across the connection axis or stirrups positioned in two sides of the connection, bolted to the timber piece showed the best results.

5. Conclusions

Given the discussed topics it is possible to conclude that cultural heritage buildings carry within themselves important parts of history and the remains of the technology, culture and other aspects of past societies. In order to maintain these old constructions a thorough examination of its condition and latter repair intervention should also take in consideration the preservation of historical and aesthetic values whenever possible.

The methods of assessment should be chosen according to the situation, and NDT are usually good options for not causing damage to the structure. Different NDT should be performed for the same structure, so that each test can complement each other, thus providing more reliable information about the structural condition, since some tests, such as VSG alone, could lead to over conservative values.

Repair proposals are as important as any other step when approaching historical timber constructions, and should fit the peculiarity of each case. The structure itself should always be analysed as a whole and not each element and connection completely isolated from the rest, as it might cause different stress distributions, as shown in [17].

To surpass the lack of a specific methodology for the assessment of cultural heritage timber structures, the professionals responsible for this task should familiarise themselves with the work of many authors that discuss the reliability of tests, show case studies with different conditions and interventions and provide more information on the topic.

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