Camilla Colla*

Verification of sonic tomography outcome through local testing of mechanical properties in historic timber beam

Weryfikacja wyników badań przeprowadzonych tomografem dźwiękowym poprzez przeprowadzane punktowo testy właściwości mechanicznych zabytkowych belek drewnianych

Słowa kluczowe: diagnoza, zabytkowe belki drewniane, tomografia dźwiękowa, właściwości mechaniczne, próba ściskania

Key words: Diagnosis, Historic timber beam, Sonic tomography, Mechanical properties, Compression test

1. INTRODUCTION

Since many years a number of NDT (Non Destructive Testing) techniques have been developed and subsequentially refined for the aims of non-invasive diagnose on site, assessment of the health-state conditions and preservation state of existing and historic timber members in constructions [1–2]. Such methods, including drilling penetration resistance, surface stiffness, sonic transmission and tomography, ultrasounds, acoustic emission, GPR radar, IR thermography, exploit different principles and types of waves: mechanical, acoustic, electromagnetic signals [3–7]. They are commonly divided into local or global methods depending on whether the inspection concerns a portion of the element or the whole timber member and they are able to indirectly provide information about material geometry, density, mechanical properties, decay extent, presence of heterogeneities and knots, moisture. A combined use of more than one method, for example in an inspection approach that requires a progressive level of detail, is recommended and beneficial allowing obtaining more accurate and complete results (i.e. to detect weak and unsafe points of the structure) and estimating the overall status of the structural elements [8].

It is known, that the physical-mechanical properties of timber or the presence, location, amount and type of decay are not directly measuredvia NDT or MDT (Minor Destructive Techniques) but estimated or determined through correlations between measured parameters and the characteristic properties searched; correlations which are not always unambiguous nor lacking uncertainty [9]. As an example, in the drilling penetration resistance method, the resistance observed while drilling a small diameter bit into the timber is related to density variations within the element caused by presence of knots, decay, cracks, interior voids, etc.; thus, these features, although not visible to the naked eye, can be localized and their extension determined. Nonetheless, being it a local test, it is not sufficient nor convenient to estimate by itself the overall health-state of a structural element [8]. When acoustic signals are used (ultrasounds, sonic transmission, acoustic tomography), decayed areas and heterogeneities can be determined considering the changes in the values of time of flight or of signal propagation velocity [3–5]. Moreover, the recorded parameter scan be analysed and correlated with mechanical properties (elasticity and strength) of the structural members. However, such estimations, very important from a structural viewpoint, are based on theoretical assumptions and require the knowledge of material density which is not directly measurable on-site in a non-destructive way but it has to be estimated too (unless it is measured in the lab on samples) introducing an additional degree of uncertainty [10].

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Cytowanie / Citation: Colla C. Verification of sonic tomography outcome through local testing of mechanical properties in historic timber beam. Wiadomosci Konserwatorskie – Journal of Heritage Conservation 2016;47:71-79

Otrzymano / Received: 04.12.2015 • Zaakceptowano / Accepted: 15.12.2015 **doi:10.17425/WK47TIMBERBEAM**

Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

Electromagnetic signals based techniques such as IR thermography or GPR radar are not yet common in practice for the diagnose of timber structures but their use is rapidly spreading as they are immediately applicable to scan large areas on site allowing a quick evaluation of the health status of large portions of timber members, detect knots, cracks, decayed and moist areas [6]. IR thermography is contact less but superficial; instead GPR allows obtaining information regarding decay, knots, splits,... also within the thickness of the elemental though a skilled operator is required for data acquisition and interpretation [10].

One of the main common advantages of all the above-mentioned NDT methods is the capacity to produce distribution plots from the measured parameter values, thus easing data interpretation and supplying info about investigated areas rather than punctual information. Those are among the benefits of image diagnostics. Anyhow, more researches and investigations are needed to find proper correlations between measured parameters and characteristics properties of timber elements i.e. to accurately estimate the strength and stiffness of the structural members but also to properly locate and quantify extension of deteriorated areas.

2. AIMS OF THE WORK

Even though positive examples of NDT applications are reported for timber structural elements, often the question arises if their results are only of qualitative nature or if estimation of mechanical properties can be considered of quantitative or semi-quantitative value [8].With reference to a decayed and partialised cross-sectional slice of a historic timber beam, the laboratory experimental work presented here is aimed at correlating the outcome of sonic tomography investigations with the outcome of visual inspection from ex-post autopsy and with results from mechanical compression tests in grain direction carried out on small specimens obtained by further cutting the slice. The scope is to establish a relationship between results of NDT and mechanical parameters from destructive tests.

3. DECAY EXTENT DETERMINATION IN TIMBER BEAM BY SONIC TOMOGRAPHY

The application of sonic tomography on a portion of timber beam had the purpose of investigating with high resolution a cross-section of the element where decay due to brown rot was present. In particular it was important to grade the severity of material damage by means of a non-destructive testing technique capable of imaging the local situation in sub-areas of the cross-section.

3.1. Description of the test object

A historic timber beam was available in the LISG laboratory of Bologna University after dismantle from the roof of a historic palace in Ferrara, Emilia Romagna region, in Northern Italy. The beam included an extended decay area but its moisture conditions were in equilibrium with its new environment after many months of storing in the laboratory [9]. The silver fir beam had almost square section with average height of 28.5 cm along its length. The section contained the pith of the log in central position and presented deep shrinkage cracks (Fig. 1 left and centre). The greatest crack, on the left face, reached almost the pith. The cross-section was selected because at visual inspection it appeared severely decayed at the lower part of its right face and at the intrados. It was considered that the presence of both the deep shrinkage cracks and the decay would make challenging the investigation by acoustic tomography.

3.2. Principles of sonic tomography

The word tomography derives from the Greek language and it is made of two words: "tomos" (slice) and "gràphos" (image). Tomography allows the reconstruction of a three-dimensional object measuring the energy passing across it. Such energy is generated along the external perimeter of the object, via different techniques and by using waves of different nature (transmission tomography).

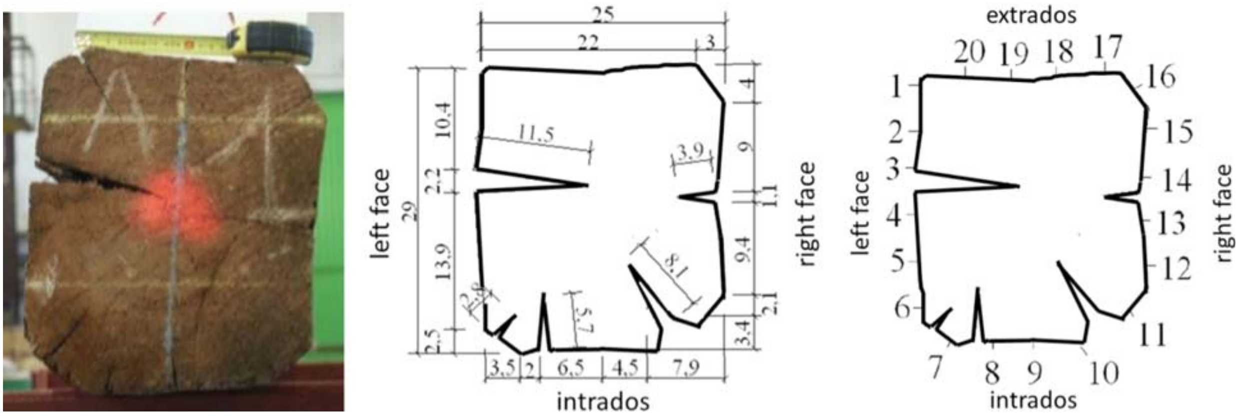

Fig. 1. Beam end view (left), geometric survey of tested cross-section (centre); tomographic stations along the perimeter (right)

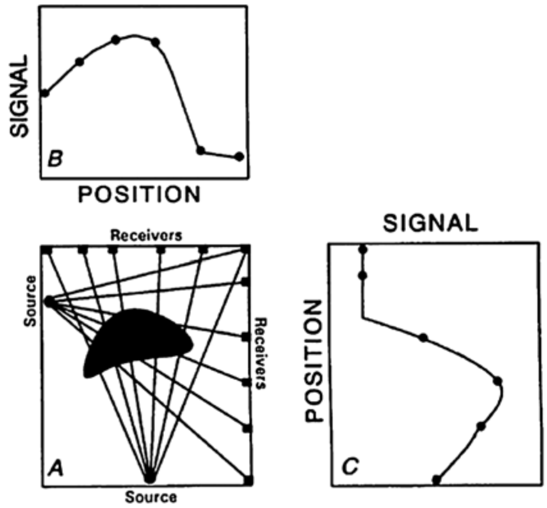

Fig. 2. Projections building in tomography of a rectangular section containing an irregular void [11]

Two-dimensional tomography is considered in the following. The object can be perfectly reconstructed through a complete set of its projections. In order to obtain the projections, the object is explored by a dense net of measurement paths. These are variously crossing each other and have different path angle. The waves interact with the material and are measured after passing through it. Variations inside the object, such as variations in density or presence of voids and cracks, are appreciated in the form of modifications of the received signal. In other words, the received signal provides a projection of the object's internal properties (Fig. 2). Transmitting and receiving points have to be placed along the perimeterso that the signal paths are distributed over the investigated section according to uniform density (Fig. 1 right and Fig. 3).

In acoustic signal tomography, such as sonic tomography, signal parameters that can be measured are primarily: travel time, amplitude and frequency. Travel time inversion foresees measuring first all the times of flight of the signals between transmitters and receivers. Known on a (X,Y) system the geometric coordinates of each measuring station along the perimeter, also the path lengths become known, if imagined as ideal straight-line paths. Starting from an average value of signal velocity in the section and after having subdivided the area in regular sub-portions or pixels, tomography reconstructs a map of signal velocity distribution by subsequent iterative calculations in the so called "velocity model".

3.3. Use of acoustic waves

Different types of signals are variously sensitive to different physical properties of the material. So, for example, acoustic waves provide indications about the elastic properties of a material. Acoustic waves are of elastic type and their velocity of propagation in the medium is a function of Young modulus (*E*), of material density (ρ) and Poisson coefficient (ν). The wave velocity (*V*) increases proportionally with the increase of elastic modulus:

$$Vp = \sqrt{\frac{E}{\rho}\frac{1-\nu}{(1+\nu)(1-2\nu)}} \qquad (1)$$

This means that sound material will be characterised by higher velocity compared to degraded material. From equation (1), the dynamic modulus of elasticity can be obtained. The application of a 10–15% reduction on this value permits estimation of the static modulus of elasticity, averaging between various experimental relations reported in [12]:

$$E_{stat} = a \cdot E_{din} + b \qquad (2)$$

Instead, other authors [13] propose elasticity modulus relations in the various anatomical directions, i.e. for soft wood:

$$E_L : E_R : E_T = 1 : 13 : 20.5 \qquad (3)$$

where E_L is the longitudinal modulus of elasticity, that is in direction parallel to grain, E_R is the transversal radial modulus and E_T is the tangential modulus transversal to grain.

In [14] are reported indicative values of modulus for various timber species. I.e., for spruce, E_L = 11.71 GPa, E_R = 0.83 GPa, E_T = 4.94 GPa. These authors also indicate

$$E_L : E_R : E_T = 20 : 1.6 : 1 \qquad (4)$$

For Italian Northern fir, [15] reports E_L =12 GPa and modulus perpendicular to grain of 0.4 GPa. In all types of waves, frequency (*f*) and wavelength (λ) are related to wave velocity:

$$V = f \cdot \lambda \qquad (5)$$

Shorter wavelengths are reflected and/or deviated by small defects and, thus, have higher resolution but short wavelengths are typical of high-frequency waves. Conversely, high-frequency signals such as ultrasounds are quickly attenuated, hence cannot penetrate great material thickness or low-density media such as decayed material. Instead, low-frequency waves such as sonics can cross greater thicknesses and lossy materials although, because of their greater wavelengths, have lower resolution. In simple signal transmission methodology, as a rule of thumb the resolution of sonic signals equals about one third of the wavelength. That is the smallest detectable defect is greater than one third of the typical signal wavelength. Instead, in tomography the obtainable physical resolution is much improved and this is one of the main advantages of applying tomography, which in itself is more time consuming and user know-how demanding.

The wood anatomical direction of wave propagation influences its velocity. This is due to the fact that

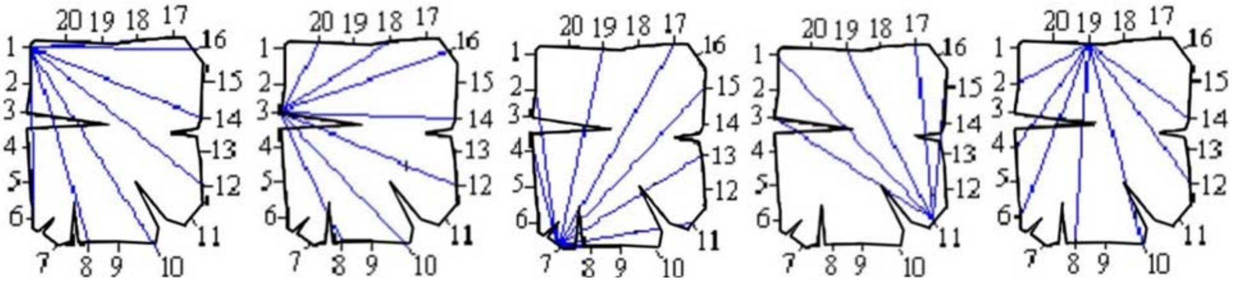

Fig. 3. Visualization of some single measurement fans: transmitting stations number 1, 3, 7, 11, 19

anisotropy affects all the wood mechanical parameters, thus also the elastic modulus, which, as seen, is related to elastic waves propagation velocity. Velocity is maximum in grain longitudinal direction and minimum in tangential direction. In radial direction, velocity values are intermediate between longitudinal and tangential. Further, wave velocity decreases when decayed areas are present. In such cases, two phenomena may occur: waves tend to deviate from the straight path in order to pass through the sound material and avoid the degraded part or voids; waves cross the decayed timber but due to its lower mechanical characteristics (elastic modulus) their velocity decreases.

3.4. Equipment, data acquisition and data elaboration

In the reported tomography, sonic pulses were generated by tapping the beam surface by means of a small instrumented hammer capable of a maximum signal frequency of 10 kHz. Much lower frequencies – 1 kHz or less – were obtained on the historic timber material. The hammer was connected to a signal conditioner and amplifier, as was a mini accelerometer used as receiving probe at the reading stations, where coupling was improved by using plasticine at the sensor/wood interface. At each measurement, 2 waveforms were recorded: one

Fig. 4. Details of the beam 4 faces with tomography stations after data acquisition: left face and intrados (top left and right), right face and extrados (bottom left and right)

from the hammer blow, a 2nd from the accelerometer. Then, the wave travel time between hammer and receiver is calculated as difference of time between arrival of the wavefront to the receiver and its generation instant by the hammer strike.

Despite strong irregularities in the material surface, 20 reading stations were marked as regularly spaced as possible along the cross-section perimeter (Fig. 1 right and Fig. 4). All stations progressively acted as signal transmitting points. Seven-ray fans were departing from each source point connecting it to 7 stations acting as receivers (Fig. 3). Hence, the beam section results homogeneously covered by the ideal ray paths. During data acquisition it was not possible to use stations 9 and 10 as transmitting point, located on strongly decayed area, because of the softness of material that inhibited transmission of signals of sufficient energy (Fig. 4 top right).

One data post-processing step was concerned with the effect of timber anisotropy on the measured sonic signal travel times across the transversal section. This effect was corrected so as to eliminate the signal velocity dependency from the test path direction, with regard to the wood annual grow rings. The procedure permits relating the sonic pulse velocity in a generic direction inside the timber element to the pulse velocity in radial direction [16, 17]. The observable benefit is an increase in signal velocity along the boundaries of the section (Fig. 5). Afterwards, the tomographic inversions were initiated starting from straight-ray iterations (contrary to reality, in this phase the sonic wavefronts are supposed to travel along straight line paths) and followed by curved-ray iterations. The monitoring of calculation error reduction after each iteration was used as criterion for deciding when to stop the inversions.

3.5. Visualisation of tomography results and their interpretation

The signal velocity distribution obtained after a number of tomographic inversions shows strong differences in values ranging from about 350 m/s to 1700 m/s. The high values in the map are representative of material in reasonably good conditions, tested in direction transversal to grain. Instead, the low velocity pixels locate 3 distinct areas: the largest at the lower right corner of the section points to the decayed timber and appears more extended than what would be appreciated by simple visual inspection. Other areas of low velocity are located by the blue and light blue pixels at mid-height on the left and right borders. These pixel positions correspond respectively to the deep crack on the left face and to a second shrinkage crack on the right face. Here, it has to be born in mind that in presence of an obstacle along the propagation path, the wavefront bypasses it, travelling a longer way around. Hence, a longer travel time is recorded, giving rise to an apparent decrease in signal velocity through the material. The map interpretation is eased when the section perimeter is overlapped to the velocity output (Fig. 6). The 2 images in this figure propose pixels of approximate dimension 2.5 × 2.5 cm^2 and 5 × 5 cm^2 respectively. It can be noted that, as anticipated above, the tomographic resolution is very much improved over the resolution of non-tomographic inspections. Overall it appears from these models that the average velocity through the section is low, that is below 1000 m/s with only limited areas – particularly in the centre of the section and at the top – where the recorded velocity seems to indicate sound material.

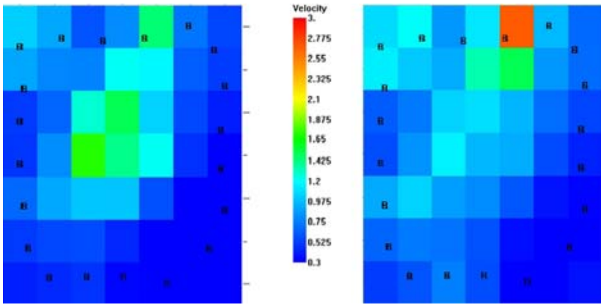

Fig. 5. Velocity model (7 × 7 pixels) of the timber section not corrected (left) and corrected (right) for material anisotropy obtained from 10 iterations of straight type. Signal velocity legend from 300 to 3000 m/s. The black dots in the images represent the reading stations along the section perimeter

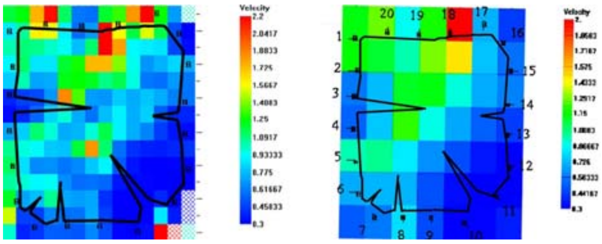

Fig. 6. Velocity model (14 × 14 pixels) of the timber section, corrected for material anisotropy, obtained from 5 iterations of straight type and 6 iterations of curved type. Signal velocity legend from 300 to 2200 m/s (left). Velocity model (7 × 7 pixels) of the section after 5 straight iterations and 5 curved iterations. Signal velocity legend from 300 to 2000 m/s (right)

4. AUTOPSY OF THE BEAM AFTER NDT INVESTIGATION

After completing tomographic analysis and outcome interpretation, the cutting of a beam slice in correspondence of the tomography tested section was intended to inspect the material and verify any possible visual correspondence between the degraded areas and the tomography results. In view of later possible mechanical verification on specimens extracted from this cross-section, the slice thickness was chosen quite thin, 5 cm, so that the decay state could be considered homogeneous in the thickness (Fig. 7 left). The outcome of close up inspection on the timber slice revealed first of all a consistent loss of material not only in correspondence of the edges of the decayed area but also at inner positions due to the combined action of rot and insect attack. Deepening of decay in the section appeared favoured along radial direction fissures and along annual grow rings. Further, darkening of the timber due to rot highlighted

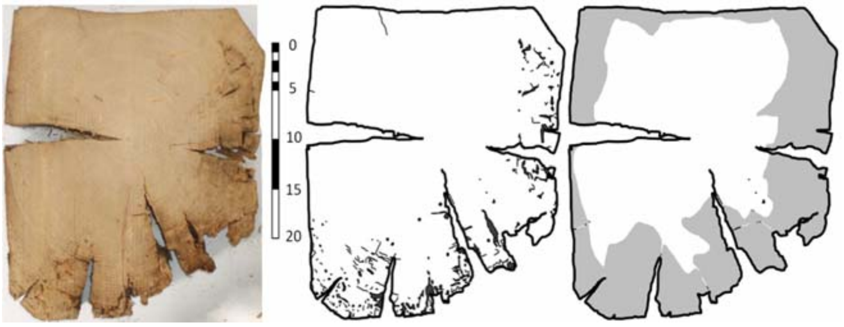

Fig. 7. Post-autopsy view of health situation of beam cross-section (legend in centimetres, left), distribution of insects attack on section surface (centre), decay distribution due to brown rot (right)

the extent of severe degradation. At these locations, the timber appeared softer and of little consistence (Fig. 7 centre and right).

5. LOCAL MECHANICAL CHARACTERISATION ACROSS BEAM SECTION

Visual inspection of the timber slice was followed by mechanical characterization of local properties of the material. The aim was to perform a certain number of mechanical tests on small timber prisms to attain direct values determination, readily comparable with indirect determinations from non-destructive tests previously carried out.

5.1. Specimens' size determination and cutting

Further cutting of the slice was needed to extract regular specimens for compression tests in grain direction. Resembling the grid of 7 × 7 pixels visualised by tomographic inversion on the timber cross-section (Fig. 6 right), a similar subdivision was planned for the specimens aimed at mechanical testing. Due to material loss at the lower right quadrant of the section during slice and specimens cutting (Fig. 8 left) only 17 cubic specimens (dimensions 4 × 5 × 5 cm^3) were obtained out of the 25 pixel visualized in tomography (Fig. 8 centre). The grid with the codes of each specimen was marked on the front face of the beam slice keeping into account also the further loss of some millimetres of timber at each cut by circular saw (Fig. 8 right). Before destructive tests, each specimen was measured, weighted and visually inspected for anomalies and defects. The average timber density for the specimens was 425 kg/m^3.

5.2. Compression testing along wood grain

Compression tests were carried out according to UNI EN 1193 (the newer UNI EN 408 which imposes the specimens height for this type of tests to be 6 times the minimum dimension in transversal section, was not applicable in this research). The loading velocity was set at 19–25 daN/s, according to the health state of the single specimen and each test lasted within the time range established by the norm (300 ±120 seconds). The time lapses of load and displacement values along the vertical direction were recorded. The collapse mechanisms were documented by photography (Figs. 9–10). As an example, two graphs are presented from two specimens of different strength: cubes 5 and 12 presented very different curves (Fig. 12) and density, 406 kg/m^3 and 446 kg/m^3, respectively. The appearance of wood after testing was also different for the two specimens: in the case of degraded wood, it appeared dusty, defibrated and not cohesive (Fig. 11 left). The load carrying capacity in terms of strength and the deformability in terms of modulus of elasticity were calculated from the experimental data. The first parameter varied over the section between 12.7–40 MPa, whilst the latter varied between 980 MPa and 2262 MPa.

5.3. Results discussion

Starting from the signal velocity map obtained from sonic tomography investigation across a decayed transversal section of the historic timber beam (Fig. 6 right), the values representing the average velocity over the area of each pixel (Fig. 13 left) were used to extract local values of the dynamic modulus of elasticity in direction perpendicular to grain (Fig. 13 centre left). Hence, the static modulus transversal to grain was estimated by using equation (2) and finally the modulus parallel to grain was indirectly determined by using equation (3) (Fig. 13 centre right). In the bottom right corner of the section, two values are missing because, due to material decay and loss, it was not possible to determine

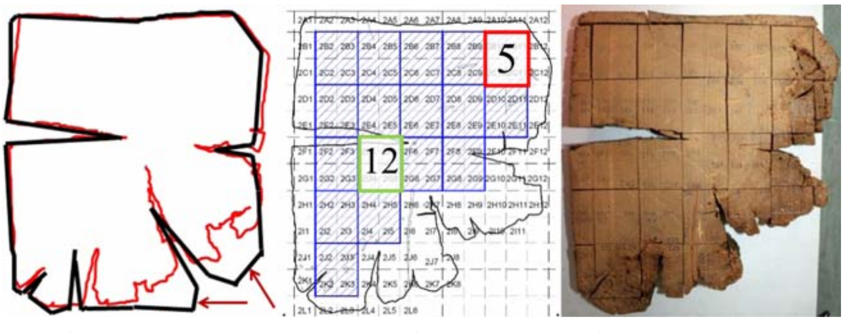

Fig. 8. Comparison between section perimeter from survey at time of tomography data collection (in black) and geometry after cutting of timber (in red); arrows point to material loss between the two phases (left). Grid of specimens for compression tests with position of specimens 5 and 12 (centre). Slice after specimens' cutting (right)

the local density. By dividing the whole set of modulus values in 3 classes and assigning traffic-light colours to each class, a simple colour map can aid in interpreting the location of timber areas in better (green colour) or worse health (red colour) (Fig. 13 right).

The values of modulus of elasticity from the experimental mechanical tests were corrected in order to keep into account the cubic shape of the specimens and make the data comparable with those from specimens of height to transversal dimension ratio recommended by the newer UNI EN 408 norm [19]. Due to space limitation, the additional tests carried out on specimens of new and old timber, in sound conditions and with various shape factors will not be reported here, nor the results obtained. It will be sufficient to know that a correction factor of 1.96 was applied to the modulus data from the cubic specimens. Thus, after correction, the new values of this parameter ranged between 1879 MPa and 4347 MPa. The local distribution of these single values is shown for all the 17 sub-areas (Fig. 14 right). Again, by using traffic-light colours for subdivision of the beam cross-section in 3 classes of deformability, the extent of the decay area becomes evident (Fig. 14 centre). The direct comparison with the distribution of the same parameter obtained from sonic tomography for the same transversal area (Fig. 14 right)highlights a strong similarity in health conditions. With the intermediate interval thresholds here chosen (2000 and 3000 MPa) this latter map appears more sensitive to material decay.

6. CONCLUSIONS

The application of NDT methodologies on-site for the investigation and evaluation of timber structural members is very convenient when the location and extent of possible areas of decay is the aim of testing. The non-invasive character of these methods

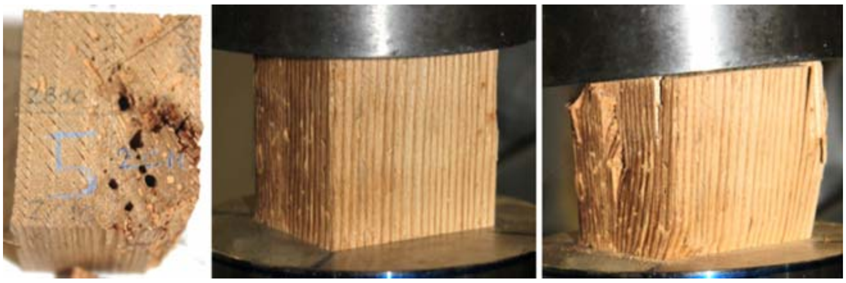

Fig. 9. Close-up photo of specimen 5 from top, before testing; behaviour of specimen under load

Fig. 10. Sequence of behaviour for specimen 12 under load

Fig. 11. Specimen 5 (left) and 12 (right) after testing

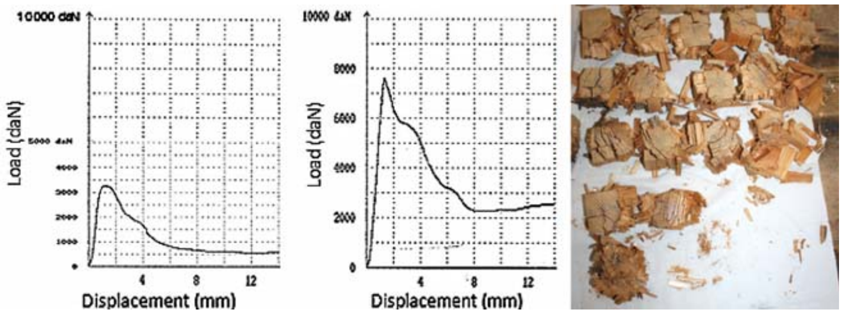

Fig. 12. Load-displacement curves for cubic specimens 5 and 12 (left and centre). Photo of all cubic specimens after testing (right)

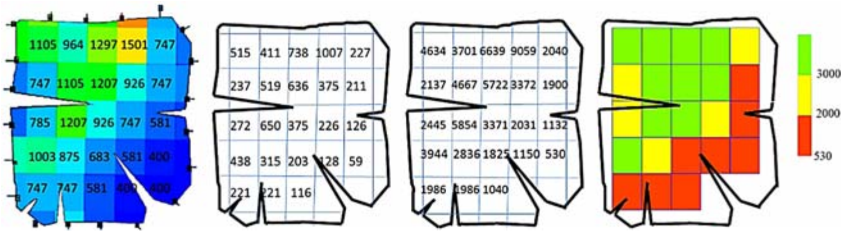

Fig. 13. Sonic tomography signal velocity (m/s) distribution across beam section (left) and indirect determination of modulus of elasticity (MPa): values of dynamic modulus transversal to grain (centre left), static modulus parallel to grain (centre right) and colour map of longitudinal modulus (right)

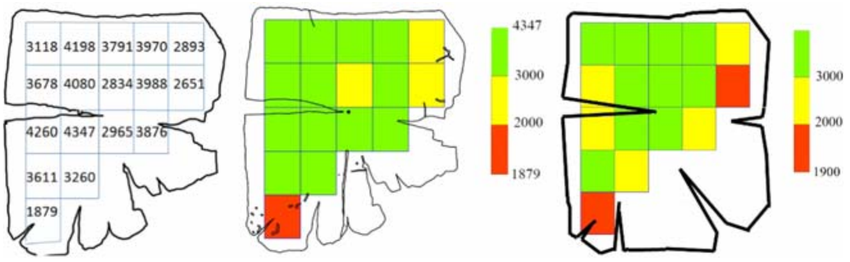

Fig. 14. Local distribution of longitudinal elastic modulus (MPa): direct determination from mechanical testing parallel to grain (left) and its colour map visualization (centre) compared with indirect determination from sonic tomography for only the 17 cubic specimens undergone to compression test (right)

makes them sustainable and recommended especially in the case of historic timber. Moreover, their imaging capabilities ease data interpretation and diagnosis. The work here reported tried to provide a contribution answer to the question if NDT results are to be considered only of qualitative nature or instead if they provide quantitative or semi-quantitative estimation of material mechanical properties.

First, the distribution of signal velocity obtained from sonic tomography investigation across a decayed transversal timber beam section was interpreted against the evidence from beam autopsy with satisfactory outcome: in particular the extent of decay appeared greater in the tomography map. Following, the local mechanical material properties directly extracted from small specimens undergone to compression test in grain direction were found to relate well with indirect determination of the same parameter from sonic tomography in direction transversal to grain.

Thus, a relation between the outcome of NDT and destructive tests was established point by point, enhancingthe confidence in using NDT for the preservation and structural assessment of historic timber.

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Abstract

Since many years a number of NDT techniques have been developed and subsequentially refined for the aims of non-invasive diagnose on site of existing and historic timber members in constructions. Such methods, including drilling penetration resistance, surface stiffness, sonic transmission and tomography, ultrasounds, acoustic emission, GPR radar, IR thermography, exploit different principles and types of waves: mechanical, acoustic, electromagnetic signals. Therefore, in single or combined use, they are able to indirectly provide information about material geometry, density, mechanical properties, decay extent, presence of heterogeneities and knots, moisture. One of their main common advantages is the capacity to produce distribution plots from the measured parameter values, thus easing data interpretation and supplying info about investigated areas rather than punctual information. Those are among the benefits of image diagnostics.

Even though positive examples of NDT applications are reported for timber structural elements, often the question arises if these results are only of qualitative nature or if estimation of mechanical properties can be considered of quantitative or semi-quantitative value. Starting from the signal velocity map obtained from sonic tomography investigation across a decayed transversal section from a historic timber beam, this contribution presents the outcome of autopsy of the beam followed by mechanical characterization of local properties of the material. The cutting of a beam slice in correspondence of the tomography tested section enabled visual correspondence of the degraded areas. Further cutting of the slice permitted to undergo small specimens to compression test in grain direction and to establish a relation between the outcome of NDT and destructive tests, point by point, with interesting consequences for the utility of use of NDT and for the preservation of historic timber.

Streszczenie

Techniki pozwalające na prowadzenie badań metodami nieniszczącymi (NDT) są rozwijane i udoskonalane na przestrzeni ostatnich lat. Umożliwiają one prowadzenie *in situ* nieinwazyjnej diagnostyki istniejących zabytkowych elementów drewnianych w konstrukcjach. Metody te, a wśród nich metoda pomiaru oporu wiercenia, pomiary sztywności powierzchniowej, metoda transmisji i tomografii dźwiękowej, ultradźwięków, emisji akustycznej, radaru GPR, badań termograficznych IR, wykorzystują różne rodzaje fal: mechaniczne, akustyczne, sygnał elektromagnetyczny. Dlatego, przy zastosowaniu indywidualnym lub łącznie, mogą pośrednio dostarczyć informacji na temat materiału – tzn. jego geometrii, gęstości, właściwości mechanicznych, stopnia rozkładu i korozji drewna, niejednorodnej struktury i obecności sęków, zawilgocenia. Jedną ze wspólnych tym metodom zalet jest możliwość generowania wykresów obrazujących rozkład wartości parametrów otrzymanych w testach, co ułatwia interpretację danych i dostarcza informacji o badanym obszarze, a nie tylko informacje punktowe. Są to zalety diagnostyki obrazowej.

Pomimo faktu, że raportowane są pozytywne przykłady zastosowania NDT do badań konstrukcyjnych elementów drewnianych, często pojawia się pytanie, czy te wyniki mają tylko charakter jakościowy, czy też szacunki dotyczące właściwości mechanicznych mogą być traktowane jako wartościowe z punktu widzenia analizy ilościowej lub półilościowej. Poczynając od mapy prędkości rozchodzenia się sygnału, obrazującej badanie tomografem dźwiękowym przekroju poprzecznego skorodowanego fragmentu zabytkowej belki drewnianej, artykuł prezentuje wyniki badań belki oraz charakterystykę punktowych mechanicznych właściwości materiału. Odcięcie segmentu belki odpowiadającego odcinkowi zbadanemu za pomocą tomografu umożliwiło wizualną weryfikację skorodowanych obszarów. Umożliwiło to również poddanie próbek z odciętego fragmentu próbie ściskania w kierunku równolegle do włókien i określenie zależności pomiędzy wynikami otrzymanymi metodą NDT oraz metodą niszczącą dla poszczególnych lokalizacji. Wnioski przekładają się na interesujące konsekwencje dla przydatności stosowania metod NDT oraz konserwacji zabytkowych elementów drewnianych.