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Inspection and condition assessment of existing timber structures

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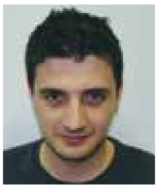

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Subject review

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Inspection and condition assessment of existing timber structures

Condition assessment and continuous monitoring of the existing timber structures have been gaining in importance in recent times. The global objective of sustainable development has been greatly directed toward preservation of the existing structures and protection of architectural heritage. Methods used for assessing condition of the existing timber structures are presented in the paper. The main emphasis is placed on the presentation of non-destructive and semi-destructive methods for frequently used timber structures. The methods are presented through the example of condition assessment of the Nikola Tesla Technical Museum in Zagreb.

Key words:
condition assessment, timber structures, non-destructive methods, architectural heritage, technical museum

Pregledni rad

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Pregled i ocjena stanja postojećih drvenih konstrukcija

Ocjena stanja i kontinuirano praćenje ponašanja postojećih drvenih konstrukcija u posljednje vrijeme sve više dobivaju na značaju. Globalni cilj održivog razvoja u velikoj mjeri usmjeren je na očuvanje postojećih konstrukcija i zaštitu graditeljske baštine. U radu su prikazane metode ocjenjivanja stanja postojećih drvenih konstrukcija. Glavni naglasak stavljen je na prikaz nedestruktivnih i poludestruktivnih metoda za drvene konstrukcije koje su često u uporabi. U radu su navedene metode na konkretnom primjeru ocjene stanja Tehničkog muzeja Nikole Tesle u Zagrebu.

Ključne riječi:
ocjena stanja, drvene konstrukcije, nedestruktivne metode, graditeljska baština, Tehnički muzej

Übersichtsarbeit

Mislav Stepinac, Vlatka Rajčić, Jure Barbalić

Übersicht und Zustandsbeurteilung bestehender Holzkonstruktionen

Die Zustandsbeurteilung und die kontinuierliche Verfolgung des Verhaltens bestehender Konstruktionen bekommen in der letzten Zeit immer mehr an Bedeutung. Das globale Ziel einer nachhaltigen Entwicklung besteht vorwiegend im Erhalt bestehender Konstruktionen und dem Schutz des Bauerbes sowie in der Zustandsbeurteilung. In der Arbeit werden die Methoden der Zustandsbeurteilung von bestehenden Holzkonstruktionen dargestellt. Der Schwerpunkt liegt dabei auf der Darstellung von häufig angewendeten nicht destruktiven und semi-destruktiven Methoden für Holzkonstruktionen. In der Arbeit werden die Methoden am konkreten Beispiel der Zustandsbeurteilung des Technischen Museums Nikola Tesla in Zagreb dargestellt.

Schlüsselwörter:
Zustandsbeurteilung, Holzkonstruktionen, nicht destruktive Methoden, Bauerbe, Technisches Museum

1. Introduction

Structural health monitoring (SHM) is an important topic for the preservation of both old and new structures. However, within the context of timber structures, SHM is not adequately represented in strategic documents. Timber is often recognized as a less durable material and timber structures as short-lived structures. Nevertheless, there are numerous examples of timber structures that defy time and are still standing despite aggressive climate and/or frequently inadequate use (Figure 1). Over the last decade an increasing number of papers have been produced to point out the problems of monitoring, assessment and reinforcement of timber structures.

While monitoring is conducted to continuously survey the condition of structures, non-destructive (NDT) methods are aimed at describing the existing condition of relevant areas of the structure [1]. There are two main areas of assessment and monitoring of timber structures; monitoring & assessment of historical timber structures, and monitoring & assessment of relatively new structures erected recently as a result of significant advances and developments in the field of new timber materials, timber structures and timber construction in general. The assessment of structural health of old timber structures differs from the assessment of new timber structures, e.g. large-span structures. Therefore, advances in construction technology and sustainability requirements, including requirements for preservation of both historical objects and new timber structures, have been increasingly captivating the interest of the scientific and professional community.

The need to assess an existing structure can be determined based on numerous parameters. As shown in [2], some of the most typical are: mistakes revealed with regard to design or construction; change of use during service life of a building; doubts about structural safety, visible damage; inadequate serviceability an usability; exceptional incidents or accidental loads; doubts related to material-, structural- or system-inherent decrease in structural safety; expiry of service life, as determined by technical assessment.

Recent decades have been marked by a significant widening of the scope of application of timber in structures, and consequently by a growing importance attributed to the assessment of these structures, and especially of timber structures of historical importance [3]. A huge variety of NDT methods exist to assess timber structures. However, the frequency and scope of their use, and the decision making approach concerning safety and necessary interventions, are far from being agreed upon [3]. The COST Action FP1101, which ended in 2015, was dealing with main problems of the existing timber structures. A lot of information is available at the COST Action website (http://www.costfp1101.eu). The main benefit of the Action is the comprehensive and coherent knowledge it provides regarding the assessment, reinforcement and monitoring of timber structures [3].

The main purpose of this paper is to summarize the most important assessment methods relating to the existing timber structures, and to illustrate them on a representative case study in Croatia.

2. Structures and guidelines

Over the last few years, a decent number of guidelines on how to approach the inspection and maintenance of existing timber structures have been published. However, only a few countries have published code-type documents that could be applied for the assessment of existing structures [2]. Although there are many methods and guidelines for the assessment of existing timber structures, some of them are applicable for a certain types of structures only. For the above mentioned reasons, a unique European document/standard has to be created, as a complementary document

Figure 1. a) Borgund Stave Church (Borgund, Norway) was built sometime between 1180 and 1250 AD (photo by www.wondermondo.com), b) Interior of Church of Peace (Jawor, Poland) – completed in 1655

for the design of new timber structures. Work on new European technical rules for assessment and retrofitting of existing structures, conducted in the frame of CEN/TC250 (EC Mandate M/515, 2012), is currently very intense, with special attention given to heritage structures, and with the aim of producing a new Eurocode part: Eurocode 12.

Historical timber structures represent an important part of the World Cultural Heritage and many of them are still in function: they must be preserved in order to guarantee their functionality and safeguard their historical value [1]. The most common method for assessing historical timber structures is a combination of the on-site inspection and non-destructive tests. Visual inspection provides an idea about the condition of an overall structure, identifies weak and critical zones and offers information about structural stability and the state of timber members and, hence, about critical elements and joints in timber structures. Many NDTs and models can be used to assess the state of conservation and physico-mechanical properties of old timber members, elements and joints. However, all methods are burdened with some limitations [1].

Although a design standard for the existing timber structures has not as yet been prepared, several guidelines have nevertheless been published in this area. A systematic review of criteria to be used in the assessment of load-bearing timber structures in heritage buildings is presented by Cruz et al. [4]. The guideline is the result of COST Action IE0601 and covers assessment principles of old timber structures of historical relevance that could be used as the basis for possible European Standards, as discussed within CEN/TC346 (Conservation of Cultural Heritage WG10 Heritage timber) [4]. CEN/TC346 is an interdisciplinary group composed not only of structural engineers and architects, but also of preservationists, wood technologists and art historians. The cooperation between individual CEN committees is operated through liaison person who participates in the work of both committees.

A coauthor of this paper, Vlatka Rajčić, is a liaison person confirmed by all mirror EU Technical Committees for CEN TC 250/SC5 (Eurocode 5: Design of Timber Structures) and CEN TC 346 (Conservation of Cultural Heritage), and she participates in preparation of the draft version of the unified European guidelines called "Guidelines for the on-site assessment of historic timber structures" which are still in the development stage. When assessing timber structures, full assessment covers the preliminary assessment (desk survey, preliminary visual survey, measured survey, structural analysis and preliminary report), as well as the detailed survey of timber (with a special emphasis on the on-site visual strength grading) and carpentry joints [4].

3. Assessment methods

3.1. Overview

A wide range of assessment methods for assessing the overall condition of existing timber structure is currently available on the market. These include acoustic, electro-magnetic, thermal and optical methods, as well as mechanical techniques [6, 11]. In this section, the majority of NDTs and semi-destructive methods for assessing the existing timber structures are listed, and the most common ones are briefly explained. Dietsch and Kreuzinger [2] summarized the most common methods: visual (hands-on) inspection, tapping (sounding), mapping of cracks, measurement of environmental conditions, measurement of timber moisture content, endoscopy, penetration resistance, pull-out resistance, drill resistance, core drilling, shear tests on core samples, stress waves, X-ray, dynamic response, load tests (proof loading), strain measurement, microscopic and chemical laboratory methods, macroscopic laboratory methods - testing of specimen. Tannert et al. in [6, 7] explained several new techniques such as the infrared thermography, glue line test, screw withdrawal, radial cores to determine compressive strength, pin pushing and surface hardness.

The last step in the assessment of timber structures is to incorporate the assessed data into probabilistic models that will be used to calculate the remaining capacity and reliability of such structures.

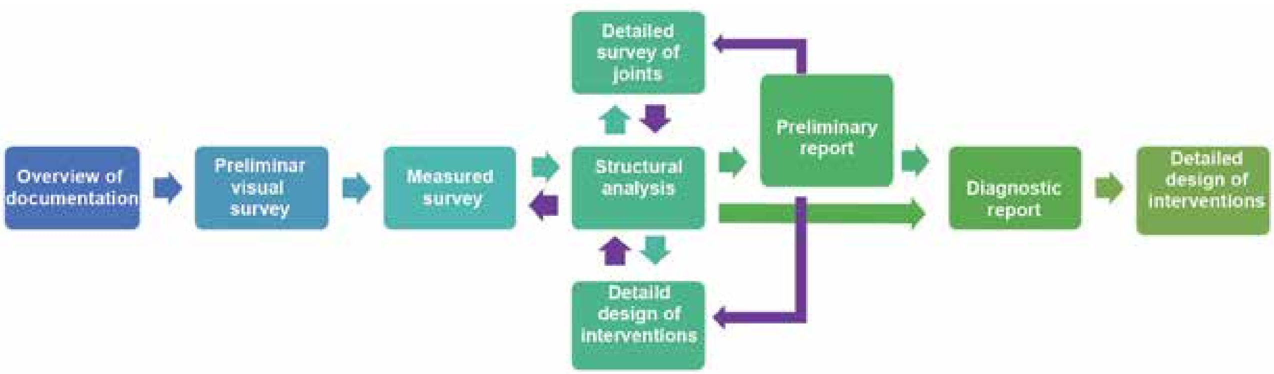

Figure 2. Steps required for assessment and planning of interventions for historic timber structures [4]

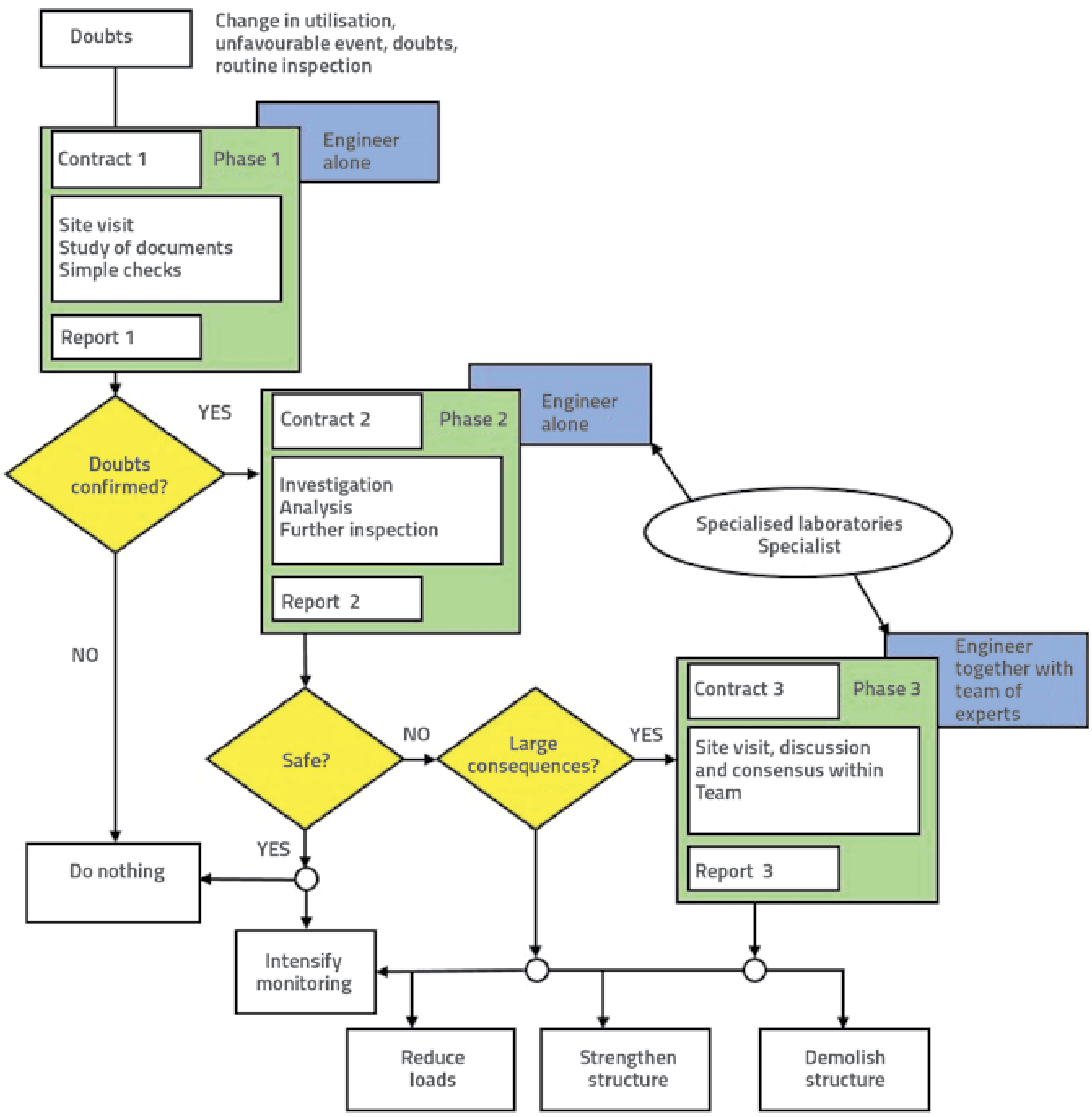

Figure 3. Steps required for probabilistic assessment of existing structures [8]

3.2. Visual inspection

The simplest and most common NDT technique is visual inspection and it should be the first step in the assessment of timber structures and constitutive timber members. Certain mistakes and errors can easily be identified; external damage to the members and the whole structure, decay of timber, crushed fibers, creep, or presence of visible and inappropriate cracks. The most common examples of damage and deterioration to structural timber elements that can be identified by visual inspection are [13]:

a) Poor construction details in structural timber elements, due to: inappropriate water drainage, poor connection of timber elements to the foundation, use of excessively thin elements that are prone to deterioration, use of excessively thin elements in combination with large diameter steel fasteners – splitting of timber elements, etc.
b) Mistakes during construction: building the structure using excessively moist timber (swelling and shrinkage of timber members), bad choice of connectors that can change static scheme of structure as a whole, miss-gluing or gluing with incompatible glues, etc.

c) Inadequate modification of the original design: removal of structural elements, removal or alteration of structures aligned with support structures, modification in the foundations, etc. [13].
d) Lack of maintenance and monitoring: cracks, rotten parts, instability of members, etc.
e) Physical-chemical-biological weathering reactions due to environmental parameters: degradation of timber properties, etc.

Natural defects in combination with deterioration of wood have a significant effect on mechanical properties of the wood. Deterioration caused by biotic attack affects the original quality of wood, not only because of the general decrease of density but also because of chemical alteration of the wood texture, as in the case of decay caused by rot [9]. Visual inspection has also definite limitations: inadequate or limited experience of personnel, problems with access to critical parts of the structure, random cross-checks, and inspection sometimes limited to the surface of the timber only, etc.

3.3. Ultrasonic echo technique

Stress wave and ultrasound methods for investigating wood are based on the propagation of compression waves through wood. The time it takes for the wave to travel from one piezoelectric sensor to another situated on the opposite side of the timber element is used to calculate speed of ultrasonic waves. Longer times generally reveal the presence of defects, rotten wood or wood of lower density [9]. Stress wave techniques are also affected by other factors, including moisture content, wood species, and growth-ring orientation [9]. The speed of ultrasonic waves is directly correlated to the modulus of elasticity (MoE). The method enables measurement and management of two ultrasonic variables, while also allowing work in the wood natural axis: longitudinal, radial and transversal [13]. When propagation velocity of the longitudinal stress wave is known, it is easy to obtain the MoE value if the density of member is has already been defined. Thus, the density must be measured prior to ultrasonic measurements. Rajčić [11, 12] proposes correlation between the ultrasound propagation velocity in a wooden element including other mechanical properties, i.e. strength of wood obtained by destructive laboratory testing. The correlation terms in [11-13] are provided for the velocity of ultrasound propagation for directions parallel and perpendicular to the grain, as derived from the "in situ" testing of very old wooden structures conducted in the scope of the FP7 project „Smart monitoring of historic structures" [13]. In the context of his master's thesis, Rajčić proposes in [14] correlations obtained by neural network analysis. Data for the study were obtained by testing the network on a large number of samples investigated using both non-destructive and destructive methods.

3.4. Measuring moisture content of timber

Moisture content is one of the most important factors affecting timber properties. The amount of water present in wood can affect its weight, strength, workability, susceptibility to biological attack, and dimensional stability [2]. The dimensional changes of wood due to changes in moisture content (shrinkage, swelling) are different along the three material axes (longitudinal, tangential or radial) and are "significant" in radial and tangential directions [2]. It is estimated that over 80 % of in-service problems associated with wood are in some way related to its moisture content.
Two general approaches aimed at determining moisture content of wood are the direct approach (determination by water extraction) and indirect approach (properties of wood are correlated with moisture content) [5]. The most common moisture measurement devices are electrical resistance meters, which are based on the principle involving decrease of electrical resistance with an increase in moisture content. Electrical resistance meters measure conductivity between more pin electrodes that are pushed into a timber element and calibrated to provide the user with the corresponding moisture content reading. It is very important that the needle electrode is long enough to enter into a half of the cross-section of wood. Cheap and broadly available moisture meters designed for measuring moisture in parquet are not appropriate (although they are very often used in Croatia) because they measure moisture directly near the outer layer of the element.

3.5. Drill resistance

Drill/penetration techniques are used to detect the quality of cross-section, as well as the decay and density of timber elements. Drilling resistance is classified as quasi-non-destructive because a small diameter (1.5 mm – 3 mm) hole remains in the specimen after testing. Drill resistance devices operate under the premise that resistance to penetration is correlated with material density [13]. Plotting the drill resistance versus drill tip depth results in a drill-resistance profile that can be used to evaluate internal condition of timber members and identify points and stage of decay [13].

3.6. Infrared thermography

Infrared thermography (IRT) is a non-destructive investigation technique that allows investigation of structural details (e.g. hidden structure or masonry texture behind the plaster), and damage and material decay (e.g. moisture, crack pattern evolution, temperature pattern evolution, microclimatic conditions mapping) on historic structures [13]. Although visual inspection is still one of the best "tools" for assessing timber surface, IRT can be helpful in remotely identifying areas of high moisture thus saving time in planning detailed survey of the members.

3.7. Other methods

New tools and methods are increasingly proposed in response to continuous growth in popularity of assessment and structural health monitoring procedures. In the case of timber structures, there are several new NDT and semi-NDT methods on the market, varying in the level of sophistication and intended use.
Visual inspection is the basic approach for assessment of timber structures, allowing detection of external wood decay, moisture stains on exposed surfaces, visible mechanical damage, and defects. However, other highly useful visual information can be gained with additional tools such as non-destructive imaging techniques [8]. Imaging techniques most commonly used in the inspection of timber members are photogrammetry, thermography, X-ray radiography, and the micro-wave and stress-wave tomography. Infrared thermography has already been explained in previous section. It can also be used also for monitoring historic timber structures using frequential analyses to determine wood porosity or presence of cracks in the first few centimeters [10]. Summary of non-destructive imaging techniques used for on-site assessment of timber structures, with their advantages, limitations and recommendations, are given in [8].
A new product, Pilodyn 6J Forest, can be used for the determination of wood density and related mechanical properties, as well as for detection of rot attacks. The instrument penetrates surface layers of timber elements with the help of an internal spring. It is based on the measurement of material resistance against penetration of an indenter, and it leaves a small damage in the elements [15]. Yamaguchi et al. [16] proposed a method for evaluating integrity of timber elements using the screw withdrawal resistance measurements. The benchmark method compares withdrawals of tested timbers with those of the benchmark timber. Withdrawals correspond to the nominal values of densities and shear strengths, with the tolerance ranging from 4,0 to 8,2 % [16].
Several semi destructive test methods can be used to estimate fracture toughness of diverse materials: indentation tests, scratch cutting tests, pull-out tests, wedge splitting tests, energy release rate methods, and near tip displacement field analysis [17]. Sandak et al. [17] proposed a new method that combines experimental cuttings to determine reference values of the mechanical characteristics and the modern fracture mechanics theory for the extraction of parameters. The method can be used in the on-line control of structural timber and for assessment of timber members in existing structures.

4. Case study – Technical museum Nikola Tesla, Zagreb, Croatia

4.1. Structure and background

Technical Museum Nikola Tesla is situated in the city of Zagreb and is under the protection of the Conservation Department Zagreb, Protection of Cultural Heritage [18].
The entire facility was designed and constructed as a timber structure and as such represents a rare existing example of the European engineering concept of large-span expo-halls (85 m x 40 m) from the early 20th century. The museum was built in 1949 (after no more than eight months of construction) for the purposes of the Zagreb Fair and, in technical terms, it is a notable example of the European architectural heritage relating to timber structures. As many as 2800 cubic meters of timber elements, 23000 square meters of floorboards, 5600 square meters of parquet, 1230 tons of cement, 100 tons of iron, 7000 cubic meters of gravel, and over 10000 different types of fasteners, were used in the construction of the complex.
The main exhibition hall of the Museum is designed as a circular segment of a ring. External dimensions of the main hall are 81.27 m (east facade) / 87.75 m (west facade) × 25.40 m. The total ground-floor area is about 2137m^2. The roof of the exhibition hall is made of thirteen truss frames spaced at 6.8 m to 7.3 meter intervals. Main timber frames are connected with eleven secondary trusses spaced at 1.6 m to 3 m intervals (Figures 4, 5, 7, and 8). The highest elevation of the hall is 19.74 m. The frame columns are made of four compression elements forming a complex vertical assembly truss column system. Spatial stabilization of the building was made using three transverse and four longitudinal wind bracings in horizontal direction, and two vertical wind bracings [18].
The objective was to make complete assessment of the Technical Museum Nikola Tesla timber structure and to design, repair and/or strengthen this structure and its parts and, finally, to prepare a maintenance and management plan to ensure long-term preservation of the museum's timber structure. The project was financed by Town of Zagreb, carried out in the period from 2010 to 2015 and was headed by professor Vlatka Rajcic, Ph. D. from the Faculty of Civil Engineering of the University of Zagreb.

4.2. Assessment of museum

Assessment of the museum structure started with preliminary visual survey, which was followed with determination of the overall position of structural members, measurement of cross-sections of members and distances between individual members, and identification of general damage to the structure. Basic visual control of structural elements revealed severe damage to many

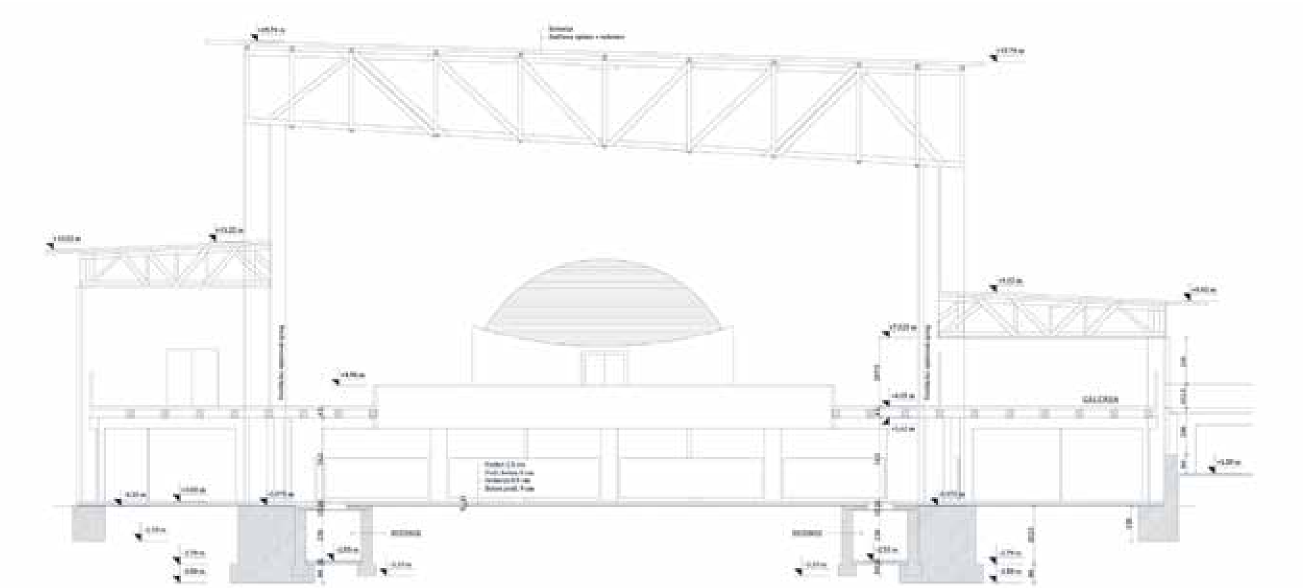

Figure 4. Transverse cross-section of the museum

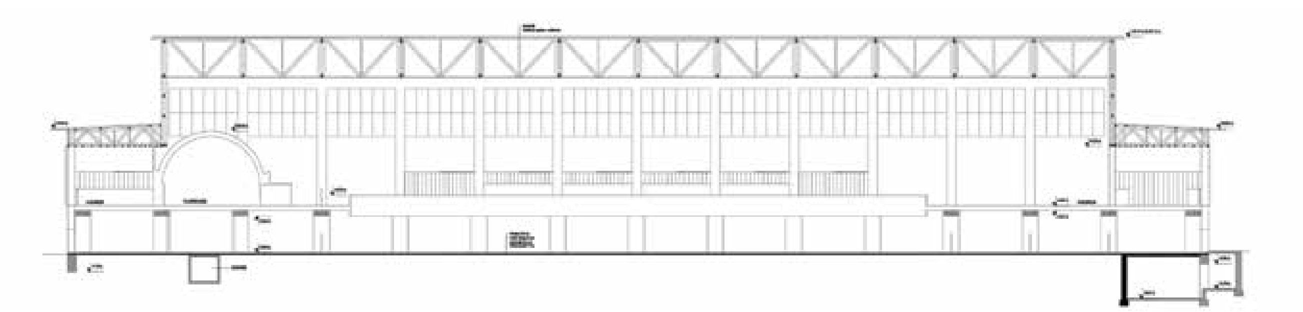

Figure 5. Longitudinal cross-section of the museum

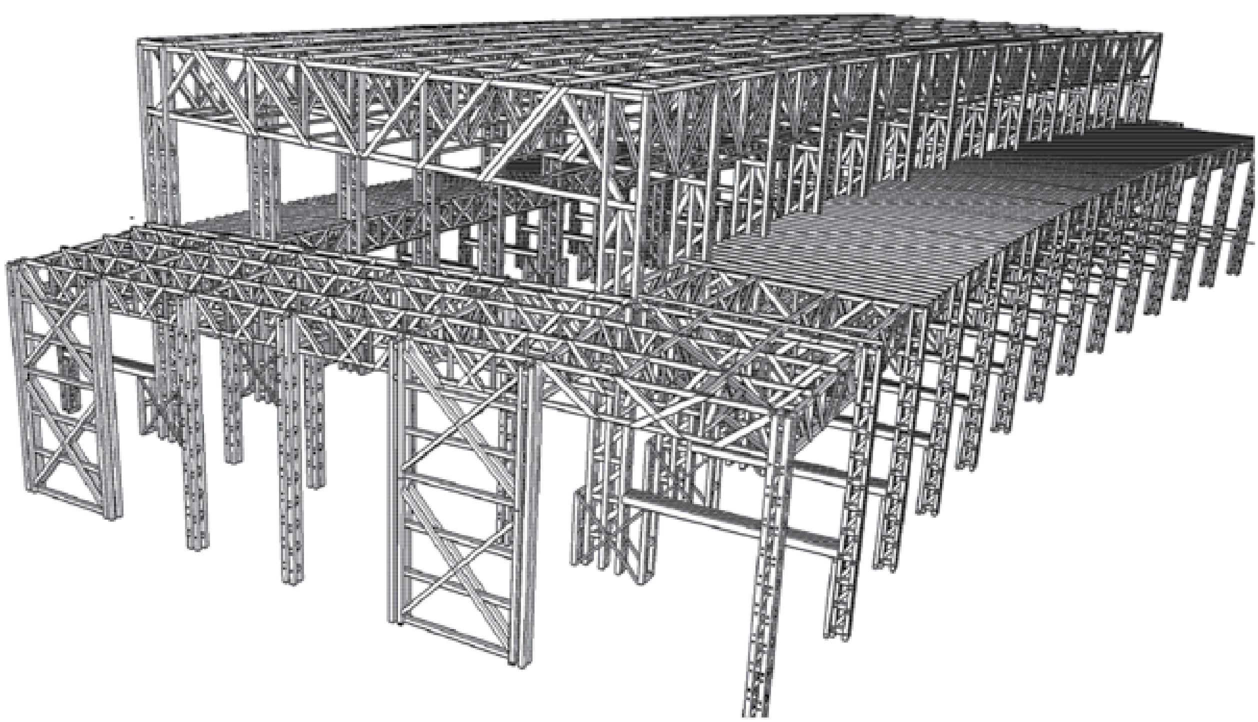

Figure 6. Simple 3D model of the museum structure

Figure 7. Ceiling of the southern roof of the museum

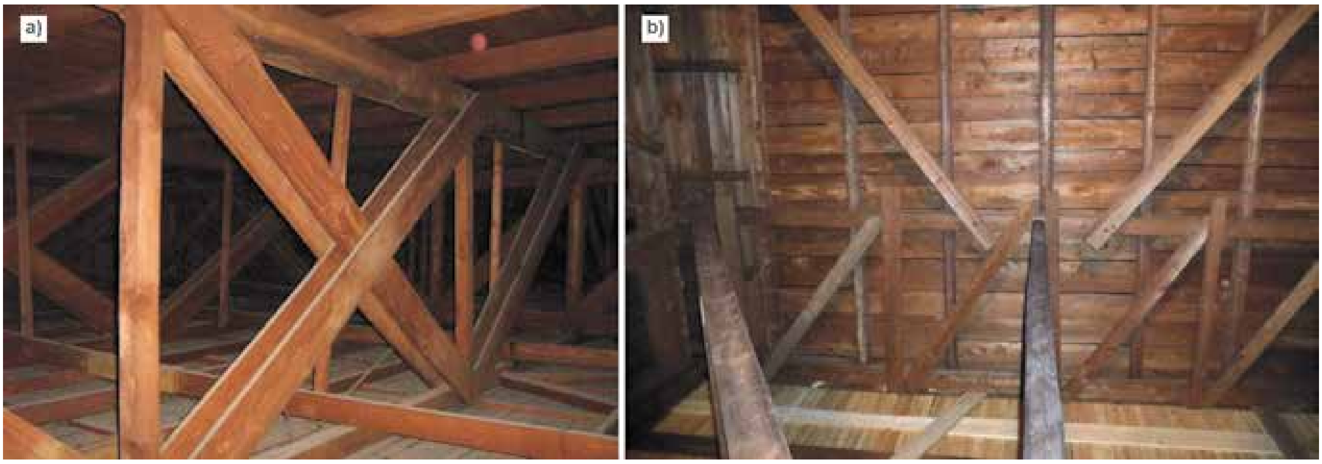

Figure 8. a) Longitudinal truss of the main roof, b) bottom view of the roof bracings

façade column assemblies, and central frame column assemblies in foundation details (Figure 9). At the western part of the façade, timber columns were in direct contact with concrete foundations, and decay was caused by a blocked drainage system that caused continuous pouring of water and/or a direct contact with water and/or soil [18]. Preliminary investigation work also revealed damage to many columns at the west and east façades, both with central frame columns (especially the ones oriented toward east). They were in direct contact with the ground and/or water because of poor drainage, which caused decay in the lower part of the columns [18].

After the preliminary visual survey, the investigation proceeded with structural analysis in order to determine internal forces in timber elements, and to check global stability of the structure. The analyses revealed errors in the bracing systems. For instance, the bracing system of the roof structure did not exist in the original structure, i.e. it was added 50 years later during the first assessment. Slender column bracings were insufficient and/or poorly executed.

Figure 9. Severe damage to central frame columns

The geometry of the building with two-dimensional drawings, partly based on historic documentation and partly on relevant on-site measurements, was included in the preliminary report. Indispensable high-priority actions were identified and methods for preserving heritage value of the structure were recommended. The list of major problems, such as biological attacks, vulnerable areas, instabilities of the structure, high stress zones, and dangerous deflections with estimation of preliminary costs, was included in the report.

The next step involved detailed survey, visual inspection and non-destructive tests of timber elements for the assessment of: mechanical characteristics of materials, moisture content, condition of the structure, timber and timber grade, and adequacy of carpentry joints. Timber members were made of softwood, spruce and fir. Service classes and load-duration classes according to EN 1995-1-1 [19] and EN 335 [20] were identified. Various parts of the structure have been affected by different humidity of air over time, and therefore exhibit different load values. Most of the elements were classified into service class 2 (in most elements, an average moisture content did not exceed 20 %).

The moisture content of timber elements was measured at characteristic elements. The measurement was taken for each timber member susceptible to biological attack (except for members strongly affected by rot) and at typical spots and locations. The timber structure was divided into characteristic sections and moisture content was measured for every typical timber member, i.e. for every member that had a distinct role in the load-bearing capacity of the structure. The measurements were performed with a VANICEK VIVA 12 moisture meter, a digital pin-type resistance meter with built-in pins designed to precisely measure moisture content of wood, up to 100 % in the 0.1 % increments (Figure 10a). As expected, timber elements closer to the ground had greater moisture content (from 16 % to 22 %). The roof structures are naturally ventilated and elements were mostly dry (from 6 % to 12 %).

The load-duration classes are characterized by the effect of constant load acting for a certain period of time in the life of the structure [19]. Complete structure of the museum is made of timber, and so different elements were classified into distinct load-duration classes according to [19].

All areas of biological damage, defects in timber elements, mechanical damage, and changes made to the original structures, were mapped during the detailed survey. A lot of minor irregularities, i.e. potential causes of local instabilities, have been noted. In many elements, deep cracks were observed in longitudinal direction and in the vicinity of connectors [18]. Visual inspection revealed that a number of elements had visible torsional rotations of the cross section with respect to the vertical axis (Figures 11.a & 12.a) [18]. These rotations were due to: long-term deformation of wooden elements, imperfections in the execution [18], use of excessively moist elements during construction, lack of stabilization systems at all levels of the structure, reduced stiffness of the members, etc.

The strength grade of timber elements was based on visual inspection (visual grading) and on NDT measurements of physical and mechanical properties of relevant members by ultrasound and drill testing. As the structure was built in 1948 timber elements experienced a reduction in strength and stiffness because of rheological phenomena, creep in particular. The existing EN 338 [21] strength classes system does not cover historic buildings of certain age, but strength grades were determined using the measured MoE and were associated with the appropriate class according to EN 338 and [22], as there is currently no other standard or guideline for historic structures.

Tests by acoustic ultrasound were carried out to obtain MoE of timber members both in longitudinal and radial directions. The ultrasonic tests were performed with a Sylvatest DUO measurement device (Figure 10c) equipped with a data-acquisition unit and two transducers. Transducers were placed on opposite faces of the members, and the ultrasonic pulse velocity (stress wave speed) was determined based on the distance between the two transducers. The measured MoE parallel to grain varied from 5400 to 8220 N/mm². The MoE perpendicular to grain ranged from 320 to 500 N/mm².

Resistographic measurements were performed with an IML RESI F500-S (Figure 10b), a drilling-resistance measurement system based on the energy needed to drive a needle

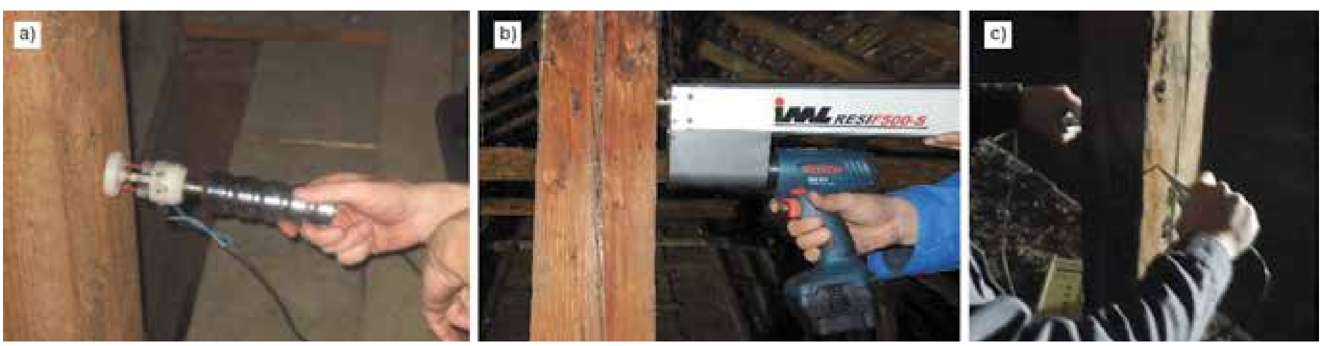

Figure 10. a) Measurement of moisture content, b) drilling with the resistograph device, c) ultrasound measurements

Figure 11. a) Longitudinal crack in column due to excessive load, b) cracks in timber element as a result of shrinkage and swelling, c) detail with questionable load-bearing capacity due to improper concept or missing fasteners

Figure 12. a) Torsional rotation of the beam, b) Improper installation of nails

through the wood. Drill tests were also performed in zones where full cross-sections of beams or columns were not visible. Tests have shown a relatively good quality of cross-sections in zones where timber elements were not subjected to biological attack.

Timber was graded into classes ranging from C16 to C27 based on visual inspection results, MoE values obtained by ultrasound device, quality of cross-sections obtained by resistograph, and general condition and moisture content of members. Lower parts of the structure mostly belonged to class C16, while the remaining parts were mostly categorized as class C24. It must be once again noted that strength classes for old timber do not exist in standard, and timber strengths are assigned according to residual quality of cross-sections.

The last part of the assessment of the timber structure was a detailed survey of timber joints and connections between elements. Lot of connections in the structure were either poorly executed or their properties have deteriorated over time (Figure 11). A number of joints were executed with improper installation of fasteners, and so their load bearing capacity is questionable [18]. Carpentry joints were generally in good condition but some were not performing in the way in which they were intended to. The main reasons for such situation are the changes that have occurred over time and/or initial improper realisation of timber joints.

A lot of other faults were observed in the structure, such as the poor fitting of timber members in joints, insufficient number of fasteners or insufficient spacing of fasteners, eccentricity in the joints, corrosion of some connectors, crushing of timber and biological attack (especially at the ground level), etc.

Proposals and recommendation for the reconstruction, repair and/or strengthening of the structure were given after complete assessment of the Technical Museum Nikola Tesla timber structure. The maintenance and management plan guideline to preserve the museum was prepared and explained in detail. Just a short overview of complex assessment and reconstruction methods for determination of residual mechanical properties of materials and classification of the Technical Museum timber members is presented in this paper. The complete project was conducted in the period from 2010 to 2015. The exceptionally huge and complicated timber structure of the museum is briefly presented, and main activities concerning assessment and structure strengthening requirements are

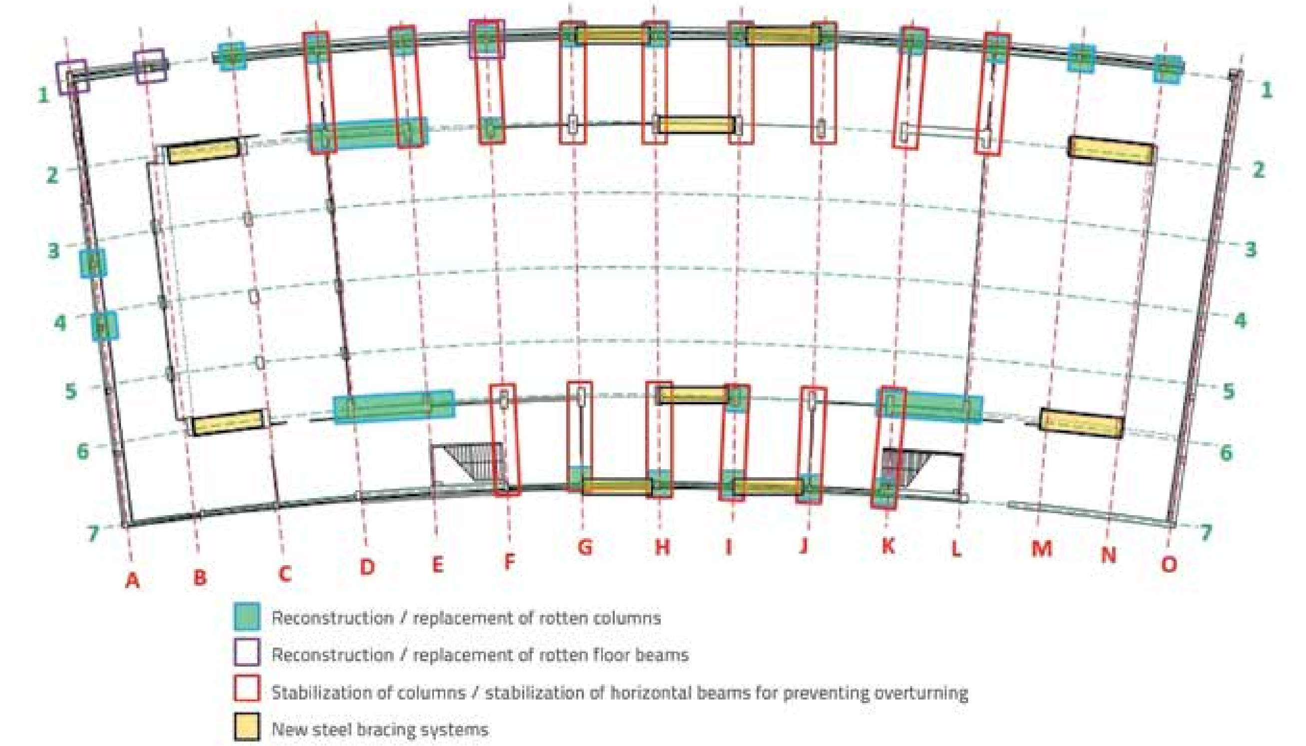

Figure 13. Reconstruction works at the ground floor of the museum

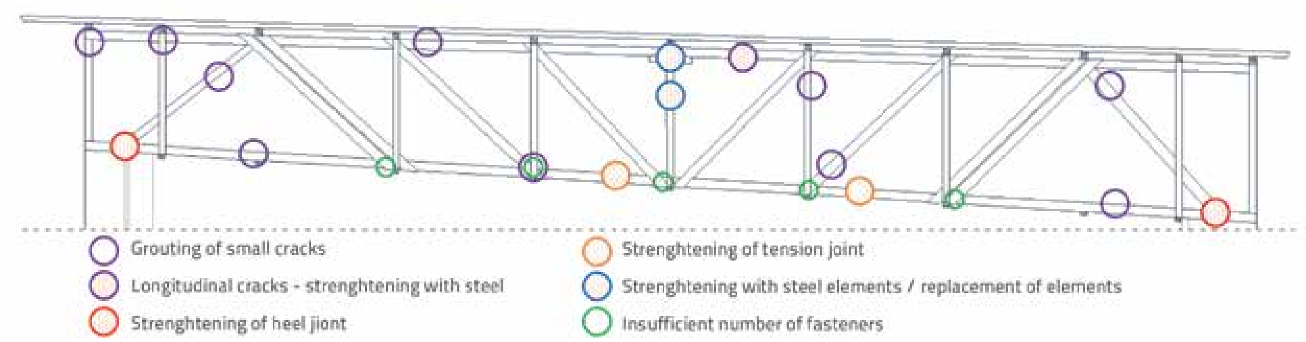

Figure 14. Reconstruction works at the main roof truss of the Museum

outlined. Principal reconstruction works and replacement of rotten parts at the ground floor are briefly presented in Figure 13. Principal reconstruction works and replacement of inadequate parts at the main roof timber truss are briefly shown in Figure 14.

5. Conclusion

A lot of different assessment techniques exist at the moment. Many of them are promising methods for quantitative description of the current condition of timber members in timber structures. This concerns material properties like modulus of elasticity, moisture content, and density, as well as structural properties such as dynamic characteristics, localization of inhomogeneities, cracks, and biological attack [1].

Although some methods and instruments have been shown to be of very high quality and are necessary for the evaluation of structures, there are also devices do not guarantee the value for which they were designed. Examples are drill/penetration devices that measure resistance to needle penetration to test quality of cross section and density of wood elements. Whilst the qualitative distribution of density over the cross-section is very clear from the very first use of the device, numerical value of the wood element density is very difficult or impossible to determine even though the manufacturer guarantees it through prior measurements. There is a wide range of moisture meters and ultrasound devices applicable for wood that are adequate and fulfil the purpose they were designed for. The problems with moisture meters in assessing condition of timber structures is the usage of moisture meters for parquets instead of moisture meters for structural timber with "pins", which are of appropriate length. The main problem of ultrasonic tests is the difficulty in assessing and reviewing available elements. Very often, only the modulus of elasticity perpendicular to the grain is measured for simplicity reasons, and the modulus of elasticity values for the direction parallel to the grain are calculated from these results (according the equations for new wood), which can lead to wrong conclusions.

The absence of standardized assessment methods may result in substandard reconstruction and reinforcement of timber structures [23]. Reinforcement of new and existing timber structures has been the subject of considerable research and development in recent years. However, there is currently a lack of harmonized European standards in this field [24]. Systematic review of criteria to be used in the assessment of load-bearing timber structures in heritage buildings is presented by Cruz et al. [4]. The main objective of this paper has been to present non-destructive and semi-destructive test methods that are widely used for assessment of old and protected heritage structures, and to illustrate such methods through a case study involving Technical Museum Nikola Tesla in Zagreb, Croatia.

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