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Review

Structural Vulnerability Assessment of Heritage Timber Buildings: A Methodological Proposal

Amirhosein Shabani [1,*], Mahdi Kioumarsi [1,*], Vagelis Plevris [1] and Haris Stamatopoulos [2]

[1] Department of Civil Engineering and Energy Technology, Oslo Metropolitan University, 0166 Oslo, Norway; vageli@oslomet.no
[2] Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway; haris.stamatopoulos@ntnu.no
* Correspondence: amirhose@oslomet.no (A.S.); mahdik@oslomet.no (M.K.)

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Abstract: The conservation of heritage structures is pivotal not only due to their cultural or historical importance for nations, but also for understanding their construction techniques as a lesson that can be applied to contemporary structures. Timber is considered to be the oldest organic construction material and is more vulnerable to environmental threats than nonorganic materials such as masonry bricks. In order to assess the structural vulnerability of heritage timber structures subjected to different types of risk, knowledge about their structural systems and configurations, the nature and properties of the materials, and the behavior of the structure when subjected to different risks, is essential for analysts. In order to facilitate the procedure, different assessment methods have been divided into the categories in situ and ex situ, which are applicable for vulnerability assessments at the element and full-scale level of a case study. An existing methodology for structural vulnerability assessments and conservation of heritage timber buildings is reviewed and a new methodology is proposed.

Keywords: heritage timber buildings; risks and their effects; structural vulnerability assessment; in situ assessment methods; visual inspection; data analysis; ex situ assessment methods; numerical simulation; experimental test; assessment and conservation methodology

1. Introduction

Timber has been utilized in construction for thousands of years, and as an organic material is susceptible to decay in aggressive environments [1]. Since the environmental conditions affect the organic nature of timber, the structural vulnerability assessment of historical timber buildings is complex compared to other types of construction materials [2].

The conservation of heritage structures is not only important from a cultural or historical point of view, but also because of their distinct features, such as architecture, ornaments and the valuable objects they contain [3]. Historical timber structures are witnesses to a rich tradition of craftsmanship, structural and material knowledge. Heritage construction techniques are not only essential to investigate as a pattern for contemporary construction, but also to find the best conservation techniques.

Nowadays, environmentally friendly and sustainable buildings are gaining momentum. By assessing their behavior and interpreting the properties of historical timber structures, valuable information can be obtained about construction techniques that can be used to live more in harmony with nature rather than in conflict with it. The Boathouse in Nordmøre, Norway, is an example of a building where the walls, as illustrated in Figure 1, are clapped with pine boards in such a way that the boards are nailed towards the upper edge, which is below the overlapping area. As a result, in dry weather, the outer edge bends outward allowing dry air into the building, while in wet weather conditions, the boards close again. The wall therefore provides a form of sustainable natural ventilation at no cost [4].

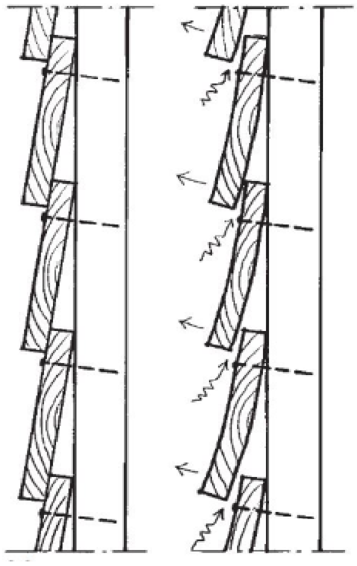


Figure 1. A traditional environmentally friendly construction technique in Norway, reprinted from [4].

1.1. Risks and Their Effects

In order to assess the vulnerability of heritage timber structures, potential risks and their effects should be investigated. Timber as a source of food is susceptible to insect or fungi attacks, which can cause voids and which in turn can affect the mechanical properties of the material as shown in Figure 2a,b. These damages can affect the resistance of structures and cause severe damages at full scale [1,4,5].

Earthquakes are considered a possible risk in vulnerability assessments of heritage timber structures. Several failures in historical buildings such as churches and temples caused by earthquakes have triggered the development of inspection template documents as well as guidelines for the conservation of cultural heritage structures [2].

Timber structures are vulnerable to fire (see Figure 2c), as are other types of structures. When it comes to historic buildings, the value of the whole structure itself and the materials and objects in the building (e.g., fabrics in textile museums or candles in religious buildings) can fuel fires and thus create more severe disasters [3]. Furthermore, experimental studies have revealed that historic timber does not perform as well as contemporary timber in fire in terms of its material performance (char rates and time to ignition) [6]. A suitable fire safety strategy should therefore be considered in order to decrease the fire risks in heritage timber buildings [4].

Atmospheric moisture changes, temperature changes, sea level rise, severe snow, wind and flooding are some of the main consequences of climate change. These can lead to an increase relative humidity of the timber material, which causes several impacts on the mechanical properties of the materials and decay. Moreover, severe snow, extreme wind and flooding apply severe loads to heritage timber structures [7–9].

1.2. Structural Systems

Vulnerability assessments of heritage timber buildings are categorized into two main areas: hygrothermal and structural [10–12]. In order to investigate the structural vulnerability of heritage timber buildings, knowledge about their structural system is required. Heritage timber buildings can be divided into three main groups based on their structural systems (a) log houses, (b) post and beam building systems and (c) timber frame buildings [4].

(a)

(b)

(c)

Figure 2. Damage caused by (**a**) Fungi and (**b**) Insect attacks in Heierstad Loft, Tønsberg, Norway; (**c**) Fire in Notre-Dame cathedral timber roof, Paris, France (reprinted from Wikipedia with license CC BY-SA 4.0).

The log house method is one of the oldest still-existing construction methods that consists of wooden walls compacted with horizontal laid logs, as shown in Figure 3a [13]. This construction method has been extensively used in the Nordic countries and in the central European Alpine region because of its high insulating values against harsh winters [4,14,15].

In the post and beam building system, vertical structural posts and horizontal beams are connected to form a structural frame, and bracing elements and connections play the critical role in the structure's stability when subjected to lateral loadings. This method was widely used in Southeast Asian countries. The Golden Hall of the Buddhist temple in Nara, Japan, is the world's oldest timber structure to be built using this method, as shown in Figure 3b [4,16].

Timber frame buildings are comprised of timber elements and infill walls, as illustrated in Figure 3c [17]. In this structural system, timber elements are used to reinforce brick or stone masonry walls in order to increase their capacity to resist lateral loadings. The origin of this building method goes back to the ancient Roman empire at the site of Herculaneum, an ancient Roman city [18].

(**a**) (**b**)

(**c**)

Figure 3. (**a**) Log house (Heierstad Loft, Tønsberg, Norway); (**b**) Post and beam (The Golden Hall (Kondo) of the Horyu-ji Buddhist temple, Nara, Japan) reprinted from [4]; (**c**) Timber frame building (Baden-Württemberg, Germany) reprinted from [19].

1.3. Assessment Methods

The various methods for conducting vulnerability assessments of heritage timber buildings can be divided into in situ and ex situ methods. By utilizing in situ methods, the current behavior of the building is evaluated by performing a preliminary survey and non-destructive tests (NDTs) or semi-destructive tests (SDTs). In situ methods are employed as the first step of the vulnerability assessment procedure in order to increase the analyst's knowledge of the structural system, previous interventions, defects and voids in elements, mechanical properties of the material, etc.

In ex situ methods, the structure is modelled, and loads corresponding to different risks are applied to the model to assess the structure's vulnerability. Experimental tests can be utilized in order to investigate the exact behavior of the simulated sub-structures or full-scale structure subjected to different types of loads. The results from the tests can be used to develop numerical models that can, in turn, be used to investigate different scenarios for different types of risks. Figure 4 shows all the methods presented in this paper.

The aim of this paper is to provide a summary of different types of methods for structural vulnerability assessments of heritage timber buildings in a structured and organized manner, with relevant references for each method. Firstly, in situ methods are presented. Preliminary surveys as the basis for vulnerability assessments of the structures is the first essential step. Afterwards, detailed in situ methods including NDT and SDT are presented. Ex situ methods, which are recommended for evaluating the behavior of buildings subjected to different risks, are then described and divided into experimental and numerical analyses. Finally, the existing methodology concerning the conservation of heritage timber buildings is presented and further developed to build a new procedure. The new methodology will be utilized in "HYPERION", a European project related to the preservation of tangible cultural heritage.

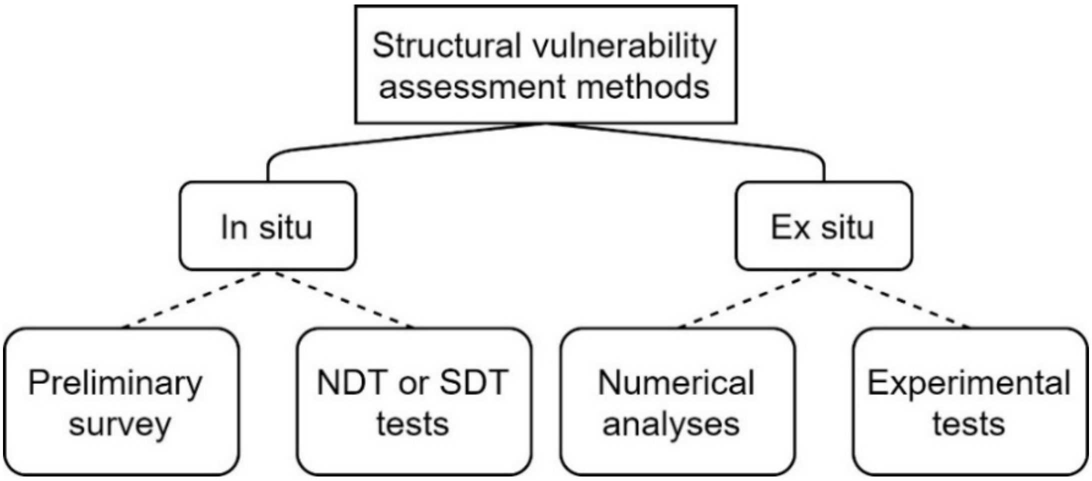


Figure 4. Classification of methods for vulnerability assessments of heritage timber buildings.

2. In Situ Methods

In situ assessment methods are divided into two main parts; a preliminary survey and a detailed survey, which are used to evaluate the current condition and mechanical properties of timber elements. In this section, all in situ techniques are highlighted with emphasis on their application in relation to heritage timber buildings.

2.1. Preliminary Survey

A preliminary survey is the simplest method of the vulnerability assessment process and forms the basis of the vulnerability assessment of different types of structures. A preliminary survey comprises different steps, as described in the following.

2.1.1. Visual Inspection

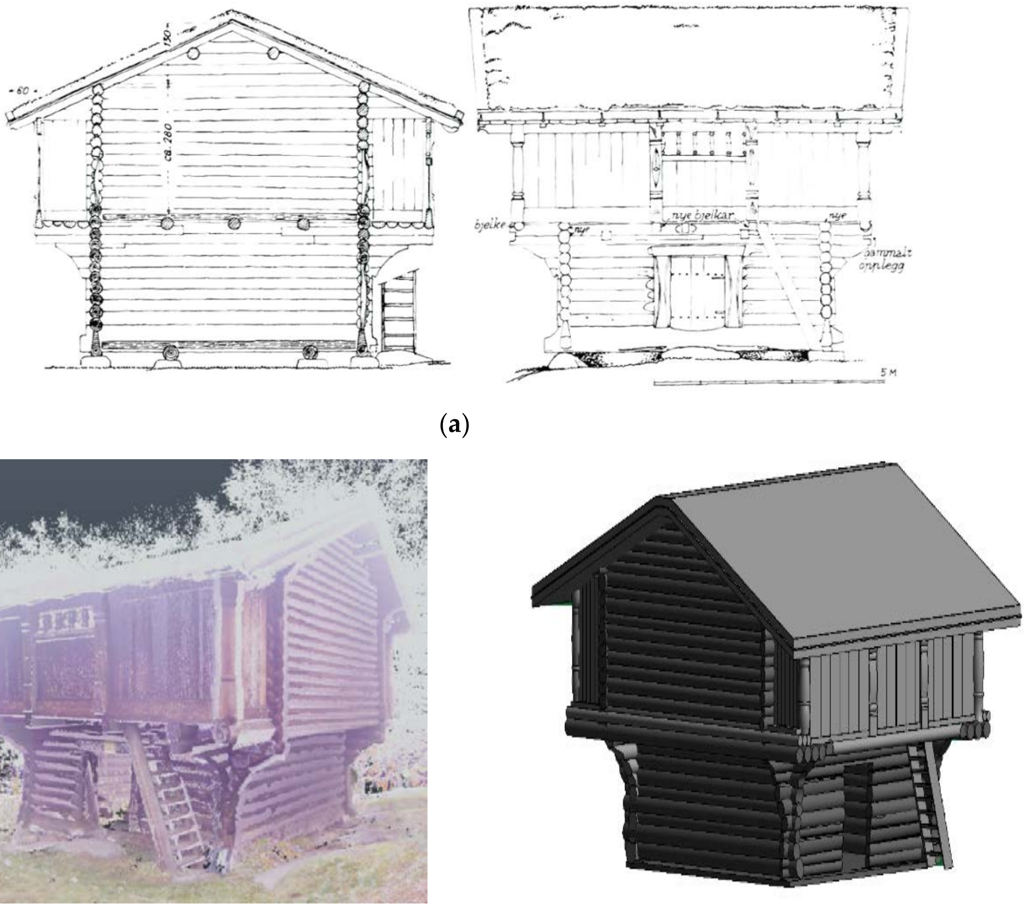
This step is an essential part of the preliminary survey with the aim of gathering information about the historical aspects of the building and its status. Moreover, any intervention, restoration or change in loading conditions during its lifetime [20,21], in addition to past exposure to different risks, must be identified and recorded.

The identification of wood species, any indications of biological or fire damage, cracks or delamination and the working conditions such as safety, lighting, accessibility (for further assessments) should be investigated and documented by experts at this stage [5,20,22–24].

2.1.2. Geometric Survey

A geometric survey consists of precise drawings, which are helpful tools in the assessment work. Common two-dimensional (2D) drawings from different views (see e.g., Figure 5a), and of timber members and joints details are required at this stage. Moreover, the inspector can easily indicate damaged areas in the drawings.

Three-dimensional (3D) laser scanners and computer programs can also be used to measure and record geometrical information about historical buildings. Point clouds are the raw material derived from 3D laser scanners, as shown in Figure 5b, and the 3D drawing files can be derived using different software packages from the point clouds, as illustrated in Figure 5c. Drawing and documenting the geometry of the building in this way is less time consuming and more accurate as compared to 2D drawings [25–27].



(**a**) (**b**) (**c**)

Figure 5. (**a**) Traditional two-dimensional (2D) view, reprinted from [28]; (**b**) Point clouds from three-dimensional (3D) laser scanner; (**c**) 3D drawing view of the Heierstad Loft, Tønsberg, Norway.

2.1.3. Recording Templates

After collecting qualitative data from the preliminary survey, a systematic recording is required. Several templates have been introduced, including ASCE 41-17 [29], ATC 20 [30], FEMA P-154 [31], and AeDES [32] which are applicable for different types of construction material.

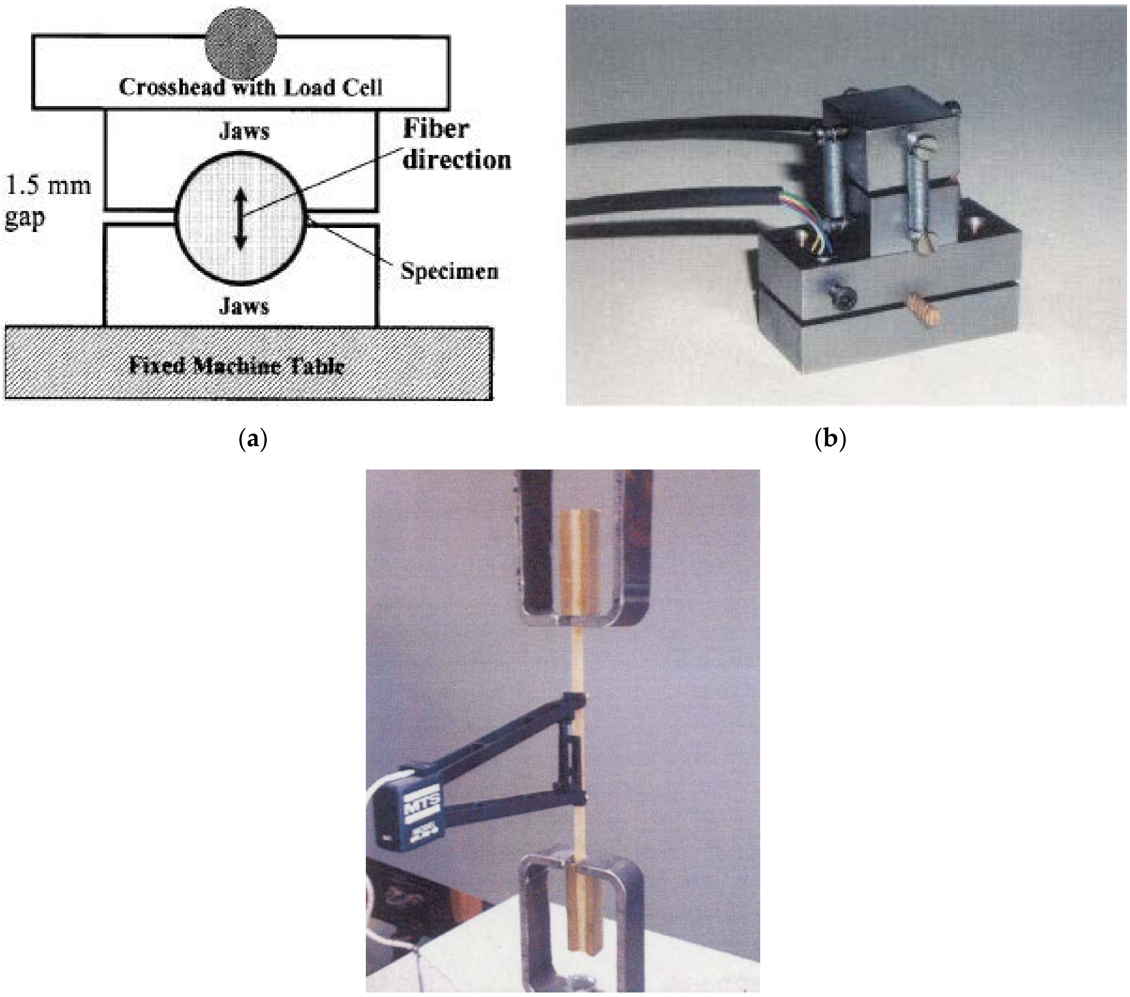
A procedure was proposed by D'Ayala et al. [33] for collecting data in order to investigate different collapse mechanisms of historical masonry structures. This has been developed and specially adapted for heritage churches in the Philippines subjected to the Bohol earthquake [34]. However, these procedures do not take into account the various historical structural types of timber buildings and do not reflect all the different scopes of the evaluation such as structural system, elements and connections [2].

A recording template is especially developed for the assessment of heritage timber buildings that is the goal of the task group 1-TG1, COST Action FP1101-WG [35]. This template intends to fill the gap between the guidelines and the more detailed steps to follow in practice. Different kinds of damage and their causes are included in the template, and it includes different types of assessment methods. This template still needs to be upgraded to cover all types of heritage timber structural systems [22].

2.2. Detailed Survey

Data about the history of the buildings and any previous interventions, types of damage that are detectable by the experts' eyes, and configuration of the building including 2D or 3D maps, are gathered and recorded during the preliminary survey stage. In the next step, a detailed survey of the buildings' elements is required in order to investigate any defects inside the timber elements that cannot be detected from the previous step. Performing destructive tests in heritage buildings is practically impossible and detailed survey methods therefore need to be based on the NDT and SDT to derive the mechanical properties of timber that are essential for numerical simulations. Moreover, accelerometer sensors can be utilized in order to investigate the dynamic characteristics of the building through operational modal analysis, which can then be used to verify the numerical model of the building.

Different types of the NDT and SDT that are applicable to heritage timber buildings are categorized in Table 1. For more information, the interested reader is kindly referred to [36–38]. Test setups of two SDTs are illustrated in Figure 6.



(**a**) (**b**)

(**c**)

Figure 6. (**a**) Schematic drawing; (**b**) Overview of the test setup of the core-drilling technique; (**c**) Test set up of the tension micro-specimen. Reprinted from [38].

Table 1. Non-destructive test (NDT)/semi-destructive test (SDT) applicable for in situ assessment of heritage timber buildings with the outcome of each test and relevant case studies.

Test Type	Test Name	Brief Description of the Process	Output	Case Studies
NDT	Operational modal analysis	Accelerometers are installed at different heights of the building in order to detect ambient vibration	Dynamic characteristics of the building	[39–41]
NDT	Drilling resistance	A small-diameter needle-like drill penetrates the element in order to investigate its resistance as a function of depth	Density, biological defects, voids	[42–46]
NDT	Hardness	The penetration depth of a small needle with an applied constant load is evaluated	Density, biological defects, voids	[47]
NDT	X-ray radioscopy	X-ray penetrates the elements and reflects to produce several types of photographs from inside the wood	Density, biological defects, voids	[48–54]
NDT	NIR spectroscopy	Near infrared light invisible to the human eye is emitted onto the element, causing vibration in the molecules, which is detected	Mechanical properties, chemical properties, decay	[55–59]
NDT	Ultrasonic velocity	Propagation velocity of longitudinal and transversal waves of sound plays a key role in this method	Elasticity modulus, shear modulus, voids	[59–62]
NDT	Ground penetrating radar (GPR)	Electromagnetic waves are utilized, which can penetrate and propagate through timber elements in order to produce several types of photographs from inside the wood	Biological defect, voids	[63–67]
NDT	Thermography	This method is based on differences between heat conductivity of wood and defects	Delamination, voids	[59,68–70]
SDT	Core-drilling technique	A compression test is performed by a concave head by applying a load parallel to the grain of the specimen	Compressive strength, elasticity modulus in compression	[71–73]
SDT	Tension micro-specimen	A tensile test is performed by attaching the ends of the specimen to two blocks of the test equipment	Tension strength, elasticity modulus in tension	[74]

Data Analysis

In many cases, it is not sufficient to use one NDT or SDT to evaluate material properties and different types of sensors are therefore required. After obtaining data from different sensors, a large amount of data is available that are related to each other. Multivariate analysis can be utilized to extract valuable facts from big data by knowing the underlying relations. Moreover, multivariate analysis methods can be employed to predict the mechanical properties of timber elements for long-term structural analyses of buildings [75–77].

A methodology has been proposed for safety assessments of timber elements by combining the results from different tests with visual inspection, which can be used to determine the present condition of an existing timber element. Bayesian methods are recommended in the methodology in order to update the mechanical properties of the elements [78].

3. Ex Situ Methods

Ex situ methods for conducting structural vulnerability assessments of heritage timber buildings can be categorized into numerical analysis and experimental tests. Experimental tests can illustrate the behavior of full-scale buildings as well as structural components. The hybrid simulation method is a combination of numerical and experimental analyses using the results from the tests to verify and develop the numerical models for evaluating the building in different risk scenarios. In this section, experimental tests and numerical simulation methods for each risk will be described. Depending on the type of potential risks, the mentioned ex situ methods may be used separately or in conjunction with one another to assess the structure. In this section, the application of experimental tests and numerical simulation methods are therefore described on the basis of the relevant risk scenarios.

3.1. Seismic Vulnerability Assessment

Several experimental tests have been carried out to investigate the behavior of full-scale structures using shaking tables (see e.g., Figure 7a) or sub-structures subjected to lateral loadings [79–94]. At the component scale, for log houses and timber frame buildings, cyclic or monotonic tests have been performed on shear walls as the lateral load-bearing system, while in post and beam systems with beam-column connections that resist lateral loads, the connections are simulated as illustrated in Figure 7b,c.

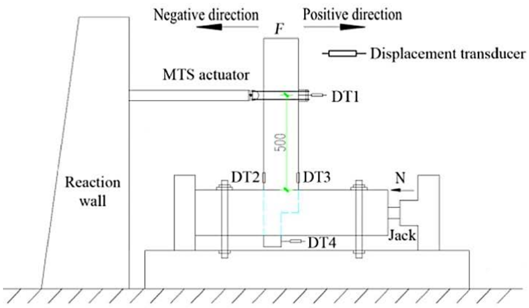
Finite element modelling (FEM) can be utilized for the numerical simulation of heritage timber buildings subjected to seismic loads. To obtain an accurate representation of the geometry of the timber building and accelerate the modelling procedure, building information modelling (BIM) drawing files can be utilized, which can be imported to different FEM software packages [95–97].

After modelling the structure, linear static or dynamic analyses can be conducted to investigate the critical elements by comparing the demand with their capacity [14,98,99]. Linear analyses do not show near collapse behavior of structures, and they are mostly used for designing new buildings rather than assessing existing ones.

A simplified hybrid method has been presented for nonlinear FEM, particularly for timber frame buildings, such that the elements are modelled using the experimental testing results from the substructures [100]. Hybrid simulation has been utilized to investigate the seismic vulnerability of timber frame buildings [101–109], and then developed for numerical simulation of log houses [110–115] and post and beam structures [116–121].

In the hybrid simulation method, experimental tests are performed on load-bearing structural components to obtain knowledge about their behavior against cyclic loads (see Figure 8a) [100,115]. For timber frame buildings and log houses, cyclic or monotonic tests with specified loading protocols have been performed on different types of timber shear walls to investigate their nonlinear behavior (see Figure 8b). Numerical models of the walls are developed using nonlinear rotational springs and elastic beam–column elements or rigid links for connecting them. Loads that are applied in experimental tests are applied to the models in order to calibrate them (see Figure 8c).

(**a**)



(**b**) (**c**)

Figure 7. (**a**) A timber frame building on a shaking table reprinted from [89]; (**b**) Schematic drawing; (**c**) Overview of the cyclic tests setup of a timber connection. Reprinted from [93].

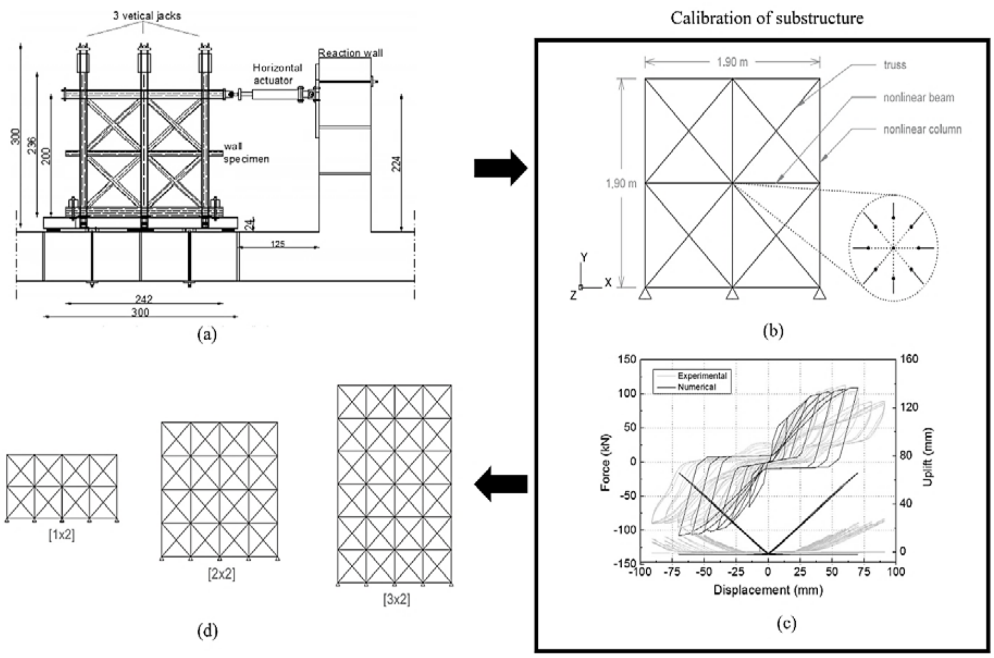


Figure 8. (**a**) Schematic drawing of cyclic test setup of a timber frame wall; (**b**) Numerical model of the wall including the nonlinear springs; (**c**) Calibration of the substructure model based on the hysteresis behaviors of the test results and the numerical model; (**d**) Developing nonlinear models for the buildings with different configurations. Reprinted from [108].

The hybrid simulation of the post and beam structural system is different from the other two systems because of the lack of timber shear walls. Instead of performing experimental tests on shear walls, cyclic or monotonic tests have been performed on the connections and the building is simulated by linear timber post and beam elements with nonlinear rotational springs, which are calibrated with the experiment results.

The calibrated component numerical models are developed in order to construct the full-scale nonlinear numerical models of the structures. Therefore, the seismic performance of large groups of archetypes with different configurations, in different seismic zones and with different subbase soil, can be evaluated (see Figure 8d). Incremental dynamic and static pushover are two common types of analyses that can be performed to derive fragility curves showing the damage probability of each building based on a parameter that quantifies the intensity of the seismic action. Fragility curves can be derived from the intersection between the capacity curve and different seismic records, which are upscaled to cover different damage thresholds. For further investigation into these two methods, ref. [122] is recommended.

3.2. Wind and Snow Vulnerability Assessment

Timber roofs are mostly vulnerable to wind risk, and several studies have been carried out to assess the vulnerability of heritage timber roofs subjected to wind load [21,98,123–128]. For this purpose, a linear analysis is performed on a numerical model of the roofs in order to evaluate the critical elements and derive the displacement of the structure. To assess heritage timber buildings subjected to wind or snow loads, static linear analysis is usually sufficient to obtain a reliable result based on previous studies. Figure 9 shows a timber roof structure subjected to wind loads. In this study, all joints are modeled as hinge joints and it was investigated that the connections between the timber roof and the masonry structure under the roof have a significant effect on the building's behavior subjected to wind load. For investigating the near-collapse behavior of the buildings subjected to lateral wind loads, nonlinear modelling is recommended. For this purpose, detailed information about the behavior of the connection should be ascertained through experimental tests on the simulated connections.

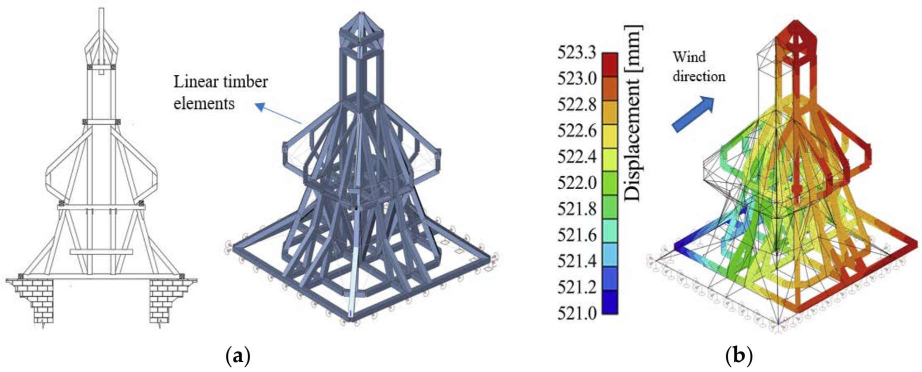


Figure 9. (**a**) Linear numerical modeling of a timber roof; (**b**) Displacement of each part of the timber roof subjected to wind load by considering the sliding support between the timber roof and the lower level masonry structure. Reprinted from [123].

Structural behavior of masonry timber frames to flood and wind-driven rain exposure is assessed through a hybrid method including experimental tests and numerical simulation. It is proved that the weathering diminishes the structural integrity and changes the failure mechanism of the timber frame walls [129].

3.3. Fire Risk Assessment

Structural analysis is traditionally based on loads, which are derived from the codes in a probabilistic framework. However, in the case of fire, it is almost impossible to find a loading scenario due to the many sources of uncertainty The building material and other ignitable non-structural elements, which may be considered available fuel, and charring and water vapor are some of the sources of uncertainties. Although huge developments have been made in methods to determine the capacity of buildings subjected to fire risk, fire science and structural engineering need to overlap more, and must be addressed by experts in the field [3,130,131].

For fire safety of heritage timber buildings, fire risk assessment methods through qualitative or quantitative approaches can help to solve different issues of uncertainties, but these are not within the scope of this paper [3]. The National Fire Protection Association (NFPA) has several codes and standards relating to fire risk assessment and protection of different types of buildings. NFPA 914 [132] is specially focused on heritage buildings and this code introduces a flowchart for the fire safety assessment of heritage buildings using a performance-based design method.

4. Proposed Methodology

Under the scope of European Cooperation in Science and Technology–Wood Science for Conservation of Cultural Heritage (COST IE0601–WoodCultHer), guidelines for the assessment of historic timber structures are presented and explained through a flowchart [20]. Although this flowchart can be used to understand the procedure for conducting structural vulnerability assessments of heritage timber buildings, it has some drawbacks that need to be further worked on.

In the flowchart, three loops are seen, as shown in Figure 10, but the guidelines do not provide any definitions or explanations about them. The red arrow in the flowchart is an alternative to the structural analysis part of the diagnostic report, which is not clear or separate from the other alternatives. Moreover, the detailed design of interventions is set out under the last step, as shown in Figure 10, but different types of interventions should in fact be checked several times by performing structural analyses in order to choose the best retrofitting technique.

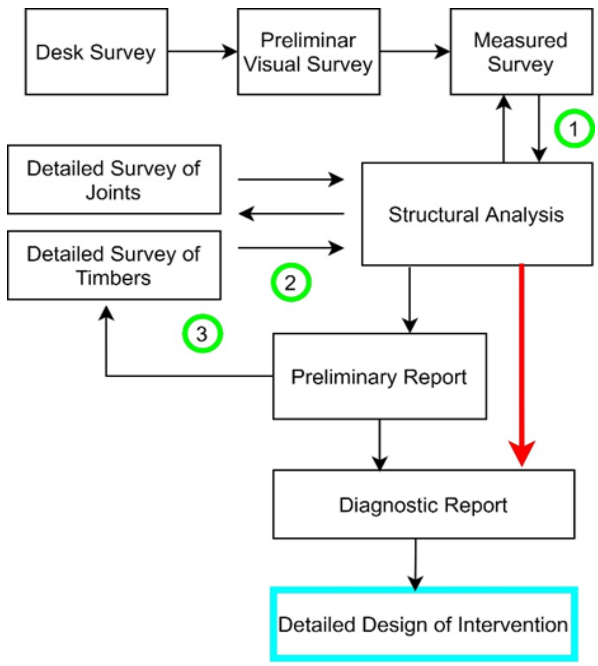


Figure 10. European Cooperation in Science and Technology (COST) action flowchart for vulnerability assessment and conservation of historic timber buildings. Adopted from [20].

In order to improve the COST action guidelines flowchart, a new methodology for the conservation of heritage building is proposed in this study, which can be seen in Figure 11. This flowchart will be used for the structural vulnerability assessment of heritage buildings in the HYPERION project.

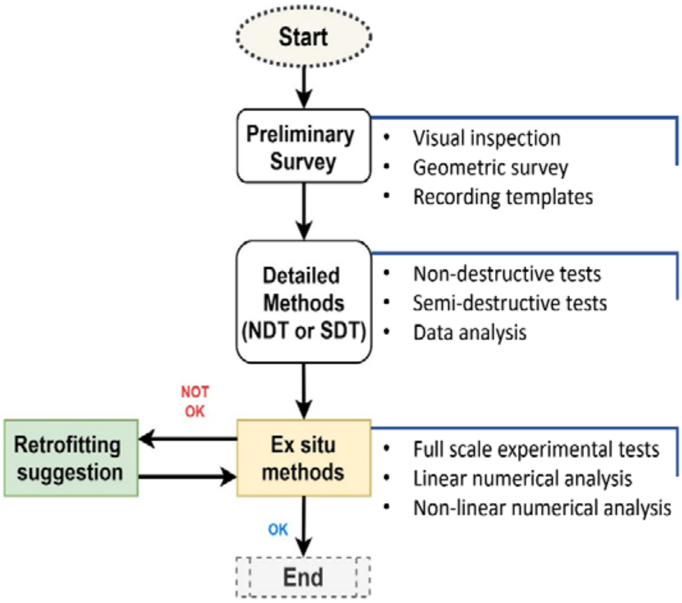


Figure 11. HYPERION methodology for vulnerability assessment and conservation of heritage timber buildings.

The preliminary survey, including desk survey, visual inspection and geometrical survey, is the first step of the vulnerability assessment, which is included in both flowcharts. Detailed in situ methods, including NDT or SDT, comprise the next step to investigate the general defects in the structure and mechanical properties of the timber material. Afterwards, simulation is necessary to assess the current condition (subjected to gravity loads) or predict the behavior of the buildings subjected to different risks scenarios (earthquake, wind, etc.).

For the structural analysis of the models, two approaches are employed in order to accelerate the analysis procedure. For buildings that are in very high or high seismicity zones or in locations with high speed winds, sophisticated nonlinear models are recommended. Seismicity or wind risks can be taken into account based on code provisions [133–135]. For buildings subjected to snow loads or located in low-risk areas, linear simulation will usually sufficient.

The retrofitting suggestions are presented based on the results from the previous assessment methods and will be checked several times in the loop until the most optimized and effective intervention technique has been achieved.

5. Conclusions

Several methods and techniques for performing vulnerability assessments of heritage timber buildings have been presented in the above. The main objective of this state-of-the-art review study is to gather and classify the methods in a systematic and organized way. The different methods have been divided into two main categories: in-situ and ex situ methods.

A preliminary survey, as the first step of the in-situ methods of assessing buildings, is essential in order to increase knowledge about the current condition of the building. In this step, 3D documentation of the heritage buildings using 3D laser scanners is beneficial because of the method's increased accuracy and speed compared to traditional 2D methods.

NDT and SDT are introduced to assess damage that is not detectable during the preliminary survey phase. Afterwards, mechanical properties of the elements are derived, which are used in the numerical simulation.

Multivariate data analysis can be utilized in order to derive valuable data from the results of different sensors at the element scale, with the possibility of inference and updating of the mechanical properties of the elements.

Ex situ methods, including experimental tests or numerical FEM, are employed in order to assess the vulnerability of the buildings subjected to potential future risks. For seismic vulnerability assessments of buildings, hybrid modelling consisting of nonlinear rotational springs calibrated by experimental tests is recommended in order to accelerate the assessment procedure and assess the vulnerability of the buildings subjected to different seismic scenarios.

For vulnerability assessments of timber roofs that are susceptible to wind load, a linear analysis is sufficient to investigate the critical elements based on the stress and maximum displacement of the structure. However, a detailed nonlinear analysis can show accurate results at a near-collapse state of the structure.

Due to the numerous uncertainties relating to fire risk, the fire resistance of heritage timber buildings is difficult to assess, and experimental tests cannot be performed on the heritage buildings. For this reason, fire risk assessment is recommended in order to select the best fire safety strategy for the conservation of the building.

Vulnerability assessment methods are used for risk mitigation by implementing the most proficient and optimized strategies. In fact, it is possible to select an effective and cost-efficient intervention strategy based only on comprehensive knowledge of the behavior of the buildings and their structural vulnerabilities. A methodology for the conservation of heritage timber buildings has been proposed here for detecting the best intervention method.

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