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.)

Received: 13 July 2020; Accepted: 10 August 2020; Published: 13 August 2020

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].
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].
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.

![Classification of methods for vulnerability assessments of heritage timber buildings.](image)

**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].

![Figure 5](image-url)

**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.

![Figure 6](image-url)

**Figure 6.** (a) Schematic drawing; (b) Overview of the test setup of the core-drilling technique; (c) Test setup of the tension micro-specimen. Reprinted from [38].
| 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).
Forests 2020, 11, x FOR PEER REVIEW 9 of 20

A simplified hybrid method has been presented for nonlinear FEM, particularly for timber frame buildings [108], and then developed for numerical simulation of log houses [110–115] and post and beam structures [116–121].

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].

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].](image)

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.

![Flowchart](image-url)

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.
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 suffice.

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.

**Author Contributions**: Conceptualization, A.S. and M.K.; methodology, A.S. and M.K.; validation, A.S. and V.P.; investigation, A.S.; resources, A.S.; data curation, A.S.; writing—original draft preparation, A.S.; writing—review and editing, A.S., M.K., V.P. and H.S.; visualization, A.S.; supervision, M.K. and V.P.; project administration, M.K. and V.P.; funding acquisition, V.P. All authors have read and agreed to the published version of the manuscript.

**Funding**: This work is a part of the HYPERION project. HYPERION has received funding from the European Union’s Framework Program for Research and Innovation (Horizon 2020) under grant agreement no. 821054. The content of this publication is the sole responsibility of Oslo Metropolitan University (Work Package 5, Task 2) and does not necessarily reflect the opinion of the European Union. Permission for all figures have been obtained from the owners.

**Conflicts of Interest**: The authors declare no conflict of interest.

**References**

1. Nilsson, T.; Rowell, R. Historical wood–structure and properties. *J. Cult. Heritage* 2012, 13, S5–S9. [CrossRef]
2. Riggio, M.; D’Ayala, D.; Parisi, M.A.; Tardini, C. Assessment of heritage timber structures: Review of standards, guidelines and procedures. *J. Cult. Heritage* 2018, 31, 220–235. [CrossRef]
3. Torero, J.L. Fire Safety of Historical Buildings: Principles and Methodological Approach. *Int. J. Arch. Heritage* 2019, 13, 926–940. [CrossRef]
4. Larsen, K.E.; Marstein, N. *Conservation of Historic Timber Structures. An Ecological Approach*; Riksantikvaren: Oslo, Norway, 2016.
5. Cândido, A.; Henriques, D.F. Inspection and diagnosis of timber structures by non-destructive methods. In Proceedings of the 9th International Symposium on the Conservation of Monuments in the Mediterranean Basin–MONUBASIN, Ankara, Turkey, 2–4 June 2014; pp. 469–480.
6. Chorlton, B.; Gales, J. Fire performance of cultural heritage and contemporary timbers. *Eng. Struct.* 2019, 201, 109739. [CrossRef]
7. Fatorić, S.; Seekamp, E. Are cultural heritage and resources threatened by climate change? A systematic literature review. *Clim. Chang.* 2017, 142, 227–254. [CrossRef]
8. Kelman, I.; Haugen, A.; Mattson, J. Preparations for climate change’s influences on cultural heritage. *Int. J. Clim. Chang. Strateg. Manag.* 2011, 3, 386–401.
9. Bertolin, C. Preservation of Cultural Heritage and Resources Threatened by Climate Change. *Geosciences* 2019, 9, 250. [CrossRef]
10. Riggio, M.; Dilmaghani, M. Structural health monitoring of timber buildings: A literature survey. *Build. Res. Inf.* 2019, 1–21. [CrossRef]
11. Baas, E.J. A Methodological Approach for Structural Health Monitoring of Mass-Timber Buildings under Construction. Master’s Thesis, Oregon State University, Corvallis, OR, USA, 2020.
12. Choidis, P.; Tsikaloudaki, K.; Kraniotis, D. Hygrothermal performance of log walls in a building of 18th century and prediction of climate change impact on biological deterioration. *E3S Web Conf.* **2020**, *172*, 15006. [CrossRef]

13. Klein, A.; Grabner, M. Analysis of Construction Timber in Rural Austria: Wooden Log Walls. *Int. J. Arch. Heritage* **2015**, *9*, 553–563. [CrossRef]

14. Aranha, C.A. Experimental and Numerical Assessment of the Seismic Behaviour of Log and Cross-Laminated Timber Systems. Ph.D. Thesis, Universidade do Minho, Braga, Portugal, 2016.

15. Güçhan, N.Ş. History and Characteristics of Construction Techniques Used in Traditional Timber Ottoman Houses. *Int. J. Arch. Heritage* **2018**, *12*, 1–20. [CrossRef]

16. Liu, Y.; Cai, J.; Zhang, J. Research on the Characteristics of Timber Frames of Tingtang in Residences of Ming and Qing Dynasties in Shanghai. *Int. J. Arch. Heritage* **2018**, *14*, 196–207. [CrossRef]

17. Ortega, J.; Vasconcelos, G.; Rodrigues, H.; Correia, M.; Lourenço, P.B. Traditional earthquake resistant techniques for vernacular architecture and local seismic cultures: A literature review. *J. Cult. Heritage* **2017**, *27*, 181–196. [CrossRef]

18. Stellacci, S.; Rato, V. Timber-Framing Construction in Herculaneum Archaeological Site: Characterisation and Main Reasons for its Diffusion. *Int. J. Arch. Heritage* **2019**, *1*, 1–19. [CrossRef]

19. Poletti, E. Characterization of the Seismic Behaviour of Traditional Timber Frame Walls. Ph.D. Thesis, Universidade do Minho Escola de Engenharia, Braga, Portugal, 2013.

20. Cruz, H.; Yeomans, D.; Tsakanika, E.; Macchioni, N.; Jorissen, A.; Touza, M.; Mannucci, M.; Lourenço, P.B. Guidelines for on-site assessment of historic timber structures. *Int. J. Arch. Heritage* **2015**, *9*, 277–289. [CrossRef]

21. Bertolini-Cestari, C.; Brino, G.; Cestari, L.; Crivellaro, A.; Marzi, T.; Pignatelli, O.; Rolla, S.; Violante, A. The Great Timber Roof of Porta Nuova Railway Station in Turin: The Role of Assessment and Diagnosis for Sustainable Repair and Conservation. *Int. J. Arch. Heritage* **2019**, *13*, 172–191. [CrossRef]

22. Riggio, M.; Parisi, M.A.V.; Tardini, C.; Tsakanika, E.; D’Ayala, D.; Ruggieri, N.; Tampone, G.; Augelli, F. Existing timber structures: Proposal for an assessment template. In *Proceedings of the SHATIS*, Wroclaw, Poland, 9–11 September 2015; pp. 100–107.

23. Palanti, S.; Pecoraro, E.; Scarpino, F. Wooden doors and windows in the Church of the Nativity: Evaluation of biotic and abiotic decay and proposals of interventions. *J. Cult. Heritage* **2012**, *13*, e82–e92. [CrossRef]

24. Palanti, S.; Macchioni, N.; Paoli, R.; Feci, E.; Scarpino, F. A case study: The evaluation of biological decay of a historical hayloft in Rendena Valley, Trento, Italy. *Int. Biodeterior. Biodegradation* **2014**, *86*, 179–187. [CrossRef]

25. Zhang, Y.; Ying, Z.; Shen, Z.; Nishino, T.; Chen, X. 3D laser scanning technology-based historic building mapping for historic preservation. *Int. Rev. Spat. Plan. Sustain. Dev.* **2015**, *3*, 53–67. [CrossRef]

26. Riveiro, B.; Conde-Carnero, B.; Arias-Sánchez, P. Laser Scanning for the Evaluation of Historic Structures. In *Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures*; IGI Global: Vigo, Spain, 2015; pp. 765–793.

27. Yang, X.; Koehl, M.; Grussenmeyer, P. *Automating Parametric Modelling From Reality-Based Data by Revit Api Development*; MDPI: Basel, Switzerland, 2018.

28. Berg, A. *Norske tømmerhus frå mellomalderen, bd. II: Hus for hus i Buskerud, Vestfold og Oppland; Landbruksforlaget: Oslo, Norway, 1990.*

29. Engineers, A.S.O.C. *Seismic Evaluation and Retrofit of Existing Buildings: ASCE/SEI, 41-17*; American Society of Civil Engineers: Reston, VA, USA, 2017.

30. Rojah, C. *ATC-20-1 Field Manual: Postearthquake Safety Evaluation of Buildings*; Applied Technology Council: Redwood City, CA, USA, 2005.

31. Agency, F.E.M. *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*; Government Printing Office: Washington, DC, USA, 2017.

32. Baggio, C.; Bernardini, A.; Colozza, R.; Corazza, L. Manuale per la compilazione della scheda di 1 livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell’e emergenza post-sismica ( AeDES). In *Servizio Sismico Nazionale e Gruppo Nazionale Per La Difesa Dai Terremoti*; Editrice Italiani nel Mondo srl-Roma: Roma, Italy, 2000; Volume 112.

33. D’Ayala, D.; Speranza, E. Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. *Earthq. Spectra* **2003**, *19*, 479–509. [CrossRef]
34. D’Ayala, D.; Galasso, C.; Putrino, V.; Fanciullacci, D.; Barucco, P.; Fanciullacci, V.; Bronzino, C.; Zerrudo, E.; Manalo, M.; Fradiquela, C. Assessment of the multi-hazard vulnerability of priority cultural heritage structures in the Philippines. In Proceedings of the 1st International Conference on Natural Hazards & Infrastructure, Chania, Greece, 28–30 June 2016.

35. D’Ayala, D.; Branco, J.M.; Riggio, M.; Harte, A.; Kurz, J.; Descamps, T. Assessment, reinforcement and monitoring of timber structures: FPS Cost Action FP1101. In Proceedings of the SAHC2014–9th International Conference on Structural Analysis of Historical Constructions, Mexico City, Mexico, 14–17 October 2014.

36. Kasal, B.; Tannert, T. In Situ Assessment of Structural Timber; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2011; Volume 7.

37. Niemz, P.; Mannes, D. Non-destructive testing of wood and wood-based materials. J. Cult. Heritage 2012, 13, S26–S34. [CrossRef]

38. Kasal, B.; Anthony, R.W. Advances in in situ evaluation of timber structures. Progress Struct. Eng. Mater. 2004, 6, 94–103. [CrossRef]

39. Ramos, L.E.; Aguilar, R.; Lourenço, P.B. Operational modal analysis of historical constructions using commercial wireless platforms. Struct. Heal. Monit. 2011, 10, 511–521. [CrossRef]

40. Reynolds, T.; Casagrande, D.; Tomasi, R. Comparison of multi-storey cross-laminated timber and timber frame buildings by in situ modal analysis. Constr. Build. Mater. 2016, 102, 1009–1017. [CrossRef]

41. Kouroussis, G.; Fekih, L.B.; Descamps, T. Assessment of timber element mechanical properties using experimental modal analysis. Constr. Build. Mater. 2017, 134, 254–261. [CrossRef]

42. Rinn, F.; Schweingruber, F.-H.; Schär, E. Resistograph and X-ray density profiles of wood. Comparative evaluation of drill resistance profiles and X-ray density charts of different wood species. Holzforsch. -Int. J. Biol. Chem. Phys. Technol. Wood 1996, 50, 303–311. [CrossRef]

43. Van Roy, N.; Verstrynge, E.; Van Balen, K. Enhancement of the Identification of Historical Timber Element’s Local Stiffness Based on Resistance Drilling Measurements. In Structural Analysis of Historical Constructions; Springer: Cham, Switzerland, 2019; pp. 495–503.

44. Cuartero, J.; Cabaleiro, M.; Sousa, H.S.; Branco, J.M. Tridimensional parametric model for prediction of structural safety of existing timber roofs using laser scanner and drilling resistance tests. Eng. Struct. 2019, 185, 58–67. [CrossRef]

45. Nowak, T.P.; Jasienko, J.; Hamrol-Bielecka, K. In situ assessment of structural timber using the resistance drilling method–Evaluation of usefulness. Constr. Build. Mater. 2016, 102, 403–415. [CrossRef]

46. Cabaleiro, M.; Branco, J.M.; Sousa, H.S.; Conde, B. First results on the combination of laser scanner and drilling resistance tests for the assessment of the geometrical condition of irregular cross-sections of timber beams. Mater. Struct. 2018, 51, 99. [CrossRef]

47. Piazza, M.; Riggio, M. Visual strength-grading and NDT of timber in traditional structures. J. Build. Apprais. 2008, 3, 267–296. [CrossRef]

48. Lechner, T.; Sandin, Y.; Kliger, R. Assessment of density in timber using X-ray equipment. Int. J. Arch. Heritage 2013, 7, 416–433. [CrossRef]

49. Parracha, J.; Pereira, M.F.; Mauricio, A.; Faria, P.; Nunes, L. Using X-ray micro-CT to evaluate density loss in anobiid infested. In Proceedings of the IRG50 Scientific Conference on Wood Protection, Quebec City, QC, Canada, 12–16 May 2019.

50. Schofield, E.J. Illuminating the past: X-ray analysis of our cultural heritage. Nat. Rev. Mater. 2018, 3, 285. [CrossRef]

51. Ilharco, T.; Lechner, T.; Nowak, T. Assessment of timber floors by means of non-destructive testing methods. Constr. Build. Mater. 2015, 101, 1206–1214. [CrossRef]

52. Drdäcky, M.; Urushadze, S. Retrofitting of Imperfect Halved Dovetail Carpentry Joints for Increased Seismic Resistance. Buildings 2019, 9, 48. [CrossRef]

53. Chadwick, A.V.; Berko, A.; Schofield, E.J.; Jones, A.M.; Mosselmans, J.F.W.; Smith, A.D. Application of Microfocus X-ray Beams from Synchrotrons in Heritage Conservation. Int. J. Arch. Heritage 2012, 6, 228–258. [CrossRef]

54. Wedvik, B.; Stein, M.; Stornes, J.M.; Mattsson, J. On-site Radioscopic Qualitative Assessment of Historic Timber Structures: Identification and Mapping of Biological Deterioration of Wood. Int. J. Arch. Heritage 2016, 10, 646–662. [CrossRef]
55. Schimleck, L.R. Near infrared spectroscopy: A rapid, non-destructive method for measuring wood properties and its application to tree breeding. *N. Z. J. For. Sci.* 2008, 38, 14–35.
56. Kelley, S.S.; Rials, T.G.; Snell, R.; Groom, L.H.; Sluiter, A. Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. *Wood Sci. Technol.* 2004, 38, 257–276. [CrossRef]
57. Sandak, A.; Sandak, J.; Riggio, M. Estimation of physical and mechanical properties of timber members in service by means of infrared spectroscopy. *Constr. Build. Mater.* 2015, 101, 1197–1205. [CrossRef]
58. Faella, G.; Frunzio, G.; Guadagnuolo, M.; Donadio, A.; Ferri, L. The Church of the Nativity in Bethlehem: Non-destructive tests for the structural knowledge. *J. Cult. Heritage* 2012, 13, e27–e41. [CrossRef]
59. Kandemir-Yucel, A.; Tavukcuoglu, A.; Caner-Saltik, E. In situ assessment of structural timber elements of a historic building by infrared thermography and ultrasonic velocity. *Infrared Phys. Technol.* 2007, 49, 243–248. [CrossRef]
60. Rivera-Gomez, C.; Galán-Marín, C. In situ assessment of structural timber elements of a historic building by moisture content analyses and ultrasonic velocity tests. *Int. J. Hous. Sci.* 2013, 37, 33–42.
61. Carrillo, M.; Carreón, H. Ultrasonic determination of the elastic and shear modulus on aged wood. In Proceedings of the Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XIII, Denver, CO, USA, 4–7 March 2019; p. 109711Z.
62. Kránitz, K.; Deublein, M.; Niemz, P. Determination of dynamic elastic moduli and shear moduli of aged wood by means of ultrasonic devices. *Mater. Struct.* 2014, 47, 925–936. [CrossRef]
63. Rajičić, V.; Cola, C. Correlation between destructive and four NDT techniques tests on historic timber elements. In Proceedings of the 1st European Workshop of Cultural Heritage Protection Berlin, Berlin/Heidelberg, Germany, 18–24 June 2018.
64. Rodríguez-Abad, I.; Martínez-Sala, R.; García-García, F.; Capuz-Lladro, R. Non-destructive methodologies for the evaluation of moisture content in sawn timber structures: Ground-penetrating radar and ultrasound techniques. *Near Surf. Geophys.* 2010, 8, 475–482. [CrossRef]
65. Pérez-Gracia, V.; Santos-Assunção, S.; Caselles, O.; Clapés, J.; Canas, J.A. Study of wood beams in buildings with ground penetrating radar. In Proceedings of the 15th International Conference on Ground Penetrating Radar, Brussels, Belgium, 30 June–July 2014; pp. 31–35.
66. Martínez-Sala, R.; Rodríguez-Abad, I.; Diez Barra, R.; Capuz-Lladró, R. Assessment of the dielectric anisotropy in timber using the nondestructive GPR technique. *Constr. Build. Mater.* 2013, 38, 903–911. [CrossRef]
67. Butnor, J.R.; Pruyn, M.L.; Shaw, D.C.; Harmon, M.E.; Mucciardi, A.N.; Ryan, M.G. Detecting defects in conifers with ground penetrating radar: Applications and challenges. *For. Pathol.* 2009, 39, 309–322. [CrossRef]
68. Kordatos, E.; Exarchos, D.; Stavrakos, C.; Moropoulou, A.; Matikas, T. Infrared thermographic inspection of murals and characterization of degradation in historic monuments. *Constr. Build. Mater.* 2013, 48, 1261–1265. [CrossRef]
69. Maierhofer, C.; Röllig, M.; Krankenhagen, R. Integration of active thermography into the assessment of cultural heritage buildings. *J. Mod. Opt.* 2010, 57, 1790–1802. [CrossRef]
70. López, G.; Basterra, L.-A.; Ramón-Cueto, G.; Diego, A.d. Detection of singularities and subsurface defects in wood by infrared thermography. *Int. J. Arch. Heritage* 2014, 8, 517–536. [CrossRef]
71. Kasal, B. Semi-destructive method for In-Situ evaluation of compressive strength of wood structural members. *For. Prod. J.* 2003, 53, 55–58.
72. Kloiber, M.; Tippner, J.; Hrivnák, J. Mechanical properties of wood examined by semi-destructive devices. *Mater. Struct.* 2014, 47, 199–212. [CrossRef]
73. Bobadilla, I.; Martínez, R.D.; Esteban, M.; Llana, D.F. Estimation of wood density by the core drilling technique. *Holzforschung* 2018, 72, 1051–1056. [CrossRef]
74. Brites, R.D.; Lourenço, P.B.; Machado, J.S. A semi-destructive tension method for evaluating the strength and stiffness of clear wood zones of structural timber elements in-service. *Constr. Build. Mater.* 2012, 34, 136–144. [CrossRef]
75. Sandak, J.; Sandak, A.; Riggio, M. Multivariate analysis of multi-sensor data for assessment of timber structures: Principles and applications. *Constr. Build. Mater.* 2015, 101, 1172–1180. [CrossRef]
76. Sousa, H.S.; Sørensen, J.D.; Kirkegaard, P.H.; Branco, J.M.; Lourenço, P.B. On the use of NDT data for reliability-based assessment of existing timber structures. *Eng. Struct.* 2013, 56, 298–311. [CrossRef]
77. Lourenço, P.B.; Sousa, H.S.; Brites, R.D.; Neves, L.C. In situ measured cross section geometry of old timber structures and its influence on structural safety. *Mater. Struct.* 2013, 46, 1193–1208. [CrossRef]
78. Sousa, H.S.; Branco, J.M.; Lourenço, P.B. A holistic methodology for probabilistic safety assessment of timber elements combining onsite and laboratory data. Int. J. Arch. Heritage 2016, 10, 526–538. [CrossRef]
79. Xue, J.; Xu, D.; Qi, L. Experimental seismic response of a column-and-tie wooden structure. Adv. Struct. Eng. 2019, 22, 1909–1922. [CrossRef]
80. Chen, J.; Chen, Y.F.; Shi, X.; Zhao, Y.; Li, T. Hysteresis behavior of traditional timber structures by full-scale tests. Adv. Struct. Eng. 2018, 21, 287–299. [CrossRef]
81. Xue, J.; Xu, D. Shake table tests on the traditional column-and-tie timber structures. Eng. Struct. 2018, 175, 847–860. [CrossRef]
82. Li, X.; Zhao, J.; Ma, G.; Chen, W. Experimental study on the seismic performance of a double-span traditional timber frame. Eng. Struct. 2019, 98, 141–150. [CrossRef]
83. Wu, Y.J.; Song, X.B.; Luo, L. Experimental Investigation on the Seismic Performance of a Chinese Traditional Wooden Pagoda. Appl. Mech. Mater. 2016, 858, 119–124. [CrossRef]
84. Sandak, J.; Riggio, M.; Ruggieri, N.; Sandak, A. Damage progression analysis in a historical timber framed wall under cyclic loads through an image-based tracking method. Constr. Build. Mater. 2019, 199, 483–491. [CrossRef]
85. Xue, J.; Wu, Z.; Zhang, F.; Zhao, H. Seismic damage evaluation model of Chinese ancient timber buildings. Adv. Struct. Eng. 2015, 18, 1671–1683. [CrossRef]
86. Xue, J.; Xu, D.; Xia, H. Experimental Study on Seismic Performance of Through-Tenon Joints with Looseness in Ancient Timber Structures. Int. J. Arch. Heritage 2018, 14, 483–495. [CrossRef]
87. Branco, J.M.; Lourenço, P.B.; Aranha, C.A. Seismic analysis of a 2-storey log house. Adv. Mater. Res. 2013, 778, 478–485. [CrossRef]
88. Dutu, A.; Niste, M.; Spatarelu, I.; Dima, D.I.; Kishiki, S. Seismic evaluation of Romanian traditional buildings with timber frame and mud masonry infills by in-plane static cyclic tests. Eng. Struct. 2018, 167, 655–670. [CrossRef]
89. Sieffert, Y.; Vieux-Champagne, F.; Grange, S.; Garnier, P.; Duccini, J.C.; Daudeville, L. Full-field measurement with a digital image correlation analysis of a shake table test on a timber-framed structure filled with stones and earth. Eng. Struct. 2016, 123, 451–472. [CrossRef]
90. Huang, H.; Wu, Y.; Li, Z.; Sun, Z.; Chen, Z. Seismic behavior of Chuan-Dou type timber frames. Eng. Struct. 2018, 167, 725–739. [CrossRef]
91. Vieux-Champagne, F.; Sieffert, Y.; Grange, S.; Polastri, A.; Ceccotti, A.; Daudeville, L. Experimental analysis of seismic resistance of timber-framed structures with stones and earth infill. Eng. Struct. 2014, 69, 102–115. [CrossRef]
92. Xie, Q.; Wang, L.; Zhang, L.; Hu, W.; Zhou, T. Seismic behaviour of a traditional timber structure: Shaking table tests, energy dissipation mechanism and damage assessment model. Bull. Earthq. Eng. 2019, 17, 1689–1714. [CrossRef]
93. Ma, L.; Xue, J.; Dai, W.; Zhang, X.; Zhao, X. Moment-rotation relationship of mortise-through-tenon connections in historic timber structures. Constr. Build. Mater. 2020, 232, 117285. [CrossRef]
94. Li, S.; Zhou, Z.; Luo, H.; Milani, G.; Abruzzese, D. Behavior of traditional Chinese mortise-tenon joints: Experimental and numerical insight for coupled vertical and reversed cyclic horizontal loads. J. Build. Eng. 2020, 30, 101257. [CrossRef]
95. Bassier, M.; Hadjidemetriou, G.; Vergauwen, M.; Van Roy, N.; Verstrynge, E. Implementation of Scan-to-BIM and FEM for the Documentation and Analysis of Heritage Timber Roof Structures. In Proceedings of the Digital Heritage, Progress in Cultural Heritage: Documentation, Preservation, and Protection, Nicosia, Cyprus, 31 October–5 November 2016; pp. 79–90.
96. Pöchtrager, M.; Styhler-Aydın, G.; Döring-Williams, M.; Pfeifer, N. Digital reconstruction of historic roof structures: Developing a workflow for a highly automated analysis. Virtual Archaeol. Rev. 2018, 9, 21–33. [CrossRef]
97. Bertolini Cestari, C.; Marzi, T. Conservation of historic timber roof structures of Italian architectural heritage: Diagnosis, assessment, and intervention. Int. J. Arch. Heritage 2018, 12, 632–665. [CrossRef]
98. Milch, J.; Tippner, J.; Sebera, V.; Kunecký, J.; Kloiber, M.; Navrátil, M. The numerical assessment of a full-scale historical truss structure reconstructed with use of traditional all-wooden joints. J. Cult. Heritage 2016, 21, 759–766. [CrossRef]
99. Ferreira, J.; Teixeira, M.; Duțu, A.; Branco, F.; Gonçalves, A. Experimental evaluation and numerical modelling of timber-framed walls. Exp. Tech. 2014, 38, 45–53. [CrossRef]
100. Ceccotti, A.; Sandhaas, C.A.; Sandhaas, C. A proposal for a procedure to evaluate the seismic vulnerability of historic timber frame buildings. In Historical Earthquake-Resistant Timber Frames in the Mediterranean Area; Springer: Cosenza, Italy, 2015; pp. 105–118.
101. Fritsch, E.; Sieffert, Y.; Algusab, H.; Grange, S.; Garnier, P.; Daudeville, L. Numerical analysis on seismic resistance of a two-story timber-framed structure with stone and earth infill. Int. J. Arch. Heritage 2018, 13, 820–840. [CrossRef]
102. Duțu, A.; Yamazaki, Y.; Sakata, H. Shear spring model proposed for seismic evaluation of a timber framed masonry infilled wall. Eng. Struct. 2018, 167, 671–682. [CrossRef]
103. Xie, Q.; Wang, L. Seismic Behavior of Chinese Traditional Timber Frames with Masonry Infill Wall: Experimental Tests and Hysteretic Model. Int. J. Arch. Heritage 2019, 1, 1–15. [CrossRef]
104. Guerra, S. Numerical Modelling of the Seismic Behavior of Timber-Frame Structures Based on Macro-Elements. 2017. Available online: https://www.researchgate.net/publication/323398505_Numerical_Modelling_of_the_seismic_behavior_of_timber-framed_structures_based_on_macro-elements (accessed on 10 August 2020).
105. Kouris, L.A.S.; Kappos, A.J. Detailed and simplified non-linear models for timber-framed masonry structures. J. Cult. Heritage 2012, 13, 47–58. [CrossRef]
106. Chand, B.; Kaushik, H.B.; Das, S. Lateral Load Behavior of Traditional Assam-Type Wooden House. J. Struct. Eng. 2019, 145, 04019072. [CrossRef]
107. Ahmad, N.; Ali, Q.; Umar, M. Simplified engineering tools for seismic analysis and design of traditional Dhajji-Dewari structures. Bull. Earthq. Eng. 2012, 10, 1503–1534. [CrossRef]
108. Lukic, R.; Poletti, E.; Rodrigues, H.; Vasconcelos, G. Numerical modelling of the cyclic behavior of timber-framed structures. Eng. Struct. 2018, 165, 210–221. [CrossRef]
109. Galassi, S.; Ruggieri, N.; Tempesta, G. Seismic performance evaluation of timber—framed masonry walls experimental tests and numerical modelling. In Historical Earthquake-Resistant Timber Frames in the Mediterranean Area; Springer: Cosenza, Italy, 2015; pp. 95–103.
110. Grossi, P.; Sartori, T.; Giorgi, I.; Tomasi, R. Analysis of timber log-house construction system via experimental testing and analytical modelling. Constr. Build. Mater. 2016, 102, 1127–1144. [CrossRef]
111. Branco, J.M.; Araújo, J.P. Structural behaviour of log timber walls under lateral in-plane loads. Eng. Struct. 2012, 40, 371–382. [CrossRef]
112. Bedon, C.; Rinaldin, G.; Fragiacoimo, M. Non-linear modelling of the in-plane seismic behaviour of timber Blockhaus log-walls. Eng. Struct. 2015, 91, 112–124. [CrossRef]
113. Sciomenta, M.; Bedon, C.; Fragiacoimo, M.; Luongo, A. Shear Performance Assessment of Timber Log-House Walls under In-Plane Lateral Loads via Numerical and Analytical Modelling. Buildings 2018, 8, 99. [CrossRef]
114. Scott, R.J.; Leichti, R.J.; Miller, T.H. Finite-element modeling of log wall lateral force resistance. For. Prod. J. 2005, 55, 48–54. [CrossRef]
115. Bedon, C.; Rinaldin, G.; Fragiacoimo, M.; Noé, S. q-factor estimation for 3D log-house timber buildings via Finite Element analyses. Soil Dyn. Earthq. Eng. 2019, 116, 215–229. [CrossRef]
116. Xie, Q.; Zhang, L.; Li, S.; Zhou, W.; Wang, L. Cyclic behavior of Chinese ancient wooden frame with mortise–tenon joints: Friction constitutive model and finite element modelling. J. Wood Sci. 2017, 64, 40–51. [CrossRef]
117. Huan, J.; Ma, D.; Wang, W. Vulnerability Analysis of Ancient Timber Architecture by Considering the Correlation of Different Failure Modes. Math. Probl. Eng. 2018, 2018, 1–10. [CrossRef]
118. Yeo, S.-Y.; Komatsu, K.; Hsu, M.-F.; Que, Z. Mechanical model for complex brackets system of the Taiwanese traditional Dieh-Dou timber structures. Adv. Struct. Eng. 2016, 19, 65–85. [CrossRef]
119. Tsai, P.-H.; D’Ayala, D. Performance-based seismic assessment method for Taiwanese historic Dieh-Dou timber structures. Earthq. Eng. Struct. Dyn. 2011, 40, 709–729. [CrossRef]
120. Chen, L.-K.; Li, S.-C.; Zhao, K.-P.; Chen, Z.-Y.; Song, T.; Zhang, L.; Jiang, Z.-J. Experimental and Numerical Investigation on Seismic Performance of One-Way Straight Mortise–Tenon Joints Based on a Novel Method to Simulate Damage of Deteriorated Ancient Chinese Timber Buildings. J. Perform. Constr. Facil. 2020, 34, 04019119. [CrossRef]
121. D’Ayala, D.F.; Tsai, P.H. Seismic vulnerability of historic Dieh–Dou timber structures in Taiwan. Eng. Struct. 2008, 30, 2101–2113. [CrossRef]
122. D'ayala, D.; Meslem, A.; Vamvatsikos, D.; Porter, K.; Rossetto, T.; Crowley, H.; Silva, V. Guidelines for Analytical Vulnerability Assessment of Low/Mid-rise Buildings—Methodology; Vulnerability Global Component Project: Pavia, Italy, 2014.
123. Mosoarca, M.; Keller, A.I.; Bocan, C. Failure analysis of church towers and roof structures due to high wind velocities. Eng. Fail. Anal. 2019, 100, 76–87. [CrossRef]
124. Chun, Q.; Han, Y.; Jin, H.; Lin, Y. Research on Wind Vibration Performance of Chinese Early Traditional Timber Structure—A case study of the Main hall of Tianning Temple. MATEC Web Conf. 2019, 275, 01005. [CrossRef]
125. Bertolini-Cestari, C.; Invernizzi, S.; Marzi, T.; Spano, A. Numerical survey, analysis and assessment of past interventions on historical timber structures: The roof of valentino castle. Wind. Konserw. 2016, 45, 87–97.
126. Candelas-Gutiérrez, A.; Borrarlo-Jimenez, M. Methodology of Restoration of Historical Timber Roof Frames. Application to Traditional Spanish Structural Carpentry. Int. J. Arch. Heritage 2018, 14, 51–74. [CrossRef]
127. Verbist, M.; Matos, F.T.; Branco, J.M. Structural and health assessment of historic timber roofs from the Convent of Christ in Tomar. J. Civ. Struct. Heal. Monit. 2019, 9, 491–511. [CrossRef]
128. Parisi, M.A.; Chesi, C.; Tardini, C. Inferring Seismic Behavior From Morphology in Timber Roofs. Int. J. Arch. Heritage 2012, 6, 100–116. [CrossRef]
129. Stephenson, V.; D’Ayala, D. Structural Response of Masonry Infilled Timber Frames to Flood and Wind Driven Rain Exposure. J. Perform. Constr. Facil. 2019, 33, 04019028. [CrossRef]
130. Buchanan, A. The challenges of predicting structural performance in fires. Fire Saf. Sci. 2008, 9, 79–90. [CrossRef]
131. Gernay, T.; Khorasani, N.E. Resilience of the Built Environment to Fire and Fire-Following-Earthquake. In Resilient Structures and Infrastructure; Springer: Singapore, 2019; pp. 417–449.
132. National Fire Protection Association. NFPA 914. In Code for Fire Protection of Historic Structures; National Fire Protection Association: Quincy, MA, USA, 2019. Available online: https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=914 (accessed on 10 August 2020).
133. European Committee for Standardization. Eurocode 8: Design of structures for earthquake resistance. Part 2005, 1, 1998-1.
134. European Committee for Standardization. Eurocode 1: Actions on Structures. 2006. Available online: http://www.unirc.it/documentazione/materiale_didattico/599_2008_92_1049.pdf (accessed on 10 August 2020).
135. American Society of Civil Engineers. Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-16); American Society of Civil Engineers: Reston, VA, USA, 2016.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).