

Review

Seismic Vulnerability Assessment and Strengthening of Heritage Timber Buildings: A Review

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Abstract: Recent studies highlight the potential impact of earthquakes on cultural heritage sites and monuments, which in turn yield significant adverse impacts on economies, politics, and societies. Several aspects such as building materials, structural responses, and restoration strategies must be considered in the conservation of heritage structures. Timber is an old organic construction material. Most of the historic timber structures were not designed to withstand seismic forces; therefore, the seismic vulnerability assessment of heritage timber structures in areas with high seismic hazard is essential for their conservation. For this purpose, different strategies for the numerical modeling of heritage timber buildings have been developed and validated against tests results. After performing seismic analysis using detailed analytical methods and predicting the susceptible structural components, strengthening techniques should be utilized to mitigate the risk level. To this aim, various methods using wooden components, composite material, steel components, SMA etc., have been utilized and tested and are reviewed in this study. There are still some gaps, such as full-scale numerical modeling of strengthened buildings and investigating the soil–structure interaction effects on the seismic behavior of buildings that should be investigated.

Keywords: heritage timber buildings; nonlinear numerical modeling; vulnerability assessment; strengthening techniques; seismic analysis; literature review

1. Introduction

Not only from a spiritual or a historical point of view but also because of their technological value, conservation of heritage structures is important for our generation and the future ones. Technological knowledge about their construction can help us find the best way for their conservation and learn from them as a pattern for our new structural systems. Moreover, losing cultural heritage sites can have irreplaceable detriments because of monumental artifacts inside the building and the structure itself.

Timber, as the oldest organic construction material, has been utilized with less global emissions to help to reduce the global warming impact [1]. As depicted in Figure 1, the number of timber buildings in the northern European countries is more compared to the southern countries. The structural vulnerability assessment of timber structures is complex because of the material diversity and high susceptibility to different environmental risks because of its organic nature compared to other materials, such as brick [2–4].

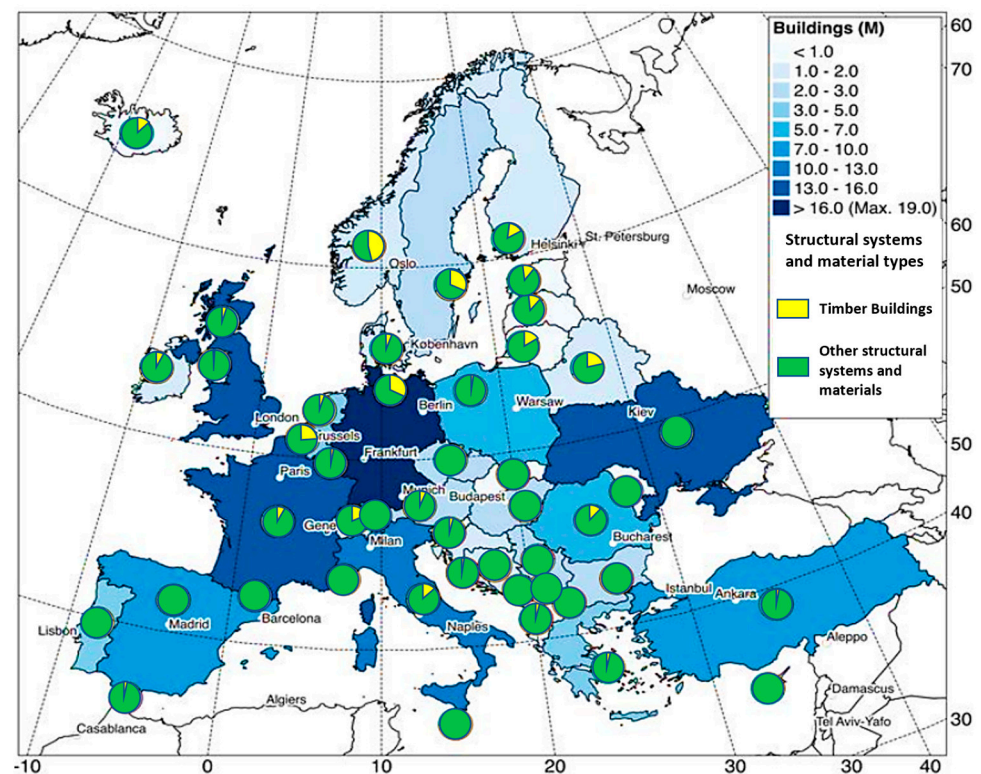


Figure 1. Total number of buildings in the European countries (in millions) and the exposure distribution of timber buildings [5].

Since most of the heritage structures were not designed based on reliable seismic codes, an earthquake can be a threat for them, particularly in zones of high seismic hazard [6,7]. A combination of experimental and numerical studies has been used in the past for seismic analysis of heritage timber buildings so that experimental tests at the structural component scale were performed, and a simplified, efficient numerical simulation method validated by the experimental results was developed for the simulation of the whole building. The simulation can be based on nonlinear rotational springs where all the nonlinear behavior of the building elements is concentrated. After the simulation of the building, nonlinear static pushover analysis or incremental dynamic analysis are conducted for the seismic vulnerability assessment of a case study [8]. In order to investigate the seismic vulnerability assessment methodologies of heritage timber buildings, they can be categorized into three main groups based on their structure: (1) timber frame buildings, (2) log house systems, and (3) post and beam systems [9].

Timber frame buildings are one of the well-known heritage timber structural systems and consist of timber frame elements with masonry infills [10]. In this structural system, which can be considered as the most efficient one, timber is utilized to compensate for the low strength of masonry materials in tension and confine the masonry infills to work better in shear [11,12]. In Figure 2, the seismic hazard map of Europe is depicted [13], and timber frame building typologies with various configurations of timber elements are highlighted. It can be pointed out that some types of timber frame typologies are located in areas with high seismicity zones. Indeed, traditional timber frame constructions with infill exhibited a remarkable behavior during large earthquakes [14]. This system was widely used not only in European countries but also for example in Haiti and India, in different categories based on the timber elements typologies [11].

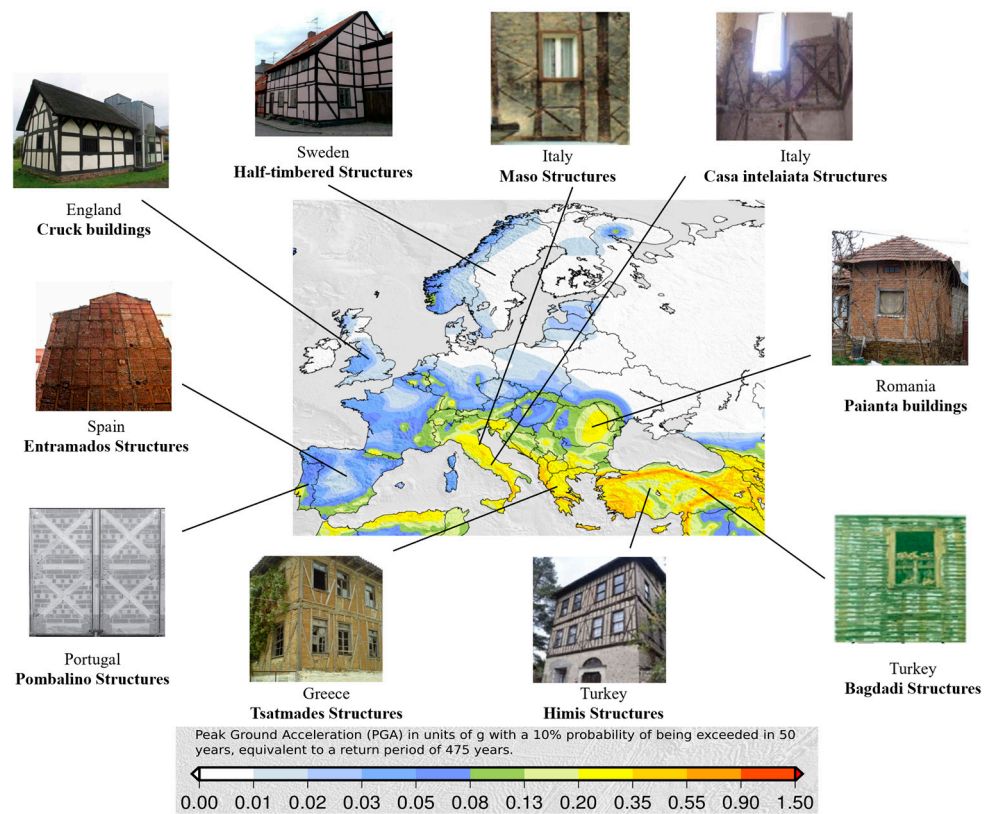


Figure 2. Hazard map of the European countries based on PGA [15] and various types of timber frame buildings in different European countries, adapted and updated from [16,17].

The log house system, as the second structural system type of heritage timber buildings, consists of timber logs that are connected in the horizontal direction [18]. This ancient structural system is famous because of its good insulating values and has been widely used in cold European countries [9,19]. An example of a log house is shown in Figure 3a. The corner joint, which is particularly effective on the lateral load-bearing behavior of this type of structural system, is shown in Figure 3b.



Figure 3. (a) A heritage log house building in Tønsberg, Norway. (b) Carpentry corner joint of the logs.

Last but not least, the post and beam system is another heritage timber structural system, shown in Figure 4. Post and beam structures are widely seen in eastern Asian countries, where timber beams and posts are connected by complex joints [20].

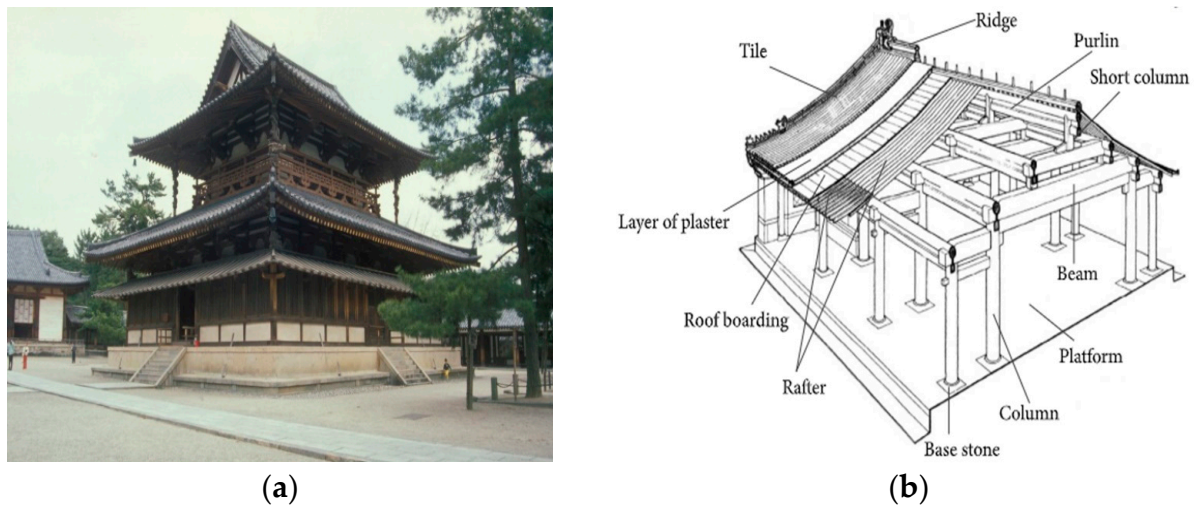


Figure 4. (a) A post and beam structure [9]. (b) A 3D drawing for a frame from a post and beam structure with its details [21].

Several experimental studies have been conducted to assess the vulnerability of these types of structures against lateral loadings at full-scale or structural component scale [22–30]. However, there is a need to investigate the modeling method and their vulnerability against different loading protocols and perform several analyses instead of a limited number of time-consuming and expensive full-scale experimental tests.

Various seismic analysis methodologies have been developed, which can be categorized into three main groups: (1) empirical methods, (2) hybrid methods, and (3) analytical methods [31]. The main focus of this study is on the application of detailed analytical methods that can be considered as the most robust method with a lower level of uncertainties compared to other methodologies. However, more computational efforts, a higher level of input data needed for the assessment, and the need for a skilled interpreter of the results are the main limitations of detailed analytical methods [31].

After performing seismic analysis to investigate the vulnerability of buildings and define critical structural components, strengthening is required to mitigate the seismic risk [32,33]. The strengthening technique can be found based on the Hyperion methodology for structural vulnerability assessment of heritage timber buildings. The analysis is performed on the retrofitted building, and this loop is repeated until the most efficient strengthening technique is defined [7]. However, different criteria should be considered when planning for the restoration process [34]. Reversibility is a principle in the restoration methodology that should be considered. For this purpose, the possibility of eliminating previous work and applying new interventions in the future should be provided. All interventions should be harmonized with the present structural context. Moreover, resins or concrete are widely used to repair damaged parts, which cause discontinuities in mechanical properties and increase the possibility of brittle failure. For this reason, substitutions and prostheses with materials other than wood should be prohibited [35].

A comprehensive review of standards, guidelines, and procedures for the assessment of heritage structures has been completed in [2]. Diverse technical committees were also contributed to developing a generally accepted methodology for assessing and reinforcing heritage structures [36–40]. However, there is still a need for performing an in-depth review study focusing on the seismic vulnerability assessment and strengthening methodologies.

At this point, a review is necessary to evaluate the state-of-the-art of numerical methods and strengthening methods used for the seismic vulnerability assessment of heritage timber buildings. In this study, firstly a systematic review was performed to investigate the growth of research studies related to the seismic vulnerability assessment and strengthening of heritage timber buildings. Furthermore, the main topics in this area, as well as the state-of-the-art topics, were investigated. Nonlinear numerical modeling procedures of heritage timber buildings are reviewed for each of the three structural systems. Each section

is related to a particular structural system, and previous related studies were collected and presented. After providing an accurate numerical model, seismic analysis is needed to evaluate the seismic vulnerability of structures. Therefore, different applicable strategies are introduced, and the relevant research studies are reviewed. Finally, particular attention is given to the strengthening techniques by investigating their pros and cons.

2. Systematic Literature Review

For conducting a systematic literature review about seismic vulnerability assessment and retrofitting of heritage timber buildings, a set of keywords was selected, and all published articles were searched in the Scopus database. In this step, 262 papers were found containing at least one of the following keywords in the title, keywords, or the abstract: (1) seismic timber historical, (2) retrofitting timber historical, (3) assessment heritage timber building, (4) seismic timber heritage, (5) retrofitting timber heritage, (6) seismic timber frame historical, (7) seismic timber log house, (8) traditional seismic timber post and beam, (9) historic seismic timber post and beam, (10) timber Blockhaus buildings, (11) traditional timber joint load, (12) historic timber joint load, (13) mortise and tenon joint load. Note that AND operator was used between the terms of the keywords.

Then, two filters were applied, including being indexed in journals and written in the English language, and then 253 articles were derived. Afterward, the journals that are indexed in Web of Science (WoS) were selected to filter the papers, and finally, 239 papers were found for performing a bibliometric analysis. The whole methodology is summarized in Figure 5.

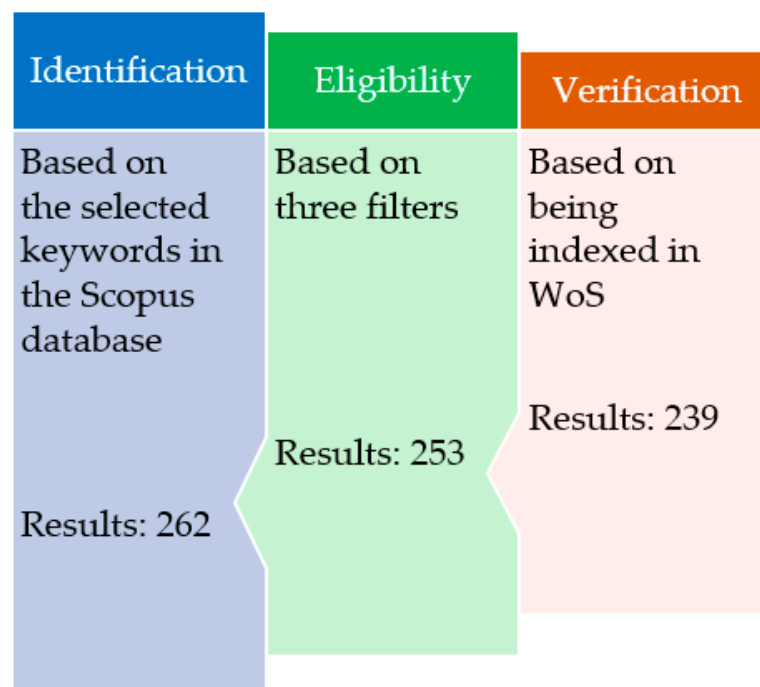


Figure 5. Methodology diagram of selected articles.

Figure 6 displays the number of published articles since 1999 that shows how attention shifted toward the topic in the last decade. Table 1 shows the scientific journals that had at least seven published articles. *Engineering Structures*, *International Journal of Architectural Heritage*, and *Construction and Building Materials* are three well-known journals that published the highest number of articles.

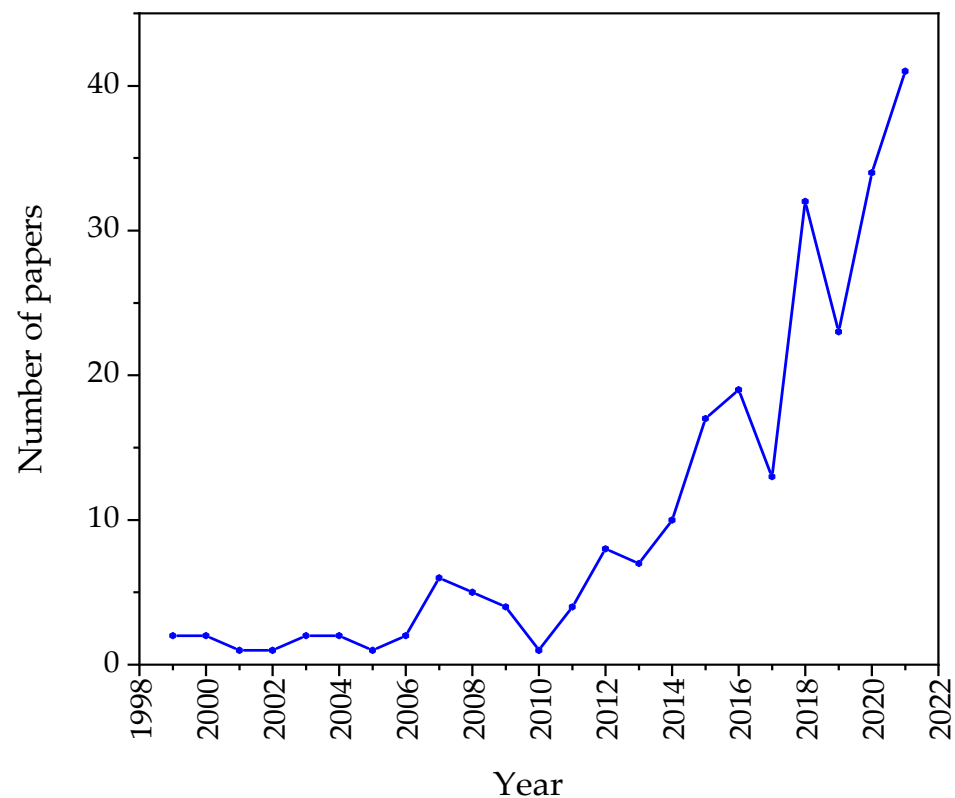


Figure 6. Number of published articles since 1999.

Table 1. Journals with the most relevant articles.

Publication	Documents
<i>Engineering Structures</i>	28
<i>International Journal of Architectural Heritage</i>	24
<i>Construction and Building Materials</i>	15
<i>Forest Products Journal</i>	7
<i>Proceedings of The Institution of Civil Engineers: Structures and Buildings</i>	7

The VOSviewer software (Version 1.6.17) [41] was utilized to generate visualization maps. Figure 7a shows the frequency keywords clustering. The bigger a circle is, the more frequently the keyword appears in the articles. Lines between keywords represent links, and a thicker line indicates the more robust connectivity of the keywords across different articles. Moreover, keywords that showed stronger connections are located closer to each other. The results of this analysis show that the networks connection consists of four main research areas. The conceptual part includes (1) historic timber structures and timber connections, green color; (2) structural design and experimental studies, red cluster (3) seismic vulnerability assessment and masonry construction, yellow cluster; and (4) historic preservation, which is the blue group. Figure 7b depicts the trending research topics based on the time of the published article. The yellow circles and connections mean more recent investigations.

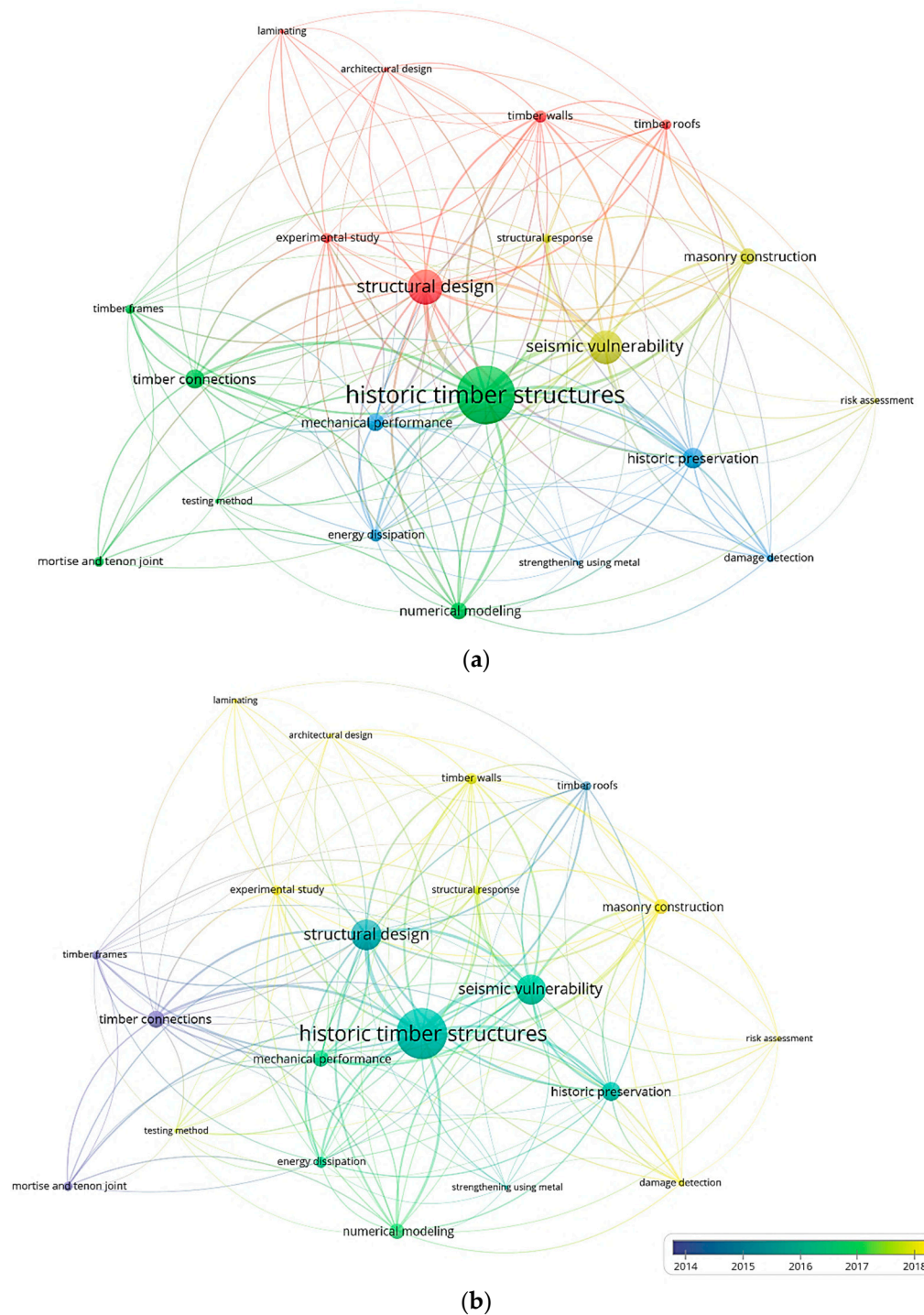


Figure 7. (a) Frequency keywords clustering. (b) Trending research topic from blue (oldest) to yellow (newest).

The visualizing bibliometric networks display that seismic vulnerability, structural design, and historic preservation are the three most used keywords and investigated areas after historic timber structure. These four topics have been investigated more than others. Moreover, the results show that research studies have recently shifted from analyzing timber connections toward performing experimental studies and masonry material that were often utilized in the construction of heritage timber buildings. The graphs depict that there are no connections (lines) between some topics in four main clusters (research areas) that show the potential knowledge gap and opportunity to start a new investigation.

In the following sections, different strategies for numerical modeling of heritage timber buildings are reviewed, different structural analysis methods have been discussed, and finally, various retrofitting and strengthening techniques are presented and reviewed. For this aim, each section is dedicated to a heritage timber structural system.

3. Numerical Modeling Methods

3.1. Timber Frame Buildings

In the timber frame structural system, timber shear walls consisting of a timber frame with masonry infill are considered as the load-bearing system. The monotonic and cyclic tests, which are shown in Figure 8a on precise models of historic timber frame walls, were performed to investigate their nonlinear behavior, including their near-collapse failure, maximum horizontal displacement, and energy dissipation [16,42]. For investigating the effect of vertical loads on the cyclic behavior of the walls, a few tests with different vertical loadings are needed. As a conservative approach, the execution of cyclic tests with a lower vertical load than in real buildings and calibration of the springs based on the results is suggested.

After deriving the cyclic behavior of the shear walls against lateral loads, the shear wall can be modeled by means of nonlinear rotational springs and rigid links for connecting them, as illustrated in Figure 8b. The springs must be calibrated to show the exact behavior of the wall. This calibration is done by repeating the analyses until the curves are fitted together.

Finally, a building is modeled with the calibrated shear walls in a way that, for a different configuration, the lateral stiffness can be assumed to be changed linearly with the length of the wall. Moreover, because of the low torsional problems due to the symmetry of the majority of historical buildings in height and plan, the 2D simulation of the buildings is adequate to represent the seismic behavior. As an effective parameter on the results, viscous damping values of 2–5% are recommended. However, 1% viscous damping is suggested to obtain results that are lying on the safe side in [8].

The simulation of timber frame walls with rotational springs was performed by employing rotational springs in different configurations [43–46]. Other types of simplified numerical models using different configurations for nonlinear springs and timber elements are also presented and calibrated by experimental results. In these alternatives, diagonal timber elements were modeled as linear strut elements, as shown in Figure 8c [46–50].

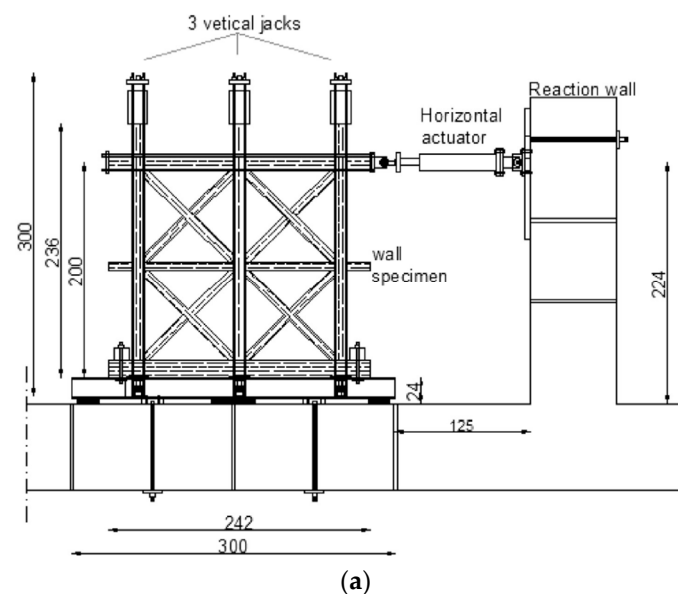


Figure 8. Cont.

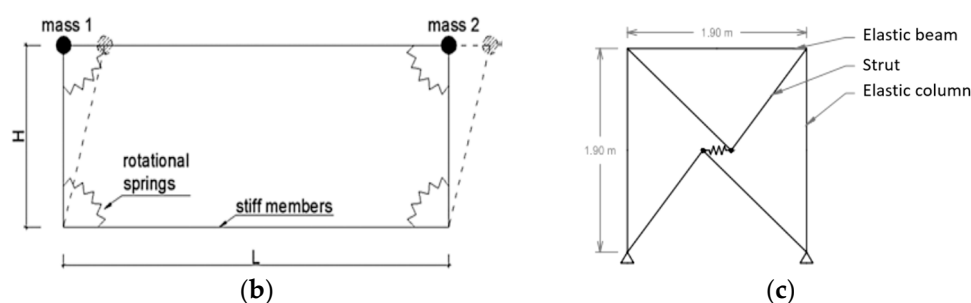


Figure 8. (a) In-plane test setup on a timber frame wall [47]. (b) A timber frame wall modeled using concentrated nonlinear springs. (c) An alternative approach for numerical modeling of the wall [46].

3.2. Log Houses

For the log house system, shear walls are the lateral load-bearing system, and the procedure for the simulation of this structural system is the same as in the case of timber frame system, which is employed in [51–53]. As illustrated in Figure 9a, the friction pendulum link element was used to model friction between the contact surfaces of the logs, and an inclined equivalent spring was modeled to simulate the interlocking between the logs [51].

As an alternative for simplified numerical simulation of log houses at building scale, logs were modeled separately, the corner joints were represented by a series of elastic spring with equivalent stiffness, the presence of n tolerance gaps was considered, and static friction was simulated by means of Coulomb forces, as shown in Figure 9b,c. For this alternative approach, the maximum displacement between the logs and the maximum displacement of the wall can be considered as damage indices in the analyses [54–57].

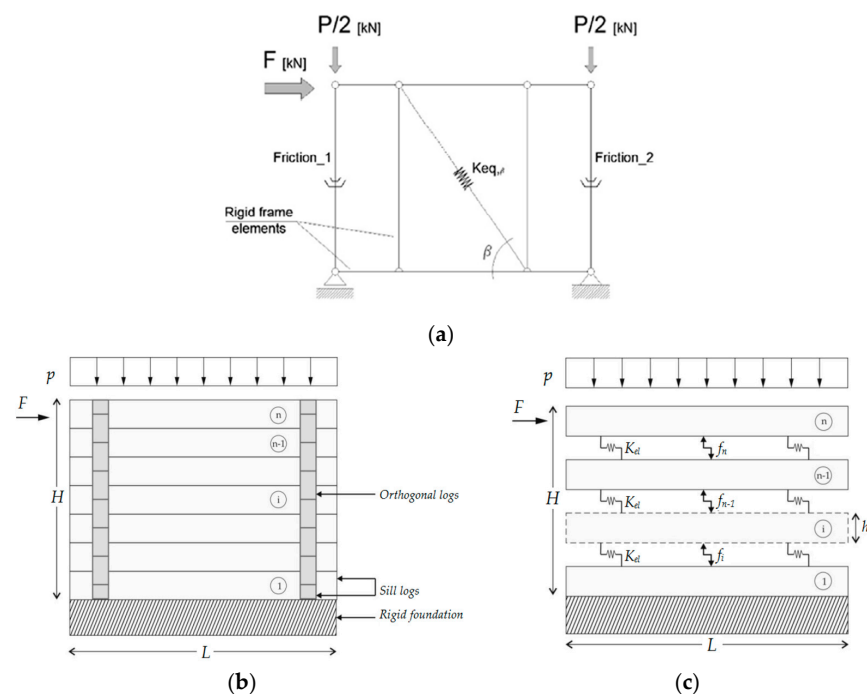


Figure 9. (a) A simplified numerical model for simulation of log house buildings based on the nonlinear spring approach [51]. (b) Full-scale assembly of a log house shear wall. (c) A simplified analytical model including different springs [55] (F : lateral load, p : vertical load, H : height, L : length, k_{eq} : equivalent stiffness of the corner joints, k_{el} : equivalent stiffness, f_i : Coulomb forces, h : timber log's height).

3.3. Post and Beam

The numerical modeling of the post and beam structural system is different from the other two systems because of the lack of timber shear walls. For this system, the cyclic behavior of the connections between post and beams plays a key role [58]. Figure 10a shows the test setup for deriving the cyclic behavior of the connections.

Instead of performing experimental tests on shear walls, the tests were conducted on the connections, and the building was simulated by linear timber post and beam elements with nonlinear rotational springs, which were calibrated with experimental results, as shown in Figure 10b as an example [59–64].

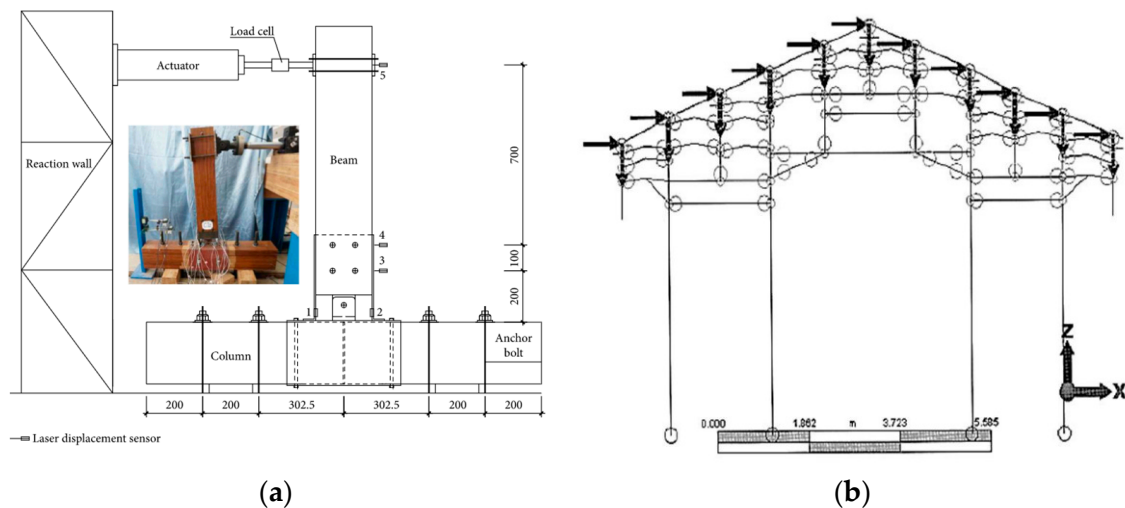


Figure 10. (a) Schematic diagram of the testing setup of a timber connection [65]. (b) Numerical model of a sample post and beam building with nonlinear springs [58].

4. Seismic Analysis Methods

After providing numerical models, seismic analyses methods should be utilized to investigate the structural behavior against the seismic loads. Nonlinear static pushover analysis (POA) is widely used for seismic analysis of buildings, and the well-known capacity curve is the ultimate result of this analysis method to investigate the stiffness, strength, and ductility subjected to seismic loads [66]. The POA method has two disadvantages; firstly, the results are dependent on the load patterns, particularly for structures in which higher mode effects are dominant. Moreover, seismic records' characteristics such as near-field velocity pulse effects, cannot be reflected by performing monotonic POA [31].

Capacity spectrum-based methods can be utilized in order to derive the performance point of structures based on the results from the POA, which are presented in FEMA 273 [67] and the N2 method [68] introduced recently in Eurocode 8 Part 3 [69]. Moreover, different modifications have been made to decrease the uncertainty level of the seismic demand derived from this efficient seismic analysis method.

Nonlinear time history analysis (NTHA) is considered the most robust seismic analysis method. Seismic records are applied to the model, and nonlinear dynamic analysis is performed during the NTHA. Ground motion selection and scaling are two effective parts on the NTHA results, and various methodologies have been proposed [70–72]. Results of the analyses to investigate the effect of the ground motion selection and scaling procedure show their inevitable sensitivity [73]. The NTHA method compensates for the aforementioned limitations of the POA and earthquake records specification, i.e., their duration, the sequence of peaks, and the frequency content that may influence the structural response [31]. However, due to the need for specialized practitioners, a high level of computational effort, and a high level of input data, the NTHA is less frequently used than the POA [66].

In order to have a more exact understanding of the seismic behavior of buildings, incremental dynamic analysis (IDA) can be utilized in which various accelerograms are applied to building models, and the intensities are increased until the predefined limit states occur [74]. The IDA results can be illustrated by plotting an engineering demand parameter (EDP) against an intensity measure (IM). Fragility curves can also be derived to depict the risk of the earthquake and predict the damage possibilities [75].

The numerical modeling and analyses method of various research studies are summarized in Table 2. It can be concluded that ABAQUS [76] and SAP2000 [77] are two well-known numerical modeling software that are widely utilized for this purpose. Furthermore, the scale of the modeling is prenoted as well as the analysis types. The cyclic and monotonic analyses are applicable for the validation of the test's specimens at structural component levels, and the POA and nonlinear dynamic analyses were utilized for the seismic analysis at a full-scale building. More research is required to investigate the effect of soil–structure interaction on the seismic behavior of heritage timber buildings with specific structural performance [78].

Table 2. Numerical modeling and analyses method of various research studies.

Type of the Structure	Software	Model Scale	Analysis Type	Analysis Purpose	Reference
Log house	ABAQUS	Structural component	Cyclic	Validation	[54]
	SAP2000	Structural component	Cyclic and Monotonic	Validation	[51]
	SAP2000	Structural component and full-scale	Cyclic, Monotonic, and simplified methods	Validation and a case study	[52]
	ABAQUS	Structural component	Monotonic	Validation and parametric study	[55]
	ABAQUS	Structural component	Monotonic	Validation and parametric study	[79]
	ABAQUS	Full-scale	Pushover	Case study	[53]
	ABAQUS	Full-scale	Nonlinear Dynamic	Validation and parametric study	[57]
	SAP2000	Full-scale	Linear Dynamic	Validation	[27]
Post and beam	ALGOR	Structural component and full-scale	Pushover	Validation and case study	[58]
	Unmentioned	Structural component	Cyclic	Validation	[63]
	ABAQUS	Structural component	Cyclic	Validation	[59]
	ANSYS	Full-scale	Nonlinear Dynamic	Case study	[60]
	ALGOR	Full-scale	Pushover and Nonlinear Dynamic	Case study	[62]
	ABAQUS	Full-scale	Nonlinear Dynamic	Case study	[80]
	ANSYS	Full-scale	Nonlinear Dynamic	Case study	[64]
	ABAQUS	Full-scale	Linear Static, Nonlinear Static and Nonlinear Dynamic	Case study	[81]
	OpenSees	Structural component	Cyclic	Validation	[82]
	DIANA FEA	Full-scale	Nonlinear Dynamic and Pushover	Case study	[83]
	OpenSees	Full-scale	Nonlinear Dynamic	Case study	[84]
	ABAQUS	Structural component	Monotonic	Validation and parametric study	[85]
	SAP2000	Structural component	Cyclic	Validation and a case study	[23]
ABAQUS	Structural component	Cyclic	Validation	[86]	
Timber frame	ATLAS	Full-scale	Nonlinear Dynamic	Case study	[43]
	OpenSees	Structural component	Cyclic and pushover	Validation and parametric study	[47]
	SAP2000	Structural component	Monotonic	Validation	[44]

Table 2. Cont.

Type of the Structure	Software	Model Scale	Analysis Type	Analysis Purpose	Reference
	ANSYS	Structural component and full-scale	Monotonic and Nonlinear static	Validation and a case study	[48]
	Autodesk Simulation Multiphysics	Structural component and full-scale	Cyclic and Pushover	Validation and a case study	[10]
	SAP2000	Structural component	Monotonic	Validation	[49]
	SAP2000	Structural component	Nonlinear static and dynamic	Validation and a case study	[50]
	OpenSees	Structural component	Cyclic	Validation	[16]
	FINAL v11	Structural component	Monotonic and Cyclic	Validation	[87]

5. Seismic Strengthening Methods

In the following sections, different seismic strengthening methods of heritage buildings are reviewed by dedicating each section to a specific technique.

5.1. Wooden Components

Wooden components are among the most important materials used for the seismic strengthening of timber frames. Using wooden members is a common practice today in historic building conservation in many countries. Chang et al. examined 18 full-scale specimens under reversed cyclic loading [88]. Shear walls used as shown in Figure 11 gained their moment-resistance from: (1) embedment between planks and beams, (2) friction between planks and beams, and (3) the shear strength of bamboo nails. To improve these factors, teak (*Tectona grandis*) and padauk (*Pterocarpus* spp.) were used as reinforcement materials. Specimens were classified in six groups: (A) and (B) without any reinforcement; (C) and (D) were reinforced by inserting teak strips into the top and bottom grooves between planks and beams; (E) and (F) specimens were reinforced by using padauk. Specimens in groups (A), (C), and (E) contained three planks; however, those in series (B), (D), and (F) contained four planks [88].

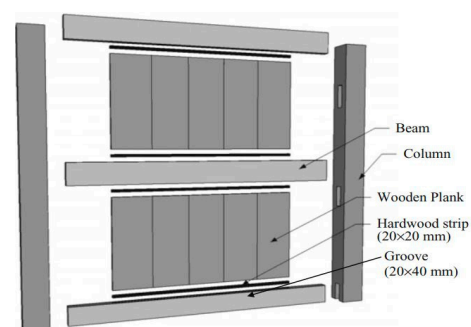


Figure 11. The structural system of Taiwanese wooden shear walls and the proposed reinforcement method [88].

The results revealed that inserting teak and padauk strips into the grooves between planks and beams increase the strength of a wooden shear wall 1.6 and 2.1 times, compared to that value of an unreinforced frame. Moreover, when teak and padauk strips were used, dissipated energy increased 1.57 and 2.15 times, compared to unreinforced specimens [88].

Another type of strengthening by wooden components was used by Tu et al. [89]. Two different methods were used for reinforcing the timber frames, and specimens were named K1 (without reinforcement), K2 (with horizontal reinforcement), K3 (with vertical reinforcement), and K4 (vertical reinforcement + two horizontal reinforcement), as shown in Figure 12. All specimens were loaded in five single cycles according to the amplitude

displacement of 1.25%, 2.5%, 5%, 7.5%, and 10% of the maximum displacement in the early stage and then loaded in three cycles in the later stage, until the horizontal displacement reached 375 mm, or severe damage occurred [89].

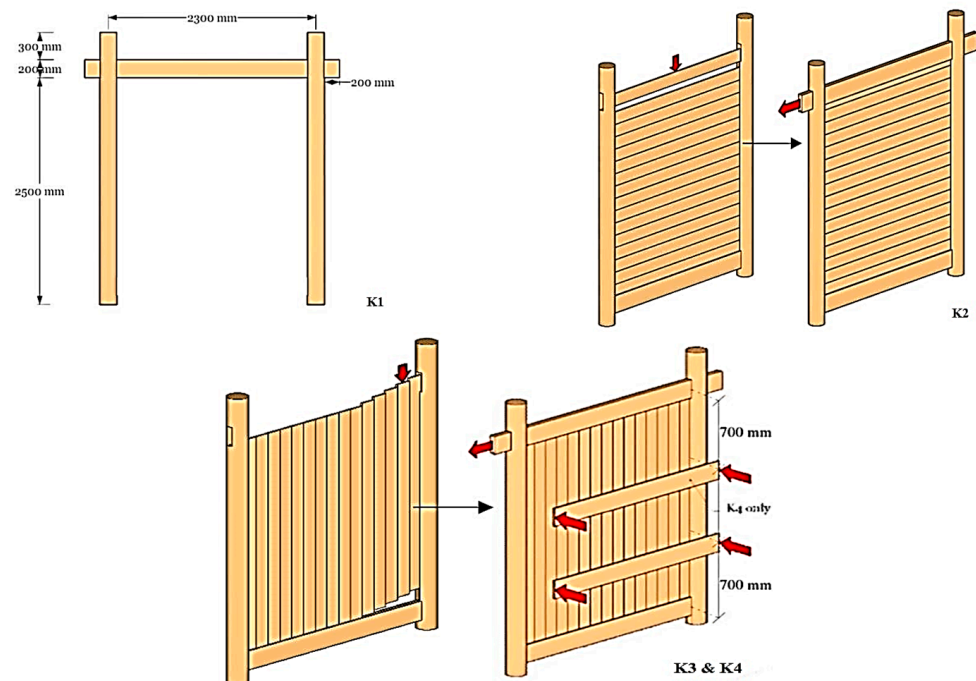


Figure 12. Specimens' configuration in Tu et al. study [89].

The results reveal that K2 showed a lower performance compared to K3 and K4. However, the panels in K2 presented more significant out-of-plane behavior than the others. Furthermore, the bearing capacity of K2, K3, and K4 in comparison with K1 increased 3.33, 6.9, and 4.69 times, respectively, which shows that using extra panels may not improve the carrying capacity effectively. In addition, the use of reinforcement increased the dissipated energy in a manner that K4 showed the most dissipated energy; moreover, the dissipated energy of K2 is more than K3, which shows that the use of horizontal reinforcement contributed to energy dissipation more than vertical one [89].

Three 1:2 scaled Chinese traditional mortise–tenon-jointed beam–column frames (one as bare frame (Frame 1), one with partial panel infill accommodating a wide window opening (Frame 2), and the third with full panel infill (Frame 3)) were tested by Crayssac et al. [90]. The configuration and dimension of the frames are shown in Figure 13. Cyclic loadings were applied by use of a hydraulic actuator with a displacement range of ± 250 mm and a capacity of 650 kN. Based on material properties as per Luo et al. [91], the concentrated vertical loads were taken at 120 kN and represented 5% of the estimated compressive strength of the columns. The results showed that the maximum load was 74.5 kN (−72.27 kN), 100 kN (−106 kN), and 97.4 kN (−109 kN) for Frames 1, 2, and 3, respectively. All three frames also exhibited a high ductility ratio (Frame 1 (the bare frame) seems to be the most ductile). This may be caused by the rather rigid and brittle behavior of the infill panels. Furthermore, the cumulative dissipated energy of Frames 2 and 3 are 1.54 and 1.15 times compared to that value of Frame 1 (after 40 cycles), respectively.

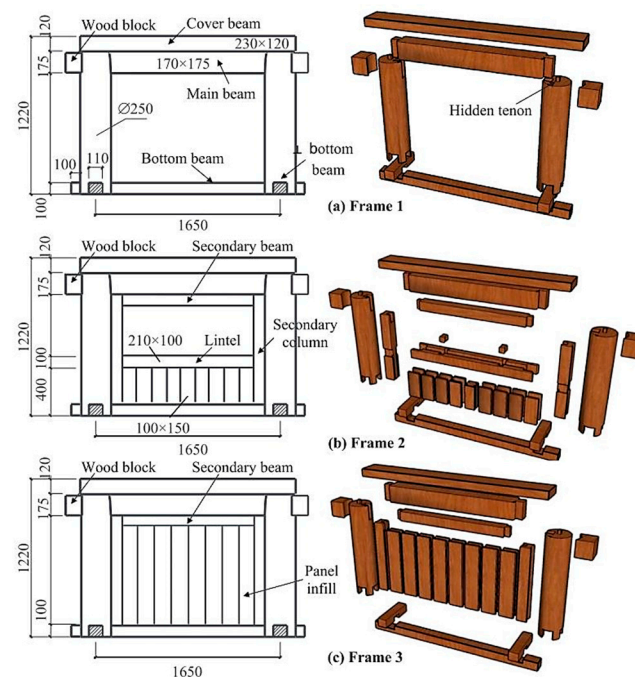


Figure 13. Layout of frames tested in [90].

Comprehensive studies about the use of traditional timber shear walls in Taiwan have been conducted by Chang et al. [92,93]. The seismic analysis method considering wall participation for ancient timber frame buildings has also been proposed to address the lack of ignoring the presence of the wall in ancient structures [94]. Moreover, the influence of wood infill walls on the seismic performance of Chinese traditional timber structures by shaking table tests was assessed in [95].

Timber-to-timber interventions on wooden floors can be considered as another method of strengthening using wooden materials, and several studies have been performed in this context [96–100].

5.2. Steel Components

Steel components in different forms are widely used for strengthening timber frame structures [101–104]. Using steel plates will increase the stiffness and dissipated energy of the frame wall during a cyclic test. Reusing the steel components in the post-earthquake strengthening of buildings is one of the advantages of this strengthening strategy compared to other methods such as composite materials. Some of the steel elements utilized for the strengthening of heritage buildings are presented in this section.

Tests were performed on timber frame walls by retrofitting the connections using steel plates, as shown in Figure 14a [105]. Based on the test results, this retrofitting technique increased 2.24 times the load-bearing capacity of the wall and improved the nonlinear behavior of it. Based on the test conducted by Poletti and Vasconcelos [106], the failure of the wall occurs due to the damage of the bottom connection, which was at the corner of the walls. The failure occurred due to the presence of the steel plate, which did not allow the column to rise. Based on the study done by Poletti et al. [107], it is concluded that using steel plates with holes increases the maximum in-plane load-bearing capacity 1.4 and 1.21 times, compared to the values of the unreinforced walls when initial compression loads of 25 kN and 50 kN are applied, respectively.

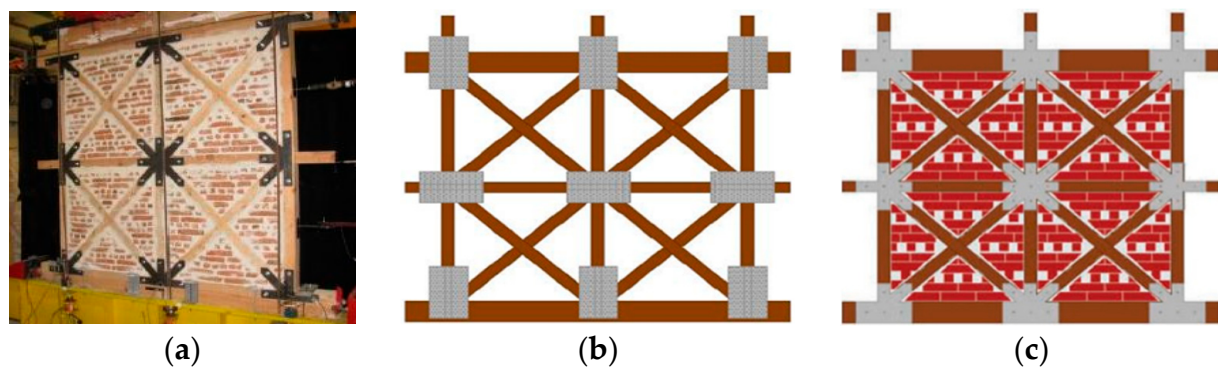


Figure 14. Strengthened timber frame wall with (a) steel plates [105], (b) steel plate without masonry infill, and (c) with masonry infill [108].

A study was done on timber frame walls with and without masonry infill [108]. For the wall without the infill, commercial rectangular steel plates are utilized to strengthen the timber connections, as shown in Figure 14b, and the walls with infill are strengthened by installing the custom steel plates on two sides of the timber connections in such a way that the plates do not confine infill, as shown in Figure 14c. The load-bearing capacity of the wall with masonry infill and without infill increased 1.86 and 3.1 times compared to the values for unreinforced specimens, respectively.

Steel flat bar is a steel component that is utilized for retrofitting the timber frame wall connections. A study was done to investigate the effect of this technique in such a way that two models were developed [106]. The first model was retrofitted using the steel plate in all connections. However, the second model was retrofitted using steel plates for the bottom connections, and other connections were retrofitted using the steel flat bars. Results show that the load-bearing capacity of the first model and second model increased 2.31 and 2.09 times.

An investigation on the retrofitting of the post and beam connections conducted by Zhou and Yan [109], as shown in Figure 15a, reveals that using Q235 steel bands with tensile and compressive strength of 200 MPa does not increase the initial in-plane stiffness of the wall but does increase the load-bearing capacity of the wall up to 2 times.

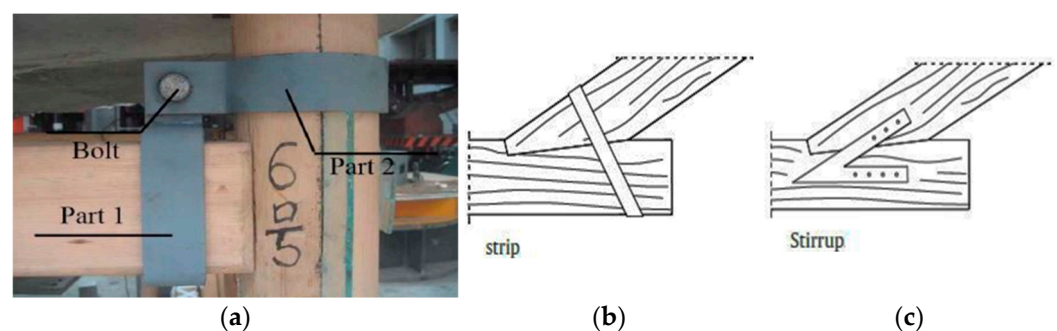


Figure 15. Strengthening timber connections using (a) steel plates [109], (b) strip, and (c) stirrup [110].

Using steel strips and stirrups are also other techniques for retrofitting timber connections, as illustrated in Figure 15b,c, and more detail about these techniques can be seen in [110]. Moreover, steel nails are also utilized to strengthen halved dovetail carpentry timber joints [111].

A few studies focus on the application of stainless steel as a reinforcement of heritage timber buildings. High durability, long-term effectiveness, and compatibility with timber, with minor safety precaution measures are the advantages of the stainless steel components [112]. In contrast, the high cost of the alloy and limited availability are two main

limitations of this material as a strengthening technique [113]. Stainless steel components can be utilized in the form of fasteners, rods, and plates [113].

5.3. Composite Materials

Fiber-reinforced plastic or fiber-reinforced polymer (FRP) is a composite material made of a polymer matrix reinforced with fibers. The main advantages of FRP are their high stiffness and tensile strength, low weight, relatively rapid installation, and a variety of available sizes and shapes. However, bonding to substrates may be critical and affected by durability problems. Utilizing composite materials for retrofitting the structures has gained much attention recently [114]. Strengthening timber frame walls using glass fiber-reinforced polymer (GFRP) bars and strips was carried out by Cruz [115]. GFRPs have high densities and medium weights and are relatively inexpensive. Two groups of models were prepared; first group, the specimens were retrofitted using GFRP bars. Figure 16a shows the second group retrofitted with GFRP strips after retrofitting with the bars. The increasing rate of the load-bearing capacity and ductility of the two models were close to each other. It can be concluded that using GFRP strips and GFRP bars does not significantly increase the load-bearing capacity.



Figure 16. (a) Retrofitted timber frame walls with GFRP strips [115], and (b) a post and beam connection strengthened by CFRP strips [109].

Another approach using composite materials for the retrofitting of post and beam connections was investigated by Zhou and Yan [109]. Carbon fiber-reinforced plastic (CFRP) sheets with a thickness of 0.11 mm and with high tensile strength were utilized to completely cover a timber post and beam connection, as illustrated in Figure 16b. CFRPs are lightweight, have low densities, and are thermosetting resins such as epoxy, polyester, or vinyl ester. It was investigated that the ultimate load-bearing capacity of the connection was increased 2.7 times. The influence of the GFRP wraps and the CFRP strips for strengthening the timber frame walls is evaluated in an experimental program. In the first phase, the specimens were strengthened using the bamboo bracing or the steel gusset plates. In the second phase, FRP components were utilized. The beneficial effects of the FRP retrofitting were highlighted [116].

Extensive research studies have been conducted for retrofitting the timber beam elements with the FRP layers by improving their flexural behavior [114,117–121]. The experimental program for the four-point bending tests shows a 46% increase in load-carrying capacity compared with unreinforced beams [122]. Moreover, an analytical investigation was also carried out for the timber beams strengthened with composite materials based on the test results [123]. U-shaped steel and CFRP components were also utilized for the strengthening of timber beams, and results of the three-point bending tests show a dramatic increase of load-bearing capacity and a combination of CFRP and steel U-shaped reinforcement provided a promising lightweight structural element against bending [124].

5.4. Damper

Using damper elements for strengthening the timber structures subjected to earthquakes is an expensive method compared to other strategies, and skilled workers are needed for the installation. Experimental tests, as shown in Figure 17a, were performed by Branco et al. [125] to investigate the effect of this retrofitting strategy. Test results reveal that this method increases the dissipated energy and load-bearing capacity up to 1.3 times that of an unreinforced wall. In contrast, the force-displacement diagram from the tests by Goncalves et al. [55] shows the asymmetric in-plane behavior of the retrofitted wall introduced by the damper that can be considered one of the disadvantages of this strategy.

Friction dampers were also utilized to reinforce straight tenon joints to improve seismic behavior, as illustrated in Figure 17b [126,127]. Three models were developed, and failure modes and the cyclic behaviors of the joint and the dampers were investigated in the performed quasistatic test. Parametric studies on the numerical models and the test results reveal that the main failure modes of the reinforced joints include the compressing dents on the column, the tenon extraction, and the surface of the friction plate being smoothed [127]. Moreover, 0.4 is considered as the optimal friction coefficient in terms of the reinforced straight tenon joints' cyclic behavior and energy dissipation [126].

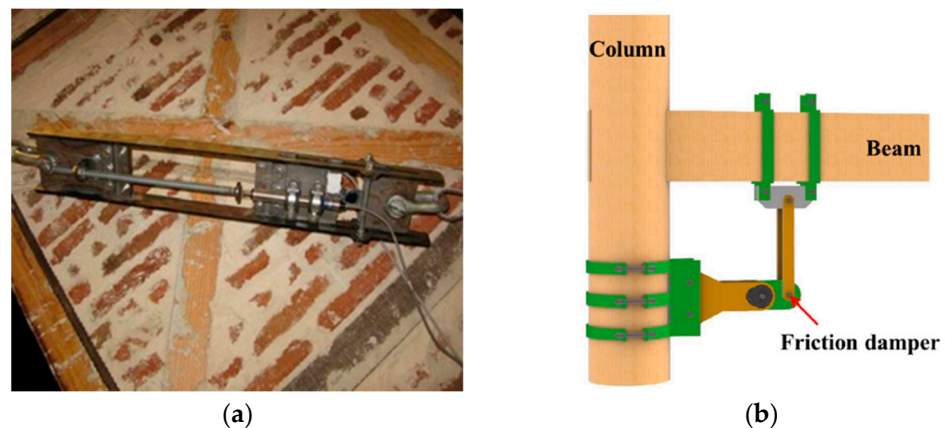


Figure 17. Retrofitting a timber frame wall using (a) super-elastic damper [125] or (b) friction damper [127].

5.5. Bolt and Screw

Bolt and screw are also considered one of the common strategies for retrofitting timber joints [128–131]. However, based on the tests done by Vasconcelos [132], using bolt and screw did not increase the in-plane load-bearing capacity (just 1.1 times), and dissipated energy of timber frame walls did not increase too. However, the out-of-plane behavior of the wall was improved. The slight increase of in-plane load-bearing capacity using bolt and screws has been confirmed by performing tests [133] on timber frame walls with simple diagonal connections and half-lap connections for main members. It was concluded that the in-plane load-bearing capacity was increased 1.14 times.

Using internal bolts (steel rods) for strengthening the timber frame walls connections is another technique that has been investigated by Branco et al. [110]. The effect of the angle of the rods on the in-plane load-bearing capacity has been investigated, and it was concluded that by increasing the angle from 30 to 60 degrees, the load-bearing capacity, stiffness, and dissipated energy have decreased.

5.6. Shape Memory Alloys (SMA)

Several studies have been performed to strengthen post and beam connections using SMA wires to tie the beam and column [134]. Xie et al. [135,136] performed tests on timber connections of traditional Chinese timber frame buildings. Firstly, three models (GJ1, GJ2, GJ3) were developed without strengthening, and loading was applied to define the ultimate

displacement. Afterward, the damaged specimens were disassembled, strengthened with 8, 8, and 16 SMA wires, and named GJ4, GJ5, and GJ6, respectively. Figure 18a shows how the specimens were strengthened by SMA. After applying vertical load, it was concluded that using 8 SMA wires is not sufficient to eliminate the initial damage effects. Using SMA also limits the pulling out of tenons from the mortise. Moreover, the load-bearing capacity of GJ4, GJ5, and GJ6 models was increased 1.1, 1.4, and 2.1 times corresponding to GJ1, GJ2, and GJ3, respectively.

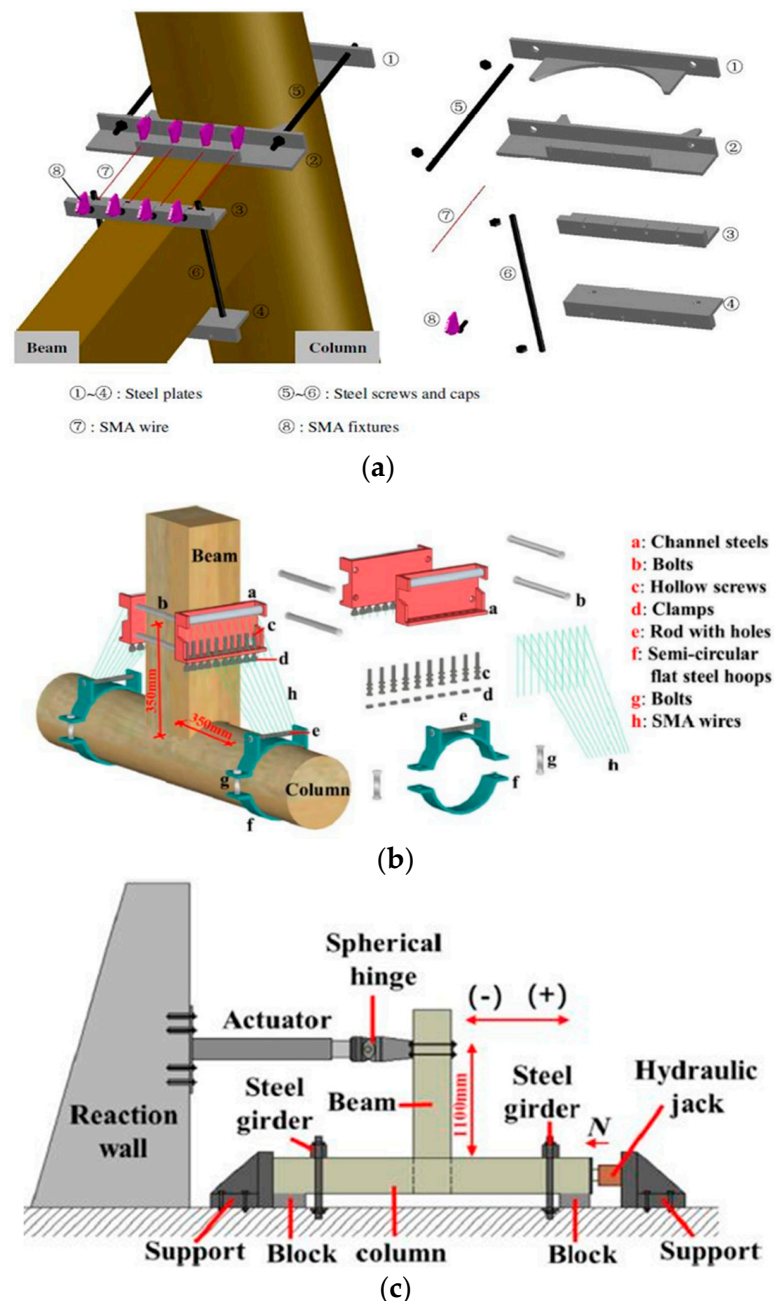


Figure 18. (a) Using SMA as a strengthener [136]. (b) Retrofitting both sides of connections by SMA. (c) Schematic view of the test setup [137].

Another study done by Xie et al. [136] developed a model without strengthening, and the vertical load was applied on the beam element. It was investigated that the load-bearing capacity of the connection without SMA was more than the model with strengthening for the rotation less than 0.875 rad. However, for rotation of more than 0.875 rad, the

strengthened model had more load-bearing capacity. Moreover, it was investigated that the principal damage mode was the pulling out of the tenon from the mortise and the timber elements were intact.

Four specimens were developed by Xue et al. [137]. T-M1 was without strengthening, but models T-M2, T-M3, and T-M4 were equipped with 12, 16, and 20 SMA wires, respectively, with a diameter of 1.5 mm. Due to the local defects in timber elements of the T-M2, its bending capacity was less than model T-M1, while the bending capacities of T-M3 and T-M4 were 1.2 and 1.5 times as large as the load-bearing capacity of the T-M1, respectively. Figure 18b shows how the specimens were retrofitted; Figure 18c demonstrates the experimental test setup.

In order to investigate the effect of pre-strain on the load-bearing behavior of the mortise–tenon connections, experimental tests were performed by Xue et al. [138]. It was concluded that 3% of pre-strain decreases 53% and 63% of tenon pulled out length in positive and negative directions.

Furthermore, SMA bars and tubes are utilized as dowels to provide the self-centering effects for the dowel-type connection systems [139]. Double-shear connections with SMA and mild steel dowels were tested under dynamic loadings at different displacement levels. The results showed that SMA dowel-type connections have good self-centering behaviors and can effectively mitigate residual deformation compared with steel dowel-type connections after excessive deformation, although the steel dowel-type connections present higher strength [139].

6. Conclusions

For the sake of reviewing the research studies about the seismic vulnerability assessment and strengthening of heritage timber buildings, three building types were categorized in this study. Timber frame buildings are one of the well-known heritage timber structural systems, consisting of timber frame elements in different configurations with masonry infills. Timber log houses that are usually in cold European countries, and post and beam structures often exist in eastern Asian countries. The systematic review shows the growth of the research studies about the seismic vulnerability assessment and strengthening of heritage timber buildings. Moreover, it is observed that the topics are shifting recently from analyzing timber connections toward performing experimental studies and investigating the masonry materials that were often utilized in the construction of heritage timber buildings.

For numerical modeling of the three aforementioned groups of buildings, various simplified and detailed strategies were reviewed. Due to the variety of the configurations of timber elements in the timber frame buildings and the different connection types that exist in post and beam structures, experimental tests are required for each typology to validate the numerical models. Tests are required to be performed in order to investigate the out-of-plane behavior of timber frame and log house shear walls. Moreover, corner carpentry joints play a crucial role in the numerical modeling of log houses. Seismic analyses, including POA and NTHA, were used to evaluate the vulnerability of the full-scale heritage timber buildings. Soil–structure interaction effects should be evaluated on the seismic behavior of heritage timber buildings with specific structural systems. Furthermore, specific empirical equations should be defined for the prediction of the natural period of each structural system.

Wooden and steel components in various shapes, except the stainless-steel material, are widely used for the strengthening of heritage timber buildings due to their availability and lower costs compared to the SMA or dampers. Extensive research studies have also been performed to investigate the influence of using composite material for the retrofitting of timber elements. The results show that composite material can improve the load-bearing behavior of timber connections and timber beams. Moreover, composite materials are also considered as a lightweight strengthening solution compared to the steel profiles. Although different studies have been conducted on the dampers and SMA as a strengthening solution

of the timber components, more studies are required to investigate the efficiency of these techniques compared to the traditional strengthening techniques. Much attention is needed to study the strengthened full-scale buildings instead of just focusing on the structural components to evaluate each strengthening method's efficiency in real building scale.

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