The Role of Timber Roof Structures in the Seismic Response of Traditional Buildings

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SUMMARY:
Timber roof structures covering traditional masonry buildings strongly influence the seismic response of the whole building system. In the seismic strengthening of these structures, their replacement or their reinforcement with massive interventions has been performed in the past, at times with adverse results. In Italy, the national design code now indicates that less invasive strengthening techniques appear as a better option and should be applied. In this perspective, a methodology for assessing the seismic vulnerability associated to timber roof structures has been developed by the authors. This necessarily includes the evaluation of previous interventions when present, as part of the assessment of the present state of the structure. This work focuses particularly on the refinement and calibration of this point in the assessment procedure. To this purpose, a set of structures has been examined and studied by numerical modeling, providing some guidance in the exam of similar cases.

Keywords: timber roof structures, seismic vulnerability, traditional buildings

1. INTRODUCTION

The timber roof structures that are present in traditional masonry buildings in many seismic regions have a strong influence on the seismic response of the building. Until recently, in Italy, for the seismic strengthening of these buildings, massive interventions that would increase significantly the stiffness of the roof structure were performed. The intent was to create through the roof a strong link enhancing connection and collaboration among walls. Elements of etherogeneous materials, like reinforced concrete, were added. In many cases the timber structure supporting the roof would be replaced completely. The new roof structures consisted in most of the cases of reinforced concrete prefabricated elements, and in some cases of elements cast on site. Because seismic strengthening of a building had become compulsory wherever extraordinary maintenance would be performed for other reasons, the number of reinforced roofs is not negligible.

In the earthquakes that have occurred since the last years of the 20th century, several cases of extended damage and collapse have been observed in buildings where the roof had undergone massive interventions. In the L'Aquila earthquake of 2009, for instance, many cases of progressive collapse of the roof and walls occurred. However, well organized and connected roof trusses, possibly strengthened with light interventions, did not disassemble or fall, and in better cases succeeded in constituting the desired link between opposite walls (Parisi et al, 2011a).

The current version of the national design code (NTC, 2008) warns on the risks related to excessive increase of mechanical properties that may derive from strong interventions and states that less invasive strengthening techniques should be adopted, specifying that the original timber roofs are usually more compatible in terms of mass and stiffness with the supporting masonry walls: it also indicates that interventions should preserve the original conceptual design when this is statically sound.

In order to provide a tool that could guide in evaluating the characteristics that affect the seismic response of roof structures, which are usually conceived and considered only in their capability of supporting vertical loads, and possibly point out if and where strengthening interventions were necessary, a methodology for assessing their seismic vulnerability has been developed by the authors (Parisi et al., 2008a, 2008b, 2009, 2011b). The criterion followed is typical of vulnerability studies and consists in examining the structure according to a codified visual inspection procedure. Data on geometry, details, and the health state of its members are collected and a series of vulnerability indicators are evaluated from the general picture resulting from this examination. Each indicator concerns a specific issue or feature that affects the capability of the structure to respond to seismic action. As a result, indications are obtained on the global level of response of the structure; possible specific criticalities are highlighted.

In the development and subsequent calibration of the indicators, particular effort was initially devoted to the highly influential issue of the typology of the structure. The assessment of the vulnerability related to the condition of carpentry joints was also developed, based on an extended experimental research program carried out previously (Parisi and Piazza, 2000, 2002, 2008c). The results could supply indications related to the most frequent joint typologies and could serve as guideline for other situations that could be met. The present work focuses particularly on the refinement and calibration of another important issue: the general state of the structure as found during inspection, with particular reference to the evaluation of the effects of previously executed strengthening interventions.

The indications developed in this work were derived from inspecting and applying the procedure to a series of cases, some of which were then further investigated with numerical models. This approach has given encouraging results. The analysis of more cases is in progress.

2. SEISMIC VULNERABILITY OF TIMBER ROOFS: A SUMMARY

The procedures for assessing the seismic vulnerability of structures and buildings are aimed at pointing out characteristics and critical features that may induce an unfavorable response during an earthquake. The vulnerability assessment procedure that has been defined and developed for the case of timber roof structures consists of two parts,

- Initially, a visual inspection of the structure is performed according to a standardized sequence and following given guidelines. In this stage, data regarding the layout of the structure, the geometry of its elements, joints and construction details, the materials, and the state of conservation are collected. This operation is currently carried out filling a paper form. Its compilation is guided by multiple-choice answers and images where applicable. When necessary, each item to be examined is developed in the form in a tree-like structure, with branches detailing different aspects to be considered. The information obtained is particularly suitable for evidencing the features that affect the seismic response, but it also supplies a detailed description of the general conditions of the structure;

- In a second step, the collected information is used in the evaluation of a series of specific vulnerability indicators, which consider different structural features and conditions of the structure that may be associated to its seismic vulnerability (Parisi et al., 2010). A rating for each examined indicator is obtained from this process, by assigning it to one of four vulnerability classes, from A to D, where A corresponds to the lowest vulnerability, equivalent to a satisfactory condition, and D to a highly vulnerable situation, B and C being the intermediate values.

The various structural conditions of interest may be grouped into the following general indicators, each gathering several points to be considered,

1. The conceptual design: roof structures, usually conceived for carrying vertical loads, are more or less suited for seismic response depending on the structural solution that has been

adopted; this indicator examines the structural typology.

2. The carpentry joints: vulnerability may be associated to the type, details, and conditions of carpentry joints; these are examined in their capability to maintain the connection during cyclic conditions, and in their expected post-elastic behavior, with the aim at sorting out possible brittle failure modes.
3. The external restraint system: this indicator considers the conditions of the connection of the timber structure to the walls, their effectiveness toward horizontal actions in preventing separation and loss of support, which often results in a progressive failure of the whole building system;
4. The current state of the structure: this indicator considers the maintenance and conservation state, the presence and quality of strengthening interventions, and any other condition specifically related to the state of the structure.

Criteria for classifying them have been expressed and synthesized in a first series of reference tables describing the rating for each indicator according to the conditions observed. While classification criteria for some indicators have been developed at a satisfactory level of detail, as for the conceptual design case (Chesi et al. 2008, Parisi et al, 2012a), for other indicators the criteria are currently basic and their development is still in progress. This is the case of the current state of the structure. Contributions of very different nature are scored under this point. Among these is the effect of strengthening interventions, a particularly critical aspect to evaluate, for the variety of situations that may be met and for the very different effects that may result.

In the following, this point is discussed in detail. Indications obtained from case studies for the assessment of the corresponding vulnerability indicator are presented.

3. RESULTS OF STRENGTHENING INTERVENTIONS

One aspect that needs be considered when assessing vulnerability is the present state of the structure, which may be described considering factors of different origin, like its maintenance state, the presence and quality of strengthening interventions, and any other observation specifically related to the current conditions. Some of the main terms to be checked have been exemplified in Table 1.

Table 1. Vulnerability from state of the structure

Item	*check*
Maintenance:	state of roof cover
	date of last general maintenance
Decay of timber:	reduction of element sections
	decay of joints
Previous interventions:	modification of original concept
	modification of elements
	increased loads

Not all the terms that contribute to the state of the structure have the same impact of vulnerability. Poor maintenance has been recognized to increase the vulnerability of buildings and structures in general and is expected to play an important role particularly in the case of timber, which may decay easily in adverse conditions. For this reason, regular versus infrequent or no maintenance is an indicator to be checked. An important check to be performed is the state of the roof cover system, because rainwater penetrating from cracks and gaps will rapidly deteriorate the underlying structure, even if such effect is not yet noticeable, reducing its capacity with effects on seismic behavior as well. Such critical situations, however, may be easily remediated.

An aspect that significantly affects vulnerability, either reducing or, at times, increasing it, is related to strengthening interventions that may have been carried out in a remote or in a recent past. Because of the variety of situations and of the high impact that these changes may have on the structure, interventions may be extremely difficult to evaluate.

Modifications of the original layout, carried out in order to eliminate initial conceptual errors that are not rare in structures usually built on heuristic bases, are frequently seen. Most interventions were performed for improving the capability of developing equilibrium or increasing capacity making reference to vertical loads, for instance eliminating unrestrained thrusts or upgrading joints. Even if not directly intended to improve the response to seismic actions, and if correctly executed, these interventions are necessarily positive on seismic vulnerability as well.

At times, however, modifications are found that may increase vulnerability. Adverse effects may be the consequence of interventions for improving the behavior with respect to common vertical loads, but in some cases they derive from seismic strengthening operations as well. Modifications that actually reduce the stiffness in one direction inducing excessive deformation and possibility of pounding with other structures or elements, or vice-versa produce locally excessive stiffness are found.

The increase in mass and stiffness that characterize strengthening interventions performed following the criteria adopted in the last part of the 20th century have been associated to some cases of serious damage and also collapse of roofs and buildings. These interventions that are of high impact and practically discontinued in present practice, were really intended to improve the seismic response in accordance with design code guidelines. Positive effects may exist, in parallel with the possibility of excessive performance of the upgraded structure with respect to the rest of the building, in particular of the roof supporting walls. The final balance depends strongly on the structural characteristics, and on the sensibility and capability of the professionals to calibrate on them the modality and parameters of the intervention. These interventions are, therefore, quite difficult to evaluate in terms of vulnerability assessment. In the following, observations and analysis results from different case studies are summarized, as a contribution to clarify this issue.

3.1 Case studies

The vulnerability assessment procedure has been originally based on the detailed observation of a series of cases collected from common as well as heritage buildings, from seismic damage cases, from numerical modeling and analysis, and from indications contributed from expert knowledge. In order to test and calibrate the procedure, to increase the typologies considered, and to improve the criteria for classification, a critical application of the procedure to a series of new cases has been performed and is still in progress.

Within this activity, the cases briefly discussed here permit some remarks on the issue of strengthening interventions, focusing on some aspects among the vast variety of situations. Although results may be limited in scope and caution is needed in extending them in general, they may provide some guidance in the exam of similar cases.

3.1.1 High impact seismic strengthening

The church of San Biagio Amiterno at L'Aquila is an interesting case of heavy seismic strengthening, which could be observed also in other heritage buildings in the area. The church, which suffered severe damage during the earthquake of 2009, including the collapse of the tympanum, as in fig. 1, is located in the historical town center and dates back to the first part of the 13th century. The timber roof structure that was present at the time of the earthquake could be dated to the beginning of the 18th century, but had undergone at different times in its history restoration interventions as well as seismic strengthening.

The roof considered covers the main nave with a series of 12 king post trusses, with a span of 11.8 m and at an interval of 2.3 m approximately. From the last truss three rafters, one orthogonal to the truss and two in diagonal directions, form pents over the apse area. Lateral naves have lower height and are covered by lean-to roofs independent of the one being considered here. The quality of fabrication of the truss members is good, with well proportioned cross sections and good detailing, but carpentry joints at inspection time appeared without metal connectors. The rafter-to-chord node, in particular, was difficult to inspect, being partially enclosed in the masonry, probably by interventions subsequent to the original construction. These details are generally considered to increase the vulnerability, even if no particular negative consequence was observed during the assessment of seismic damage. An interesting and very effective detail concerns the truss chords, which are restrained at their ends with elements protruding on the outer face of the walls and blocked with a stud. This detail, present in many heritage buildings of the area, has played a positive role in the response on the roofs and of the buildings in general, exerting a good linking effect.

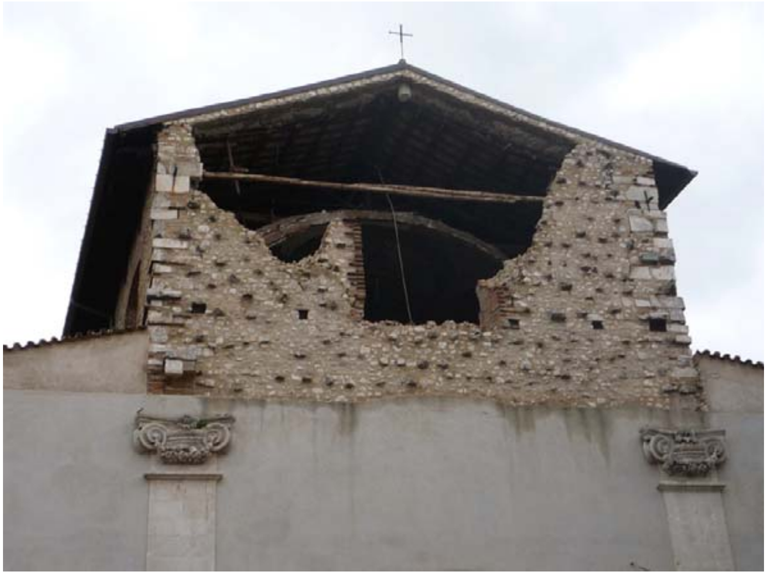

Figure 1. Façade of the church of S.Biagio Amiterno, L'Aquila, with the tympanum collapsed after the earthquake of 2009

For the church of San Biagio, as for many others in town, slabs composed of hollow brick elements and concrete, bordered with a concrete ring, were cast over the roof structure at the beginning of the eighties of the 20^{th} century. The objective of this operation was to create a strong link connecting the opposite walls in contact with the roof and develop a box behavior. This would protect particularly the upper part of the church that appeared more vulnerable with respect to the lower building, restrained transversally by the surrounding buildings forming an aggregated block. Figure 2 shows details of the section of the slab laid over the original roof structure.

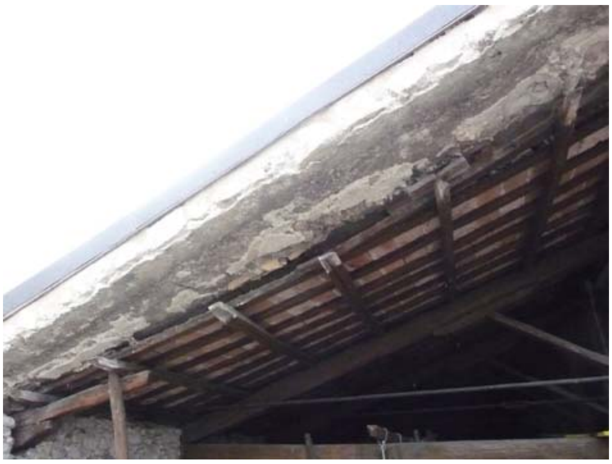

Figure 2. The roof structure loaded with a brick slab bordered with a concrete ring beam.

These massive and stiff strengthening interventions carried out in the L'Aquila region raised much debate on whether, and possibly to what extent, they triggered damage rather than avoiding it, and consequently whether they should be removed where still standing during reconstruction. For the church of San Biagio in particular, the data available on the roof history, the possibility of inspection of the church after the earthquake, and again at the beginning of reconstruction gave occasion for investigating the relationship between the strengthening of the roof and the collapse of the tympanum. An extended discussion is reported in (Parisi et al., 2012).

A finite element model of the structure in different mass conditions has been developed and a series of modal and seismic analyses have been performed. Given the type of failure, the most interesting quantity to compare was the maximum longitudinal displacement in correspondence with the ridge beam. Synthetically, values reached for the original structure were approximately 4.5 cm and 3.7 cm for the code spectrum at 975 and 475 years of return period respectively, and 3 cm for a spectrum based on the L'Aquila sequence. This included records of the main shock and of pre- and post-event shocks, necessarily scaled. Corresponding values for the heavier structure were 7.5, 5, and 3.8 cm, respectively. In the case of overload from the intervention, the longitudinal displacement increased of about 26 percent. The levels of stress in the elements were checked and found in the elastic domain for all the cases.

The displacement value at the ridge beam, as noted above, grows appreciably from the original structure to that with increased mass derived from the intervention. Yet, in the two cases the displacements are in the same order of magnitude. It has to be pointed out that the increase of stiffness, which would likely reduce the deformability of the system also in the longitudinal direction, conservatively has not been taken into account in the above figures. Therefore, for the case of San Biagio it seems not possible to attribute the collapse of the tympanum directly to pounding due to the augmented mass of the intervention performed, as originally proposed by a first inspection. Very likely a lack of connection between the roof and the top of the tympanum left the latter widely unrestrained at its borders and was not remediated during the intervention, considering as well the presence of a large window at its base and some irregularities in the masonry texture on its left side visible in pictures before the earthquake. The lack of connection very likely existed also in the primitive conditions. A more effective intervention should have limited the displacement of the roof, possibly with light systems as in a following case, and simultaneously developed a connection for the tympanum top to increase restraint at its border.

In terms of vulnerability evaluation, this case indicates once more the need to carefully examine the situation with an inquisitive eye toward all possible effects related to seismic action.

3.1.2 *Strengthening for general capability*

A very different case is that of the church of Santi Pietro e Paolo at Mettone, near Milano. In this case, at the beginning of this century, interventions were carried out on the timber roof structure, in order to improve its general stability, with no special reference to seismic response. The church is, indeed, located in an area characterized by very low seismicity. Yet, the interventions performed are of interest in general. The roof structure, dating back approximately to year 1570, consisted of a series of 6 trusses with a span of approximately 8 m, spaced 4.6 m. Diagonal bracing elements were present in the longitudinal direction, that is in the direction normal to the truss planes. Trusses had a scissor type of scheme with a half-depth joint between rafters, a very unusual layout in the country (fig. 3).

In order to improve the state of the structure, some refurbishing operations were performed on the timber elements, remediating some localized decay problem. The main intervention, however, regarded directly the trusses. The original layout was modified, cutting the top part of the rafters and introducing a post and struts, that is, transforming the structural scheme into a king post type (fig. 4). Additionally, the original diagonals were eliminated, in order to solve, with due cause, a problem of contact, as they were pointing into the vault underneath. At their place, shorter struts between the post and the ridge beam were applied.

Without discussing the validity of this intervention from a heritage preservation point of view, which is not pertinent to this work, some remarks need be made on the effect obtained on seismic vulnerability. A finite element model was set up for the structure in the two conditions, representing as well the semirigidity of the carpentry joints according to the previously cited research work. Modal analyses and seismic response spectrum analyses considering the seismicity of different regions in the national territory were performed.

Figure 3. The original roof of the church of Santi Pietro e Paolo, Mettone.
The joint at the rafters crossing and the diagonal bracing are visible.

The main result of interest here is that, given the size of elements and the general structural scheme the roof structure has a fairly low level of vulnerability, confirming the synthetic analysis by the vulnerability procedure, and is not likely to incur problems also in consideration of the low seismicity of the area. Yet, as effect of the intervention, the insertion of short struts that influence only the upper part of the trusses and the corresponding elimination of a more global bracing system has increased significantly the deformability in the longitudinal direction. In general, this deformability is particularly dangerous for the possible pounding effects on walls, as discussed in the case previously presented. The strengthening intervention, that was surely intended and meaningful for normal working conditions, has actually produced an increase of seismic vulnerability. This effect could have been avoided or limited studying a more suitable bracing system.

Figure 4. The truss after the intervention has acquired a king post scheme.

3.1.3 *Low impact interventions*

A positive effect of a well-organized roof system where low mass interventions had been carried out has been observed during recognition of seismic damage in L’Aquila after the 2009 earthquake. The roof covered an important historical building in the town center, the Carli-Benedetti palace, that suffered severe damage in various parts, like many similar buildings in town.

The strengthening intervention that had been recently performed on the roof may be seen in fig. 5. This inside view was possible from the opening caused by the unfortunate collapse of a vault. The roof had undergone intervention with light elements to improve its interior and exterior connectivity and remove thrusts. In order to appreciate the positive effect of this work, it must be considered that the earthquake had caused the opening of a significant crack on both sides of the corner corresponding to the picture. This crack pattern typically evolves into the detachment of the angle and of its subsequent possible collapse as a rigid block. In this case, the crack was well open up to the mid-height of the walls, but became narrower and was barely visible at the top, near the roof, indicating that a restraining action had occurred in this area. The roof action avoided more dramatic damage and probably collapse of a significant part of the building. The building is currently under repair.

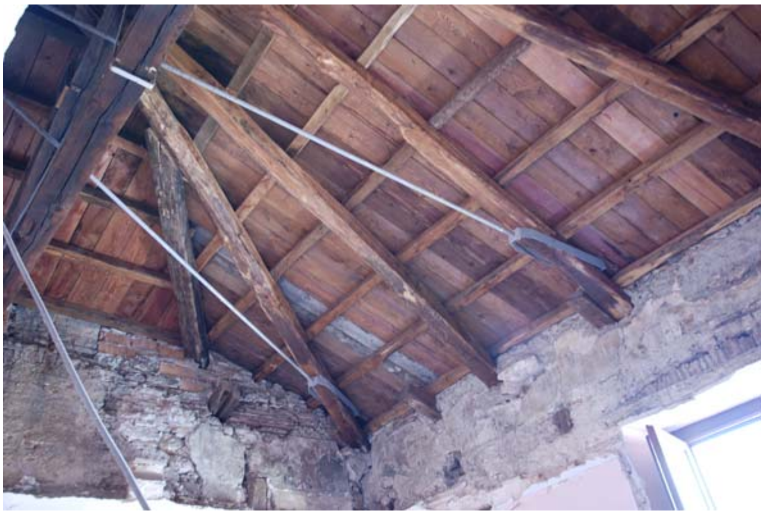

Fig. 5. Low-mass intervention on a timber roof in L'Aquila.

The second case is still under analysis, but it seems interesting because the intervention recognizes a possible problem in case of horizontal longitudinal motion of the truss top and takes care of it. The church of St Michele, in Vimercate, near Milano presents a roof structure composed of a series of king post trusses, which were irregularly spaced because one truss was missing at the intended spacing, an apparently strange situation which, on the contrary, was found also in other cases (Parisi et al, 2011b).

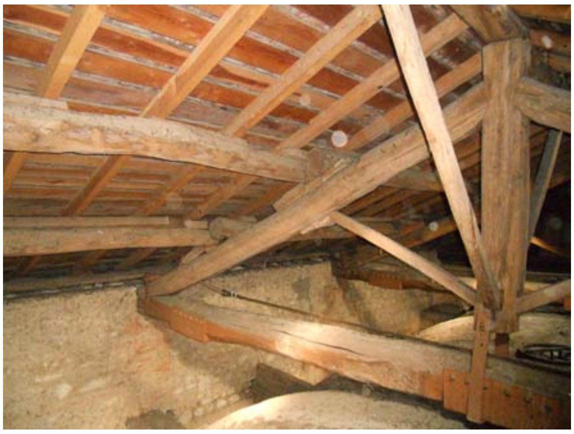

Fig. 6. Trusses of the church of St. Michael, Vimercate; the bracing element is visible.

The structure has been recently subjected to an extraordinary maintenance intervention intended to eliminate some local decay problems in timber elements and in the state of some metal connectors. Structurally, the main interventions consisted in adding a truss at the proper location and reconstituting regularity in the layout. Also, the roof system included here as well diagonal elements in the longitudinal direction (fig. 6). From the last truss near the tympanum area the bracing pointed directly onto the façade wall, inducing an extremely high risk of thrust on the most delicate area of the wall in seismic conditions. This situation, deriving from a conceptual error for not considering horizontal effects, was promptly corrected by eliminating the element, separating the structure from the wall, and creating a different horizontal retaining system. The detailed analysis of this case is in progress.

4. CONCLUSIONS

One aspect that needs be considered when assessing the seismic vulnerability of timber roof structures is the presence and quality of strengthening interventions that may have been performed at different times and with different purposes. Most times these were carried out in relation to vertical loads, but interventions for seismic strengthening are also found. Their evaluation for what concerns their impact on vulnerability is a difficult task. This work analyzes a series of different cases, in order to obtain some general indications.

Interventions for general improvement of the structure should be positive also from a seismic vulnerability point of view. However, disregarding reference to horizontal loads may bring to modifications that worsen the situation for these loads.

The stiff and massive interventions for seismic strengthening carried out in the past have been observed to induce adverse effects in many cases; yet, cases must be considered in detail, because other causes of vulnerability may be simultaneously present and risk to be undetected.

A lighter and less invasive intervention has shown good capabilities in connecting the roof structure with positive effects on the building underneath, without important visible side effects.

In terms of vulnerability evaluation, the cases studied indicate once more the need to carefully examine the situation concentrating on the characteristics of seismic action with an inquisitive eye toward all its possible effects. The complexity of the problem will require the exam of a more extended series of situations in order to give general guidelines.

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REFERENCES

Chesi, C., Parisi, M.A., Tardini, C., (2008). Concezione strutturale e risposta sismica delle strutture lignee di copertura. (in Italian). Ingegneria Sismica, **XXV: 3**, 36-47.

Norme Tecniche per le Costruzioni, (2008). (Italian Design Code for Structures, in Italian), D.M. 14 Gennaio 2008, Ministero delle Infrastrutture, Rome.

Parisi, M.A., Piazza, M., (2000). Mechanics of plain and retrofitted traditional timber connections, ASCE, *Journal of Structural Engineering*, **126:12**, 1395-1403.

Parisi, M.A., Piazza, M. (2002). Seismic Behavior and Retrofitting of Joints in Traditional Timber Roof Structures, *Soil Dynamics and Earthquake Engineering*, **22:** 1183-1191.

Parisi, M. A., Chesi, C., Tardini, C., Piazza, M., (2008a). Seismic vulnerability and preservation of timber roof structures. *6th International Conference on Structural Analysis of Cultural Heritage*, SAHC08, **Vol. 2:** 1253-1260, Bath.

Parisi, M. A., Chesi, C., Tardini, C., Piazza, M. (2008b). Seismic vulnerability assessment for timber roof structures, *14th World Conference of Earthquake Engineering*. **Vol. 1:** 05-04-0052.

Parisi, M.A., Piazza, M., (2008c). Seismic strengthening of traditional carpentry joints, *14th World Conference of Earthquake Engineering*, **Vol. 1:** 05-04-0051.

Parisi, M. A., Chesi, C., Tardini, C., Piazza, M., (2009). Traditional Timber Roof Structures: Seismic Vulnerability Assessment and Preservation. *Prohitech Conference.* **Vol. 1:** 391-396, Rome.

Parisi, M. A., Chesi, C., Tardini, C. (2010). Seismic vulnerability indicators for timber roof structures, *9th US National and 10th Canadian Conference on Earthquake Engineering*, **Vol. 1:** 157.

Parisi, M.A., Piazza, M., Chesi, C. (2011a). Seismic response of traditional timber elements and roof structures: learning from the L'Aquila earthquake. *First International Conference on Structural Health of Timber Structures, SHATIS*; **Vol. 1:** 064, Lisbon, June 16-17.

Parisi, M.A., Chesi, C., Tardini,C. (2011b). Structural Conditions and seismic vulnerability of timber roofs. *First International Conference on Structural Health of Timber Structures, SHATIS*; **Vol. 1:** 065, Lisbon, June 16-17.

Parisi, M.A., Chesi, C., Tardini,C., (2012a). Inferring seismic behaviour from morphology in timber roofs. *International Journal of Architectural Heritage*, **6:** 100-116.

Parisi, M.A., Chesi, C., Tardini,C., Altamura, F. (2012b). Seismic strengthening of timber roof strutures: a case study. Accepted for *8th International Conference on Structural Analysis of Cultural Heritage*, SAHC2012, 15-17 October, Wroclaw.