Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 157

SEISMIC VULNERABILITY INDICATORS FOR TIMBER ROOF STRUCTURES

M.A. Parisi[1], C. Chesi[2] and C. Tardini[3]

ABSTRACT

Among the factors that most likely affect the seismic response of timber roof structures are: the conceptual design of the structure, in terms of typology and of specific factors as the presence of unrestrained thrusts; the condition of the supports connecting the roof to the underlying structure; the type and condition of carpentry joints; the dimensions of timber elements; and the general state of conservation. A methodology proposed for assessing the seismic vulnerability comprises two steps. The first consists in a visual inspection of the structure, to be performed according to a standardized procedure. In the second, the information that was collected is used as the basis for evaluating a series of specific vulnerability indicators. These indicators quantify and grade the influencing factors listed above. Among them, the original conceptual design has a primary role in the capability of responding to seismic excitation. The factors associated to the structural typology that contribute positively to the seismic response, or to vulnerability when lacking, amount to: (a) a correct association of span, structural typology, and element sections according to values that comply with a sound constructional tradition, and (b) effective links between trusses.

Introduction

Methods for seismic vulnerability assessment have been developed and widely used for different types of structures and infrastructural elements. In the 1980's and 1990's in Italy assessment procedures were prepared for masonry buildings of residential type and applied in many towns and regions, yielding a detailed picture of the masonry building stock. Vulnerability of other building typologies were subsequently developed, classifying in particular the cultural heritage like churches and more recently historical palaces. All these buildings, common and monumental, are covered with timber roof structures that have significant impact on the global seismic response. Yet, the contribution of these structures is evaluated at most with a generic statement on their quality level.

Roof structures were originally conceived for carrying vertical loads, without reference to different actions and rare events as earthquakes. For long, replacing the timber roof structures of existing buildings with new elements, most often in reinforced concrete from industrial

[1]Associate Professor, Dept. of Structural Engineering, Politecnico di Milano, Milano, Italy
[2] Professor, Dept. of Structural Engineering, Politecnico di Milano, Milano, Italy
[3] Graduate Student, DIAP, Politecnico di Milano, Milano, Italy

production, has been common practice as part of the interventions for the seismic strengthening of buildings. In many cases, a poor seismic performance has resulted. The mismatch of the high mechanical characteristics of these new structures with the modest quality of the bearing walls triggered damage and often progressive collapse. For these reasons, and for the current trend to preserve these structures as part of the cultural heritage, a more precise and specific vulnerability assessment has become necessary. A proposed methodology (Parisi et al, 2008a, 2009) comprises two steps. As a first step, data are collected in a visual inspection of the structure to be performed according to a standardized procedure. In the second step this information is used as the basis for evaluating a series of specific vulnerability indicators. In the following, these indicators are discussed and criteria for their rating are presented.

The vulnerability indicators

The seismic response of timber roof structures is influenced by many factors. Among these are the presence or absence of unrestrained thrusts, the condition of supports, the conceptual design of the typology, the type and condition of carpentry joints, the size and condition of timber elements, and the general state of conservation (Parisi et al, 2008a, 2009). From these factors, a set of synthetic indicators for use in vulnerability assessment has been defined and grading criteria for each indicator or for its subelements developed.

The rating process consists in ranking each item according to a scale of values from A to D, where A represents a fully satisfactory situation and D indicates high vulnerability, that should possibly be reduced by suitable interventions. Intermediate situations are classified as B and C, depending on what is the closer extreme.

Conceptual design of the structure

Roof structures, originally conceived for carrying vertical loads, are more or less suited for seismic response depending on the structural solution that has been adopted. In order to characterize the seismic behavior and the vulnerability related to the conceptual design, a database of reference cases has been assembled with the structural typologies most common in Italy. Considering that vulnerability analyses are more effective the more delimited is the typology range, different series of structures have been examined and the relevant data collected. These data cover a variety of real cases, in addition to those found in the literature. Structures belong to two different areas in the alpine region, in northern Italy, and to the lower appennine region in the south. Each is a mountain area with a different building tradition. From the survey, different criteria adopted in the conceptual design appear.

A large number of small, simple buildings have a couple roof, i.e., no real roof truss, but barely a ridge beam supporting a series of rafters that connect directly to the walls, as in Fig. 1.a. This system may transmit horizontal components of thrust already with vertical loads and is inadequate for seismic action. Such structural layout is deemed not acceptable without interventions to restrain the thrusts.

In the Italian tradition, most roof structures correspond to gable roofs and are conceived first as planar, with a series of parallel trusses, that are then linked in a more or less effective manner to constitute a three-dimensional structure. For small spans, up to 6-7 m, the closed couple roof scheme, i.e. a simple truss consisting in two rafters and a tie-beam, is very common, Fig. 1.b. Generally, a post between the rafters facilitates connection; it is usually not connected to the tie-beam, as seen in Fig. 1b. For higher spans, up to about 15 m, a king truss is normally adopted, as in Fig. 1c. Struts improve the behavior of the rafter, which reaches significant length for these spans. Larger spans, up to 25-30 m, are found in important buildings, often for public use. More elaborated trusses are used, in order to improve the bearing capacity. A fairly common and relatively simple combination is the two-level, queen truss, as in Fig. 1.d.

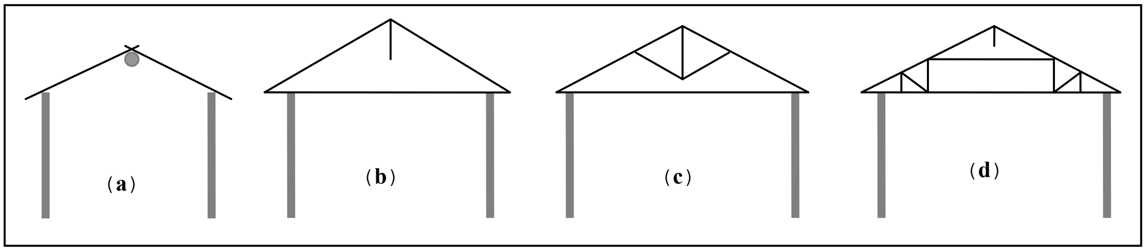

Figure 1. Truss schemes: (a) couple roof; (b) simple truss, (c) king truss, (d) queen truss.

One or two purlins for each pent usually link trusses between them. Sometimes, more complex links are used, like secondary trusses, either orthogonal or diagonal to the main ones, if the roof is hipped. A particularly efficient three-dimensional effect is obtained in these cases.
The gable roof with planar trusses linked by purlins is, however, by far the most frequent. The effect of the number and position of the purlins, of the type and quality of connections (hinged or semi-rigid), and of the element sizes associated to the span have been investigated by numerical analysis (Chesi et al., 2008). The exam of natural periods and modal forms was an effective mean to point out structural inefficiencies. Further information in terms of stress and displacement levels was obtained by simple response spectrum analysis.

Vulnerability assessment in relation to the structural scheme

The typological classification, reflecting the field survey of roof structures, leads directly to a first criterion for vulnerability assessment in relation to the conceptual design.
A favourable seismic performance is possible when stiffness and resistance resources are equally distributed in orthogonal directions; in other words, the degree of three-dimensionality of the structural scheme is directly related to vulnerability. The classification of roof structural solutions may then also be used as a vulnerability criterion, based on the following main classes:
1) a roof cover hipped at one or two extremes is typically based on a three dimensional structural system, with trusses in both orthogonal planes; alternatively, trusses may be parallel, but connected by an effective transversal bracing system. Under these conditions, the structure exhibits similar stiffness and resistance properties in orthogonal directions and the relevant indicator may therefore be assigned to a low or very low vulnerability class;
2) on the opposite side of the range, a lean-to roof and a couple roof, simply based on rafter beams with no truss structure, are typically characterized by one pent or one pent per side, respectively; a structural scheme of this kind may be regarded as one-dimensional. This situation is dangerous because of the unrestrained thrusts, which may cause damage to the underlying structures. The associated vulnerability class is necessarily high;
3) the intermediate situation corresponds again to the case of a two-pent gable roof, but supported by parallel trusses. This structural system is typically two-dimensional; in this case, the real attitude to resist seismic actions depends on the number of purlins providing connection

between trusses in the longitudinal direction of the roof. Numerical analyses have shown that an acceptable level of longitudinal stiffness requires a minimum of two effective purlins per rafter, whereas stiffness is very low with the relatively frequent case of a single purlin. Consequently, two vulnerability classes can be recognized, a medium-high class and a medium-low one, respectively.

A concise description of the above classification is given in Table 1, where vulnerability classes are defined in relation to the roof conceptual design.

Table 1. Structural typology

Structural scheme	**Vulnerability class**
Trusses in orthogonal directions	**A**
Parallel trusses with transversal bracing	**A – B**
Parallel trusses with 2 purlins per pent (or more)	**A – B**
Parallel trusses with 1 purlin per pent	**B – C**
Couple roof (no truss)	**C - D**

Vulnerability assessment in relation to the size of structural elements

The numerical analyses of several structural configurations were performed, and the response parameters were shown to present systematic behavioral trends with reference to associations of structural typologies, covered spans, and cross-section sizes. In the analyses, span values are in the range from 6 to 24 m, while the element cross-sections present a minimum of 15×15 cm and a maximum of 30×30 cm. Inappropriate and unusual combinations clearly stand out, indicated by anomalous values of response parameters. These observations are the basis for assigning each configuration to a vulnerability class.

In this perspective, the effectiveness of each structural scheme in resisting the seismic action may be clearly assessed with reference to the combination of the span to be covered with the cross section of the structural elements. Considering globally the results obtained, a synthetic classification criterion may be expressed as in Table 2. Associating periods, displacements, and stress levels for the various cases analyzed permits to assign structures to one of the 4 classes.

This table, defined on a numerical basis, is in full agreement with the best traditional practice, that was based on a careful selection of the appropriate structural scheme and section geometry for the span to be covered.

Table 2. Effect of dimensions

Section	Span (m)				
(cm × cm)	6	9	12	18	24
15 × 15	**A**	**B**	**C**		
20 × 20		**A**	**B**	**C**	**C**
25 × 25			**A**	**B**	**B**
30 × 30				**A**	**A**

Vulnerability from inadequate original design

Occasionally, structural configurations are found that are unfit for any horizontal loading or even for non symmetric vertical loading. Truss nodes often modeled as hinges in truss analysis, are actually semirigid and generally permit equilibrium. Yet, safety margins may be low in normal working conditions and would not be acceptable for the seismic case. In these cases, the vulnerability is high and the situation should be remediated promptly. Figure 2 shows a truss that would not be equilibrated should the nodes be considered hinged.

Figure 2. The rafter is not continuous in the node.

The carpentry joints

Vulnerability may derive to a truss from the type, details, and conditions of carpentry joints. The aspects to be examined may be summarized in two points,

1. the capability to maintain the connection during cyclic conditions, with possible decrease of compression, and
2. the expected post-elastic behavior, with the aim at sorting out possible brittle failure modes.

Indications for evaluating these points for different types of joints have been derived from the results of a research program on the monotonic and cyclic behavior of carpentry joints in the elastic and post-elastic range; joints reinforced with different strengthening typologies had been examined and tested (Parisi and Piazza, 2000, 2002, 2008b).

According to the period of construction and to the time of subsequent interventions, the level and quality of node binding may vary significantly. It may range from either the absence of metal connectors in very old joints or the presence of old ineffective devices as one extreme to effective, low-impact interventions to the other.

Joints that are unrestrained or ineffectively restrained may undergo disassembling; they are considered at the worse side of the vulnerability scale and are classified as D.

As to reinforced connections, nodes with excessive stiffening that may derive from interventions

carried out in a recent past, typically in the second half of the 20th century, as in the example of figure 3 are at the high vulnerability side of the scale.
Eliminating the possibility of relative rotation between the connected elements modifies the original conceptual design of the node that should be conserved for service conditions unless particular problems arose, and may trigger brittle failure in extreme conditions, as in the case of earthquakes.

Figure 3. Intervention producing overstrengthening on the rafter to tie-beam node.

Excessive strengthening and risk of brittle failure may derive as well from the use of a limited amount of connectors, when these are positioned in a pattern that prevents or limits rotation. As an example, in Fig. 4 two bolts are used to reinforce a birdsmouth joint either along the rafter axis, left in the figure, or transversally, right in the figure. Experimental analysis of the two solutions has given indication of problems related to overstiffening for the first case and of very positive outcome for the second, respectively.

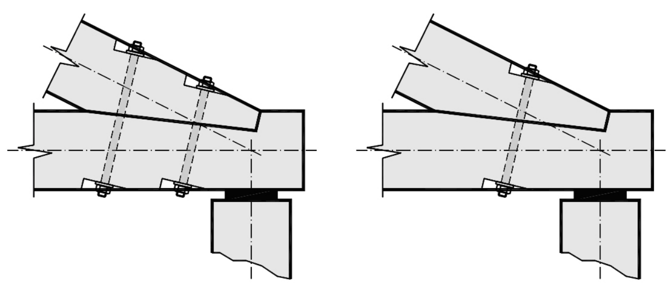

Figure 4. Birdsmouth joint reinforced with bolts either longitudinally (left) or in the transversal direction (right); the layout on the left limits the rotational capability.

The low-vulnerability extreme of the scale, i.e. grade A, corresponds to connections with provisions to avoid separation of the connected elements in case of sudden decrease of pressure or loss of contact and developing some dissipative post-elastic behavior rather than a brittle one, but otherwise maintaining a semi-rigid behavior in normal working conditions. Intermediate scale values cover a variety of situations. The class may be decided judging the effectiveness of connection, the possibility of brittle failure, and the reliability of the connecting elements. Table 3 reports indications for grading a birdsmouth joint at the rafter-to-tie connection, according to the results obtained in the study mentioned above.

Table 3. Guide for classifying carpentry joints

Reinforcement type			**class**
Unreinforced			D
Reinforced, with			
	1 bolt		B
	≥2 bolts, small diameter,		
		transversal	A
		longitudinal	C
	Stirrups		C
	Binding strip		
		fixed	B
		adjustable	A
	Steel cage		D

Supports and Connections

After the internal constraints given by the joints, the external restraint system is evaluated. Trusses connect to the supporting wall either directly or via a timber wall plate or reinforced concrete ring beam. Two basic situations occur: (a) truss supported at the top of the wall, or (b) built-in ends. In the latter case, the timber beam may either be retained at the outside surface of the walls, or be completely enclosed in the wall.

The restraint may be judged by the degrees of freedom that remain unlimited. The degrees of freedom to be considered are the horizontal translation parallel to the tie-beam axis, the horizontal lateral translation, and the rotation around the tie-beam axis. The effect of unrestrained or insufficiently restrained rotation may be more or less important depending on the existence or absence of bracings in the longitudinal direction of the roof.

For displacements parallel to the axis, that would tend to drop the truss from the support, examples of good construction techniques may be found where the tie beam is anchored with steel or even timber elements protruding from the wall and blocked on it. Figure 5 shows an example of timber restraints that gave good results in the L'Aquila, April 6, 2009 earthquake.

Another element for formulating a judgment is the possibility of inspection of the support. A built-in end where the extension of the enclosed part is not appreciable and no provisions to avoid decay are visible is an uncontrollable situation, so the possibility of unseating must be considered. Table 4 gives a first tentative grading criterion for this indicator.

Table 4. Condition of supports

supports	**class**
No restraint and insufficient support (parallel to tie beam)	D
No restraint but sufficient support (parallel or lateral)	C
Free rotation without bracings	C
Free rotation, with bracings	A-B
Fixed end, with external restraints or visible	A
Fixed end, partially or not visible	B-D

Figure 5. Different support conditions; built-in elements (left); decayed built-in beam end (top right); an old-time external restraint maintained support of the timber truss in the L'Aquila earthquake (bottom right).

Current state of the structure

The last indicator is the current state of the structure. It analyzes the conservation state, the presence and quality of strengthening interventions, and any other observation specifically related to the state of the structure. Contributions of different nature are scored under this point. Although criteria for evaluating individual items have been expressed (as in the following and in Table 5), their composition in a single value needs still to be treated. The table indicates a vulnerability range for each point considered, depending on the state observed. In the positive case, not reported in the table, the class is A. Some items are particularly critical and their vulnerability range is limited to classes C and D.

While the age of well protected timber elements should not be considered necessarily a handicap, particularly for some wood species, poor maintenance has been recognized to contribute to the vulnerability of buildings and structures in general and is recognized to play a significant role for timber in particular. Regularity of general maintenance versus lack of inspection of the structure in the recent period may be considered within this indicator. A very important check to be performed is the state of the roof cover system, because rainwater filtrating from cracks and gaps will rapidly deteriorate the underlying structure, even if such filtration and the consequent decay is not yet observable. This is also a critical situation that is fairly easy to remediate. Figure 6 shows a damaged roof cover.

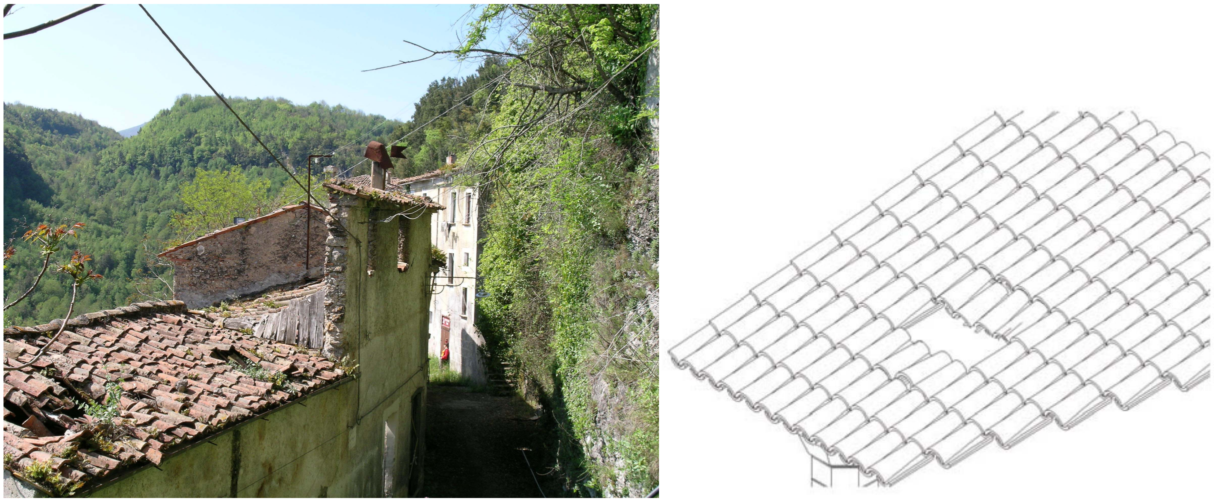

Figure 6. Damage to the tiled roof cover fastly brought the underlying structures to an end (left); at right, icon used to recognize roof damage in a survey form (MiBAC 2009).

Decay of elements and joints due to environmental conditions and biotic attack result in a decrease of response capability and increased vulnerability.

A significant cause of vulnerability may be found in changes to the original structural concept produced during the life of the structure. Interventions carried out to eliminate initial conceptual errors, not rare in constructions mostly based on traditional practice without reference to codified design principles, are frequently seen. Yet, modifications that actually induce vulnerability are equally frequent. This is the case of increased masses in strengthening interventions carried out according to criteria adopted in the last part of the 20th century. An example may be seen in Fig. 7 showing the roof of the church of S. Biagio Amiterno, damaged during the L'Aquila, Italy, earthquake of April 6, 2009. A heavy concrete slab had been laid with the aim at collaborating with the original roof structure and at constituting a stiff link between walls.

Figure 7. Increased dead load on roof structure (left), church of S. Biagio Amiterno, L'Aquila.

Finally, Table 6 gives a first guide for classifying the vulnerability from the state of the structure.

Table 6. State of the structure

Item		**Class range**
maintenance		
	roof cover	C-D
	date of last general maintenance	B-D
decay		
	reduction of element sections	B-D
	decay of joints	B-D
Previous interventions		
	modification of elements	B-D
	Increased loads	C-D

Conclusions

The work presented here is part of a research program aimed at defining a procedure for assessing the seismic vulnerability of timber roof structures. Here, attention has been focused on the main factors that affect the seismic response and on the vulnerability indicators that can be expressed to evaluate these factors. Future work will combine classes and indicators to yield also a global vulnerability index. It is significant to point out that the lowest vulnerability levels correspond to structures where sound principles of traditional construction practice had been rigorously applied.

References

Chesi, C., Parisi, M.A., Tardini, C., (2008). "Concezione strutturale e risposta sismica delle strutture lignee di copertura", (in Italian, summary in English), Ingegneria Sismica, Patron Editore, n. 3, July-September, pp. 36-45.

MiBAC (2009). Scheda di rilievo del danno ai beni culturali – palazzi; (Italian Dept of Cultural Heritage, Seismic damage evaluation form for cultural heritage – palaces).

Parisi, M.A., Piazza, M., (2000). Mechanics of plain and retrofitted traditional timber connections, Journal of Structural Engineering, ASCE, 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 assessment for timber roof structures", Procs, 14th WCEE, October 12-17, Beijing.

Parisi, M.A., Piazza, M., (2008b). Seismic strengthening of traditional carpentry joints, Procs, 14th WCEE, October 12-17, Beijing.

Parisi, M. A., Chesi, C., Tardini, C., Piazza, M., (2009). Traditional Timber Roof Structures: Seismic Vulnerability Assessment and Preservation, Procs, Prohitech Conf., pp. 391-396, Rome.