# SEISMIC VULNERABILITY ASSESSMENT FOR TIMBER ROOF STRUCTURES

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**ABSTRACT :**

In the last decades, methods for assessing the seismic vulnerability of different types of structures and infrastructure have been developed. No criteria have been so far developed for timber structures. A methodology for assessing the seismic vulnerability of timber roof structures is described. Among the elements considered in the procedure are the structural conception, the quality of the timber-to-wall connection, the type and quality of timber-to-timber carpentry joints, and the general state of conservation. Numerical analyses performed for different structural typologies, with geometrical data collected from real cases, constitute the basis for evaluating the structural conception. The key points for the evaluation of carpentry joints are the maintenance of connection during alternate excitation and their expected post elastic behaviour. The paper proposes a first version of the method and some application examples.

**KEYWORDS:** Vulnerability, timber trusses, roof structures, seismic strengthening

## 1. INTRODUCTION

Until recently, in the seismic strengthening of existing buildings the timber roof structures were most often removed and substituted with new elements of industrial origin and different material. The interaction of these new structures, of high stiffness and mass, with the surrounding walls often of modest quality has given in some cases poor seismic performance, resulting in extended damage or collapse of the building.

A different aspect to be considered and which brings to similar conclusions as the above is that now the historical significance not only of monuments but also of more common construction is widely perceived as a value to be preserved whenever possible. As a result, the trend is now to consider conservative seismic upgrading of these structures as a prime option.

In a perspective of conservation, methods are needed to assess the seismic vulnerability of these structures prior to deciding on their seismic strengthening. For many other cases where vulnerability assessment methodologies were defined, like for masonry buildings, church buildings, etc., the definition of criteria for the assessment gave also, as a second result, the opportunity of organizing and reinterpreting in a more scientific sense the wealth of empirical knowledge that came with the relevant construction tradition. This effect would be also desirable for timber structures. The work presented here proposes a methodology and a procedure for assessing the vulnerability of timber roof structures, focusing on the types that are more frequent in the southern European area.

## 2. VULNERABILITY OF TIMBER ROOF STRUCTURES

In order to define a procedure for vulnerability assessment it is necessary to identify a reference case that may be considered to satisfy seismic requirements. Other situations will be compared to this one, which becomes a sort of reference point in the vulnerability scale. This paradigmatic case will not correspond to full safety, but will present all the positive characteristics that will result in the target seismic behaviour. The paradigm for structural behaviour of masonry buildings is the realization of a box-like structure, with all its structural walls capable of collaborating to the response. A similar reference must be found for timber roof structures.

Timber structures exist in a variety of configurations; additionally, the detailing of connections seems to be very influential on the quality of the seismic response. From observation and analysis, a low-vulnerability timber roof structure should have, in order of importance, (Parisi et al., 2008),

- no unrestrained thrusts;
- an effective connection with the supporting walls
- a comparable response capability in the different directions;
- suitably reinforced carpentry connections to avoid disassembling and brittle behavior.

Vulnerability assessment procedures should indicate the weak points of a structure and give a relative measure of these inconsistencies. The measure may be expressed by assigning a class or by a numerical value to the element examined. The numerical value is useful for possible statistical treatment, but a less crisp division into classes is more objective and easier to perform, at least in a first period of application. This approach is followed here.

Another important feature that a vulnerability procedure must have is the possibility of tracing back with sufficient detail the specific elements that cause the vulnerability in the structure as a whole, in order to plan interventions.

In order to satisfy this requirement the procedure described below is organized in two steps:

- A first step collects data on the various elements of the structure. This information is directed to point out aspects that may affect the seismic response giving, as well, a detailed picture of the general state of the structure.
- A second step focuses on the items that mostly contribute to the seismic vulnerability, according to the points listed above; data collected in the first step are used for this evaluation.

Once the vulnerability level is assessed, the detailed information collected on the structure may be a basis for evaluating possible strengthening strategies as well as for analyzing costs and benefits of various interventions.

The survey of the roof structure that is the basis for the seismic vulnerability assessment requires visual inspection and some measuring of basic dimensions of the structure and elements. Collecting these data constitutes the first step of the procedure. From this information the actual seismic vulnerability assessment follows as a second step. The two levels proposed are described in detail in the following sections.

## 3. FIRST LEVEL: STRUCTURE SURVEY AND DESCRIPTION

At the first level, different types of data are collected by visual inspection of the roof structure. These data describe the structure characteristics and its state of conservation. Data are collected with the guidance of a form –at present a paper form- that lists the different items or features to be considered. Each of these is further developed in a tree-like structure, with branches detailing different aspects. Guidance for compilation is offered in the form wherever possible by multiple-choice answers and figures, or with blanks to be filled in with the required measures or observations. A users' manual is currently being prepared to support choice and decision.

With reference to figure 1, which outlines the first level procedure indicating the main points and exemplifying branching, the first point gathers some information that identifies the building (type, location, period of construction) and describes its general geometry (dimensions, general layout) and material (brick, stone masonry, etc.).

The wood species present in the roof structure are then specified. Visual grading criteria provide a basis for a simplified estimate of the expected strength. The presence of decay agents, like mushrooms, mildew, rot, insects, and excessive humidity, are observed at this point.

The type and state of the connections between the roof structure and the supporting walls are examined at the third point. This will be a very important vulnerability indicator, because a poor roof-to-wall connection is the primary source of damage and collapse of roof structures during earthquakes. The form develops into:

- type of constraint (simple support, hinge, built-in end, semi-rigid moment transmitting connection);
- supporting element (wall plate, ring beam…) and further description of each type.

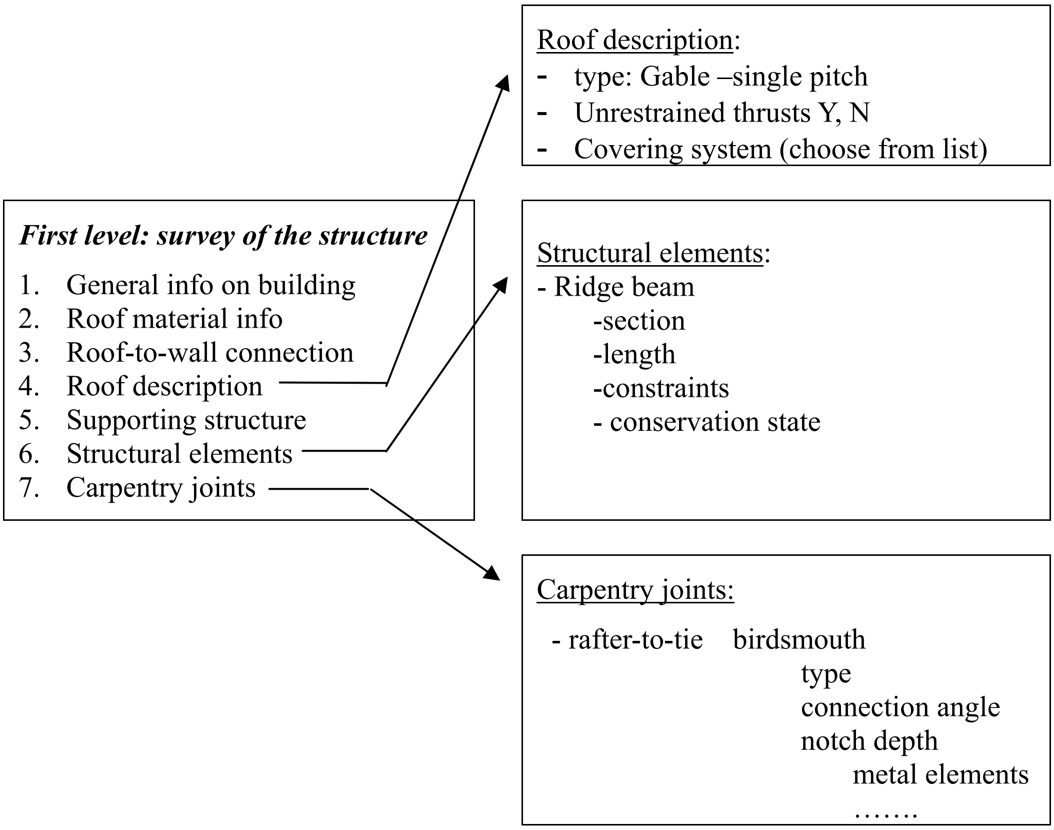


Figure 1. Vulnerability indicators and downbranching

In the points from 4 onward, the roof typology and its details are treated. The branching investigates its structure, the elements and the joints. At point 4, information on the roof type and on other general characteristics is collected. The form lists the most common roof typologies.The type is selected from a series of pictures, but a blank area is left in the form for sketching the type if not found. Approximate dimensions are gathered. Unrestrained thrusts, a major cause of unsatisfactory seismic response, are detected here. The type of cover determines the weight of the roof and thus affects inertia forces.

The description of the structural typology is at point 5. Data collection is more standardized for various typologies already present in the form, like ridge beams without trusses, trusses of different kind (simple king truss, two-level queen truss), truss beams; other situations may be described by the user.

Indication is requested at this point whether evident conceptual errors, leaving, for instance, some unrestrained degrees of freedom are detected. These situations are not rare in older construction and are occasionally found when inspecting roofs. They are dangerous even before seismic conditions occur.

The following point describes in detail the situation of the individual elements of the structure, or each substructure. Structural elements for trusses require some downbranching, with multiple answers possible. For elements occurring more than once in a truss, the location is identified (e.g. truss identification number right rafter, left rafter); reference to similar elements already described may be made avoiding repetitions.

The last point covers the carpentry joints. These connections may be realized in very different modes, according to their location within the structure and to their function. Even for the same location different choices may be adopted, depending from different requirements and from the context (e.g. structural size, workmanship) resulting in a variety of situations. The connections normally used in trusses have been considered, on the basis of a research program outlined in another article in this Conference (Parisi and Piazza, 2008). Each has been listed and developed in the form. For each connection, various choices are suggested; for each joint type, details descend in subsequent branches. Table 1 reports an example of subsequent branching, the arrows show a possible set of descritions. Downbranching for details is not complete in the table, but could continue with further details of the selection.

Table 1 – Example of downbranching for a connection

| Connection | description | properties | Details |
|---|---|---|---|
| →Rafter-to-tie beam | | | |
| | →Single notch, birdsmouth<br>Reverse<br>Double notch<br>… | →Notch<br>depth … | |
| | | Metal elements:<br>Absent<br>present, new<br>→Present, old | Type:<br>Stirrup<br>→Binding strip<br>Bolt: number<br>diameter<br>layout |
| | | … | … |

Some otherwise typical features of timber construction are not analyzed in the procedure, because of their lower impact on seismic vulnerability and in order to reduce surveying and form-filling time. Durability, for instance, is not analyzed in general, but critical situations can be pointed out and reported in the form if deemed necessary.

## 5. SECOND LEVEL: THE VULNERABILITY INDICATORS

At the second level, specific seismic vulnerability indicators are considered. Making reference to the elements and qualities that affect the seismic response, discussed above, a series of indicators has been selected,

1. unrestrained thrusts
2. supports
3. structural typology
4. carpentry joints
5. elements
6. conservation state.

The data collected at the first level are used for their assessment. With reference to the points above,

1. The negative effect of unrestrained thrusts is amplified under seismic conditions and often causes collapse of walls and roof;
2. the insufficient extension of supports or the ineffective connection with supporting walls is the main cause of collapse for roof structures, often starting a domino type collapse of the underlying stories;
3. the effects of structural typology (discussed in a further section);
4. the effect of the type and quality of connections (discussed in a further section);
5. occurrence of an earthquake modifies and generally increases the level of stress in structural elements. In general, this fact was not acknowledged in the original design but may be accommodated by the large sections and consequent safety factors that most traditional structures present. Point 5 takes into account the presence of particularly slender elements with possibly insufficient sections that are occasionally found;
6. Poor maintenance has been recognized to contribute to the vulnerability in other kinds of structures and it is believed to play a significant role for timber, therefore the conservation state, and any other specific

observation concerning the state of the structure, is evaluated at point 6.

The rating process consists in ranking each indicator in the list according to a scale of values from A to D, where A represents a satisfactory situation and D indicates a high vulnerability level, for which an improvement would be strongly recommended. Intermediate situations are indicated by values B and C, depending on what is the closer extreme.
Even if class borders may not be crisp in most cases, attributing classes is a fairly objective operation. For each indicator, a numerical value could be associated to classes, permitting to express a partial vulnerability index as other vulnerability procedures do (e.g. Petrini, 1999, applied also in Chesi et al., 2006). Combining partial indices yields, then, a global value for the case under examination. The attribution of numerical values to classes and the definition of combination weights acknowledging the different role of the indicators requires extensive calibration work that will be faced after more extensive testing of this procedure.

## 7. THE EFFECT OF STRUCTURAL TYPOLOGY

Roof structures, originally conceived for carrying vertical loads, seem more or less apt to respond to seismic excitation depending on the structural solution that has been adopted. Consequently, a vulnerability indicator grades the structural typology and the structural conception in general.

First of all, inconsistencies pointed out in the first level as present in the original conceptual design or introduced by subsequent remodeling are acknowledged here.

The capability of responding in different directions of excitation is also important. Most often roofs are supported by a series of parallel trusses reciprocally connected in more or less efficient ways. The response in the two horizontal directions, parallel and orthogonal to the truss system, may be very different. An extended study of the modal analysis and seismic response of numerous types of trusses connected with different linking elements has been carried out with the aim at constructing a first basis of reference cases and data for judging and classifying the vulnerability level of these structures due to the typology factor (Parisi et al., 2008). The source of information on typologies and their details, beyond literature data, has been a series of surveys carried out on buildings in different Italian regions (i.e. Lombardy, Trentino, Southern Tyrol and Calabria). Cases ranged from simple pent roofs in a Calabrian location to articulated threedimensional cases in the Trentino region.

Modal analysis is an expressive, yet simple method to examine the attitude of the structure toward directional response. It is a mean to interpret irregularities in the structural configuration, with the periods being the key parameters. Ranges of periods for the different typologies dimensioned according to good practice have been found. Periods computed for unusual geometric choices, like small sections, typologies inappropriate for the span, or insufficient links, yielded clearly out-of-range periods, showing the validity of this indicator, that may be associated to geometry.

By means of response spectrum analysis the same structures were compared in terms of displacements and stresses, that are the main parameters considered in design, with similar conclusions.

From these analyses, the factors associated to structural typology that contribute positively to the seismic response appeared to amount to
- a correct association of span, structural typology, and element sections according to values that comply with a sound constructional tradition;
- effective links between trusses; this aspect is well pointed out by the modal analysis and by the first modal shape: weak links result in low stiffness in the direction normal to the trusses, where the first mode develops often with long period, considerably greater than the subsequent ones, and a participating mass value near to unity (figure 2).

Criteria for classifying structures by the typology point of view stem from these bases and are being currently organized in tabular form.

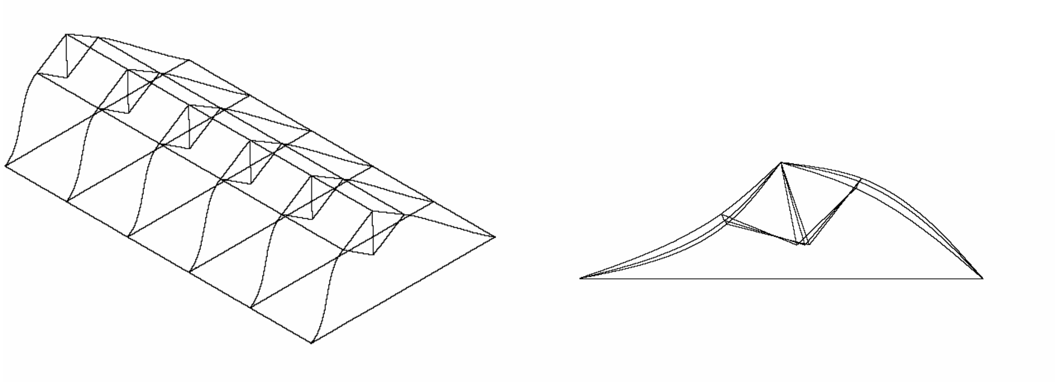

Figure 2. First modal forms in orthogonal directions for a roof structure with a seis of trusses

## 7. THE QUALITY OF CARPENTRY JOINTS

The two parameters for evaluating carpentry joints are the maintenance of the connection during alternate action and their expected post-elastic behaviour, with the aim at pointing out possible brittle failure modes. The results of the research program cited above on mechanical behaviour of carpentry joints are the basis for the following evaluation (Parisi and Piazza, 2000, 2002a, 2002b, 2008).

At the worse side of the evaluation scale, D, are joints unrestrained or ineffectively restrained against disassembling. According to the period of construction and of subsequent interventions, the level and quality of node binding may vary significantly, with absence of metal connectors in very old cases or the presence of old ineffective ones as one extreme. At the same side of the scale is the excessive stiffening of a node that may derive from reinforcing interventions carried out in a more recent past, as in the example of Figure 3.

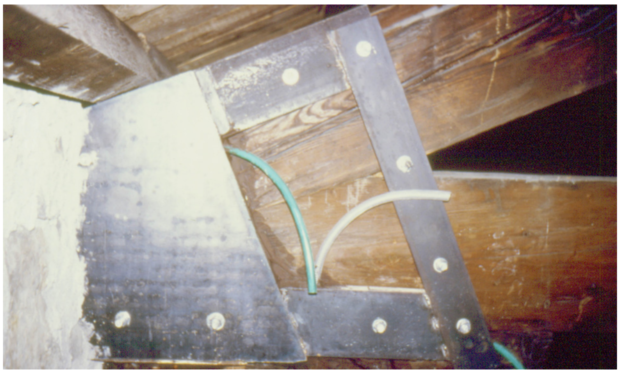

Figure 3 – Overstrengthening of a carpentry joint

Eliminating the possibility for the connected elements to rotate modifies the original node and structure, very likely triggering brittle failure under extreme conditions, as in the case of an earthquake.

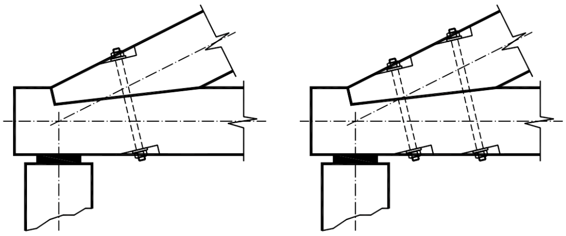

Figure 4. Birdsmouth joint reinforced with 2 bolts either in the transversal direction (left) or longitudinally (right)

Excessive strengthening that limits rotation and may induce brittle failure may also derive from the use of a limited amount of connectors as a consequence of their inapropriate positioning. In Figure 4 two bolts are used to reinforce a birdsmouth joint either transversally, as in the image on the left, or along the rafter axis, as in the right image. Experimental analysis of the two solutions has given a very positive outcome on the first layout and a very discouraging one on the second.
At the better end of the vulnerability scale, A, are connections protected against separation of the connected elements due to sudden and temporarily decrease of pressure or loss of contact, yet maintaining a semi-rigid behaviour. Intermediate scale values correspond to a variety of situations and are to be evaluated considering the effectiveness of connection, possible brittle modes, and the reliability of the connecting elements. Table 2 reports indications for grading a rafter-to-tie birdsmouth joint according to the study results.

Table 2. Vulnerability classification of a carpentry joint

| **Joint: rafter-to-tie** | **class** |
|---|---|
| ➢ birdsmouth, single notch | |
| unreinforced | **D** |
| reinforced | |
| *1 bolt* | **B** |
| *≥ 2 bolts, small ∅* | |
| *transversal* | **A** |
| *longitudinal* | **C** |
| *stirrup* | **C** |
| *binding strip* | **B** |
| *adjustable* | **A** |
| *blocked end* | **D** |
| …… | |

## 8. CONCLUSIONS

A procedure for assessing the seismic vulnerability of timber roof structures has been developed. It is organized in two steps. The first part concerns the collection of data of the structure performed by visual inspection. On this basis, in a second step specific vulnerability indicators are analyzed and graded. Data from roof structures, collected in different regions, are being used to calibrate the procedure.
An evaluation form listing the items to be inspected is used in the process. At this experimentation and calibration stage, the procedure is implemented using a paper form. As a future development of this work, the use of an information technology approach would offer the flexibility of an interactive interface and the possibility of direct data control and organization.

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