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REDUCING THE SEISMIC VULNERABILITY OF TIMBER ROOFS: A CASE STUDY

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Abstract

Introduction:
The earthquakes occurred in Italy in the last decades have shown a strong influence of the timber roof structures on the response of masonry buildings. The roof system may play a positive role linking and stabilizing the walls or, on the opposite, may suffer damage and often trigger collapse of the masonry structure. Architectural heritage, and especially church buildings, have particularly suffered collapse related to malfunctioning of the roof system, often generating pounding on walls, or resulting in progressive collapse from the roof to the underlying slabs or vaults. In order to reduce the risk of damage to roof structures, often themselves precious wooden artifacts, and to the building, it seemed necessary to define specific criteria for assessing seismic vulnerability and suitable intervention criteria, compatible with conservation requirements.

Developments:
Previous work was carried out, within a national research program (Reluis-DPC), with the objective of developing synthetic criteria permitting to assess vulnerability by inspection, with simple observations and some limited measuring operations. An assessment procedure was defined, based on estimating factors that influence seismic behaviour, like unrestrained thrusts, conceptual design and typology, dimensions of timber elements, conditions of supports and of carpentry joints, and state of conservation. Corresponding vulnerability indicators and grading criteria were developed. A complex roof, covering a large, century-old mansion which had not been recently maintained, has now been examined as case study. Its seismic vulnerability has been estimated according to the procedure; criticalities have been pointed out; on this basis, the analysis of possible intervention strategies and consequent reduction of vulnerability levels may be performed with costs-benefits considerations. A plan of possible interventions has been developed.

Remarks and Conclusion:
The application of the seismic vulnerability assessment procedure has resulted capable of indicating clearly and in an organized form the critical aspects of the structure and the interventions necessary for the improvement of its seismic response.

1 INTRODUCTION

Timber roof structures participate to the seismic response of masonry buildings influencing significantly the behaviour of the building itself, as the earthquakes that occurred in Italy in the last decades have shown. The roof system may play a positive role linking and stabilizing the walls or, on the opposite, may suffer damage and often trigger collapse of the masonry structure. Architectural heritage, and especially church buildings, have particularly suffered collapse related to malfunctioning of the roof system, often generating pounding on walls, or resulting in progressive collapse from the roof to the underlying slabs or vaults. In order to reduce the risk of damage to roof structures, which are often precious wooden artifacts, and to the building, it seemed necessary to define specific criteria for assessing seismic vulnerability and suitable intervention criteria, compatible with conservation requirements.

Timber roofs in seismic conditions have been studied for an extended period by the authors, within a national research program (Reluis-DPC) devoted to define strategies to reduce seismic risk related to a vulnerable building stock. The objective of the research has been developing synthetic criteria permitting to assess seismic vulnerability of roof structures by inspection, with simple observations and some limited measuring operations. An assessment procedure was defined, based on estimating the factors that are particularly influent on the seismic behaviour, like unrestrained thrusts, conceptual design and typology, dimensions of timber elements, conditions of supports and of carpentry joints, and state of conservation. Corresponding vulnerability indicators and grading criteria were developed.

A complex roof, covering a large, century-old mansion which had not been recently maintained, has now been examined as case study. The objective is dual: on the one side, testing the applicability of the procedure on a large roof and its effectiveness in showing the possible critical points in an organized way; on the other, considering the capability of the procedure, which synthetically indicates the need for interventions and their importance, as a basic tool for comparing and estimating costs and benefits of different intervention strategies. For the case examined, the seismic vulnerability has been estimated according to the procedure; criticalities have been pointed out; on this basis, the analysis of a possible intervention strategy and consequent reduction of vulnerability levels has been performed.

2 OUTLINE OF THE ASSESSMENT PROCEDURE

Assessment of the conditions of timber structures is a first step performed in view of further operations usually addressed to improve their safety, or their state of conservation. Much interest and research work has been conveyed on the definition of effective assessment modalities, particularly for the case of heritage structures that are subject to limitations in their treatment in order to comply with conservation requirements [e.g. 1, 2, 3, 4]. Guidance is supplied by a variety of codes and documents dealing with the different timber-related characteristics to be considered [5, 6].

When assessment concerns the seismic vulnerability, the features that most affect the structural behavior under this particular type of action must be addressed, while others typical of timber structures for other conditions may become less dominant at least for a first analysis [7, 8]. Typically, earthquakes produce significant horizontal inertia forces, which may be critical for roof structures mainly constructed with reference to vertical loads. The structural system must be configured to provide sufficient horizontal restraint, while a very accurate and detailed determination of the wood type and properties may not be a major requirement in a first, rapid vulnerability evaluation.

Based on observed earthquake damage, numerical simulations, and experimentation results, the most influencing elements to be assessed are,

1. The structural typology and the conceptual design;
2. The quality of connections;
3. The retaining system, at the roof-wall interface;
4. The current state of the structure.

These elements may be considered as the main indices, or indicators of the vulnerability level [9, 10].

The structural typology is a main element to be considered, because the different structural solutions adopted in timber construction are not equally suitable for seismic response. A first issue within this point is the capability of the structure to respond equally in different directions, i.e. to provide a three-dimensional behavior. In the Italian tradition, roof structures are mainly built as a series of trusses, that is, bi-dimensional elements, more or less effectively interconnected. The different truss types are not equally valid for the purpose of responding to horizontal forces; moreover, each is appropriate for different ranges of span lengths; sufficient cross-sections for increased loads must also be available. Similarly, different elements are used to connect the trusses into a three-dimensional system, from simple purlins that may be effective if in sufficient number, to more elaborate bracing systems. Assessment must consider the suitability of the planar elements and, in the transversal direction, the effectiveness of the connecting elements [11].

Connections between elements forming the trusses must maintain its compactness. Carpentry joints must satisfy two main requirements in the extreme seismic conditions, that is, avoid disassembly of the connection and, consequently, of the truss itself, and avoid brittle failure. Suitable metallic elements fulfill the former preventing joint opening when contact between the two joined elements happens to decrease; brittle failure may have different causes, but often occurs when the joint is excessively stiffened and its deformation blocked. For a guidance in assessing the quality of carpentry joints, reference may be made to results of experimental campaigns and their interpretations in terms of seismic vulnerability.

The quality of restraint given by the supports between walls and roof structure is an important indicator of the vulnerability of the roof, but also of the entire building. During motion, an insufficient support if often the cause of failure of the roof structure, which often entails progressive collapse of structures underneath, like floor slabs or vaults [12]. Again, different forms of the contact area, and the presence of restraining elements like metal connectors determine the vulnerability level for this index.

The last point collects different aspects, all related to the state of the structure at the time of the survey; it includes particularly the maintenance level, as well as alterations of the original concept of the structure, for interventions due to a variety of reasons, including modifications of the building, structural improvement, or the correction of original construction errors. Given the variety of conditions, these interventions may have positive or negative effects [13]. Beyond basic principles, limited guidance can be offered to the surveyor.

2.1 Grading rules

In order to arrive to a measure of the vulnerability level for each indicator, and within it for each issue considered, a grading system is needed. A linguistic variable has been adopted considering that it offers sufficient separation for distinguishing states, within the accuracy level compatible with a rapid vulnerability analysis. Table 1 shows the scale adopted.

Table 1: Classification scale

Grade	Classification
A	Complies with requirements for new construction
B	Low-to-medium vulnerability
C	Medium-to-high vulnerability
D	High vulnerability

While grade A represents the lowest vulnerability corresponding to new design, D indicates situations where a highly critical level has been reached and interventions to reduce the associated risk highly recommended. Grades B and C correspond to intermediate situations, where the former usually does not necessarily indicate a .need for improvement, which is more advisable for the latter.

2.2 Assessment procedure

The procedure that has been developed on the concepts above encompasses two main steps, namely,

1. A visual analysis
2. An evaluation of the main vulnerability indicators related to the four points above and, consequently, of the global situation of the structure

The visual analysis aims at a first appreciation of the structure state and at collecting all the relevant data, which are inserted in a survey template The use of a predefined template practically standardizes the survey process by guiding the data collection. All the elements necessary for the subsequent analysis of the vulnerability indicators are examined in an orderly manner.

From this basis, the different vulnerability indicators are then evaluated and graded. A general picture of the criticalities and of their severity results from this operation. A global grading of the structure combining the various grades is also possible.

The two steps are conducted separately, the second requiring elaboration that cannot be conveniently done on site.

3 A CASE STUDY

The assessment procedure in its present form is the result of a research work extended in time, which has included modifications and calibration based on various example applications to timber roof structures [e.g. 14, 15]. The case presented here, instead, is part of a general research project supported by the National Civil Protection Department that aims at examining and comparing different strengthening intervention strategies for reducing the seismic vulnerability of traditional masonry buildings. To this purpose, selected case studies have been treated by different research units nationwide. Even though the program, which is still in progress, was mainly addressed to interventions on masonry elements, it has given the occasion for a systematic treatment of the vulnerability of timber roof structures, which have a strong influence on the building response but are often disregarded.

Here, the reference building is a large masonry hotel located in an alpine resort that has been closed for several years. Its construction dates back to the early 1900's. The particular situation of the building, which is of municipal ownership and is listed for demolition, has offered the opportunity of direct testing of strengthening procedures and interventions.

Within this context, the seismic vulnerability of the timber roof structure has been assessed applying the criteria and procedure summarized above; the visual inspection has allowed a first appreciation of the situation and the collection of data; as a second step, their elaboration has brought to point out and quantify the main critical aspects of the roof structure.

In order to reduce the assessed vulnerability, a plan for interventions has been formulated. According to these interventions, which were detailed in type and quantities, the vulnerability would be reduced significantly. A seismic analysis of the roof structure in the strengthened situation has been performed to verify this assumption.

3.1 The roof structure

Figure 1 shows an exterior view of the building and of the roof. At a lower level the roof covers a C-shaped area, around a courtyard, while on one side the building elevates with an additional storey, which has a rectangular base and an independent roof. The study has been carried out for the lower level only, as the degraded conditions of the building did not consent safe access to the upper storey. In real cases a full evaluation would have been necessary, but in the current situation of a study that was not intended to arrive to the actual restoration of the asset, the limitation was acceptable. The relevant area with the structure plan is also shown.

The roof structure is formed by 13 trusses disposed in the three sides of the C base. They have slightly different structural schemes; they are interconnected at the building corners by diagonals and rafters. Spans range between 7 to 8 meters, with spacing between 3.2 and 4.4 meters, in order to follow the irregularities of the base area.

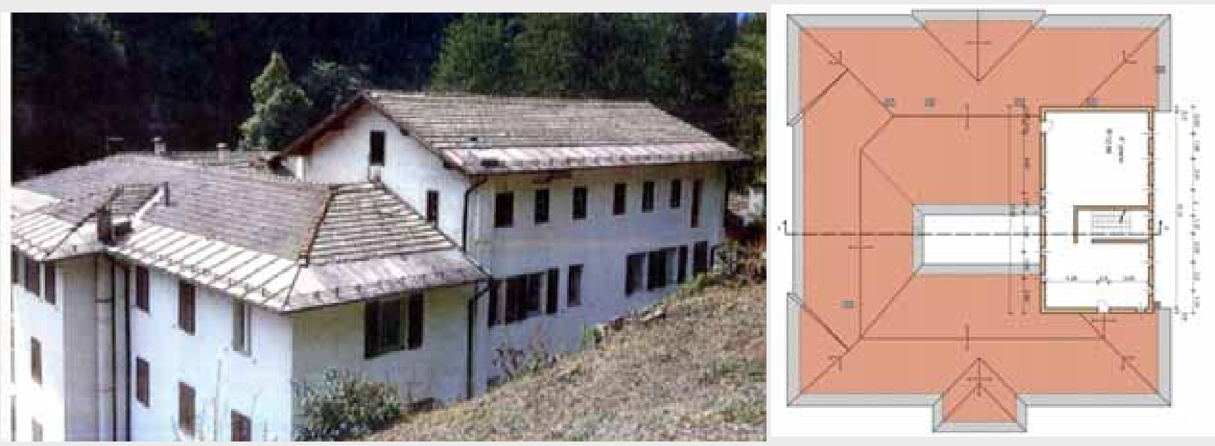

Figure 1: The roof under study covers the lower building area, with a C-shape

4 THE VULNERABILITY ANALYSIS

4.1 Visual inspection

The first phase, survey and visual inspection, has been carried out following the planned procedure and filling the survey templates, in their original paper format. A digital version of the procedure had also been implemented [16], but the environmental conditions discouraged its direct use. After the survey, data were translated into a digital version of the template in order to build a database for further elaborations. Figure 2 shows views of the roof area and figure 3 reports part of a digitalized template, concerning a truss. The digital form allows insertion of photographic material collected during the survey as part of the documentation.

Figure 2: Different trusses

22. STRUCTURAL UNIT nr. 12					
22.1 ANALYSIS of the STRUCTURAL UNIT		Is the structural unit labile?		YES	NO
				x	
		THIS STRUCTURE IS LABILE: IT IS NECESSARY TO MODIFY THE RAFTER-POST- STRAINING BEAM CONNECTION IN ORDER TO AVOID LABILITY.			
22.2 ANALYSIS of STRUCTURAL ELEMENTS   	22.2.1 Rafter			int.	ext.
		Cross section	round		
			rectangular	x	x
			other:		
		Dimension (wxd): 18x20 cm			
		Decay:			
	22.2.2 Tie beam	Cross section	round		
			rectangular		x
			other:		
		Dimension (wxd): 25x25 cm			
		Decay:			
	22.2.3 Straining beam	Cross section	round		
			rectangular		x
			other:		
		Dimension (wxd): 25x25 cm			
		Decay:			
	22.2.4 Queen Post	nr. 2		int.	ext.
		Cross section	round		
			rectangular	x	x
			other:		
		Dimension (wxd): 20x20 cm			
		Decay:			

Figure 3: A section of the survey template

4.2 Evaluation of indicators

A summary of the results from the vulnerability analysis of each truss and of the elements connecting trusses along the three main areas or forming the corners indicates the following.

4.2.1. Structural typology

Most trusses are of simple king post type, with cross-sections of regular size in proportion to the span length. The three trusses on the central part of the C have struts. All these trusses may be graded with A/B. There are, however, two trusses with a layout unfit to support asymmetric vertical loads or horizontal forces, not counting on the albeit uncertain semi-rigidity of the joints. One such case is surveyed in figure 3. The statically insufficient situation of these trusses is graded D.

Transversally, trusses are linked with a single purlin per side, which is deemed insufficient [11] for the purpose, resulting in a C/D, which, all things considered, may also be assigned to structural typology in general.

4.2.2. Connections

Connections at carpentry joints appear rather critical from a seismic point of view. The main joints, at the rafter-to-chord node, have metal closures that are degraded and hardly effective (fig. 4). The notch is mostly shallow and roughly cut. The connection between corner elements is entrusted to metal elements that appear questionable in keeping the system assembled in dynamic conditions. A global grade D may be assigned.

4.2.3. Retaining system

At the outer wall, trusses are simply supported without any retaining element, which should be introduced to avoid possible sliding off in seismic conditions. The supports on the inside wall were not inspectable. The global grade is D.

4.2.4. State of the structure

The level of maintenance, and cleanliness, appears very poor (which is normal given the state of abandonment of the structure). In spite of that, only a small number of timber elements presents damage from environmental conditions. No refurbishing or strengthening interventions had been performed, the initial design has been maintained. The grade may be C/D, requiring action but with the possibility of a better evaluation with simple interventions.

4.2.5. Global versus partial evaluation

The final grade for the structure based on the above analysis is that of a very high vulnerability. It is worth recalling that the building used for this exercise has not been in use for long and in view of demolition. Some of the characteristics that have defined the vulnerability levels are, however, due to the original construction. The global grade could be significant in a comparison with similar structures. The detailed picture that emerges from the ensemble of individual grades actually describes criticalities and allows planning for their improvement.

Figure 4: (left) A corner joint; (right) Rafter-to-chord joint

5 PROPOSED INTERVENTIONS

The general picture of the vulnerability sources allows a quick estimation of the interventions to be performed and possibly of the associated costs. The objective is to reduce the vulnerability level to A/B.

For critical situations related to structural typology, first consideration goes to the two unstable trusses. Static adequacy could be obtained either adding a bracing element or strengthening the joints with metal bolts; the latter option has been assumed in this simulation.

In order to gain stiffness in the transversal direction, where a single purlin was deemed insufficient, different alternatives exist. Among these, cross-bracing of the roof pitches is often seen; alternatively, transversal stiffness may be increased with a layer of boards, here assumed 2.5 cm thick.

Substitution of the small number of decayed elements has been taken into account.

The application of bolts to avoid disassembly has been assumed for carpentry joints at the various locations, and primarily at the rafter-to-chord joint; an estimate of the necessary number of bolts is immediate, as well an evaluation of the costs; use of small diameter screws has been assumed at the chord toe to avoid brittle failure by sliding shear (figure 5); finally, suitably designed metal connectors were proposed for the roof corner elements.

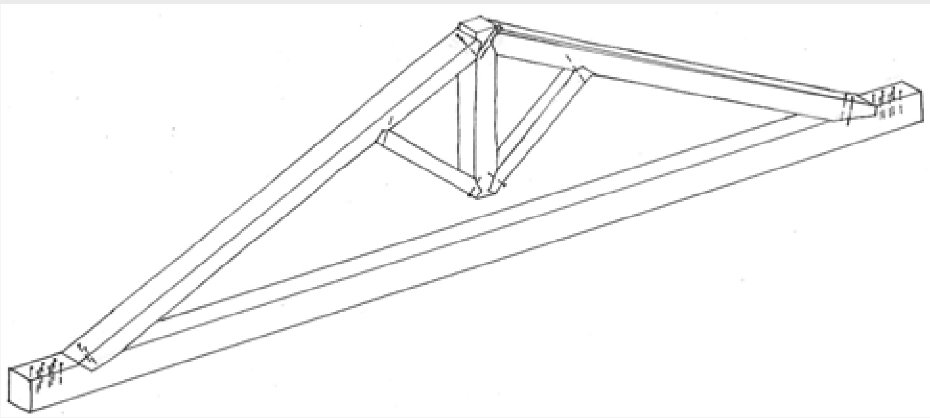

Figure 5: Metal connectors are applied at the joints to avoid disassembly and sliding shear failure

The support conditions need to be improved, adding also a metal anchor.

Finally, the roof cover must be repaired; although this is not a structural intervention, it is of primary importance to maintain structural performance. Similarly, in parallel with the seismic improvement of the roof structure and with its general refurbishing, nowadays thermal insulation would be compulsory. In a seismic behaviour evaluation, the increased masses, as well as the detailing, would have to be considered.

A preliminary dimensioning of these interventions has been performed in order to be able to estimate also the economic impact. This part is still in progress, with the objective to compare different solutions.

6 CHECKING THE EFFECTS: STRUCTURAL ANALYSIS

A numerical model of the roof structure has been developed assuming to have carried out the interventions for its improvement. A seismic analysis has been performed with reference to the response spectrum indicated by the design code for the location of the building. The response of the structure has appeared regular and all verifications were satisfied. Safety margins were relatively high. As the seismicity requirements at the building site were moderate, this result indicates that requirements are likely to be satisfied also for higher seismicity levels. This extension is in progress. This result indicates that the improved structure fully satisfies the seismic conditions. The class A/B hypothetically to be reached after the interventions may be confirmed.

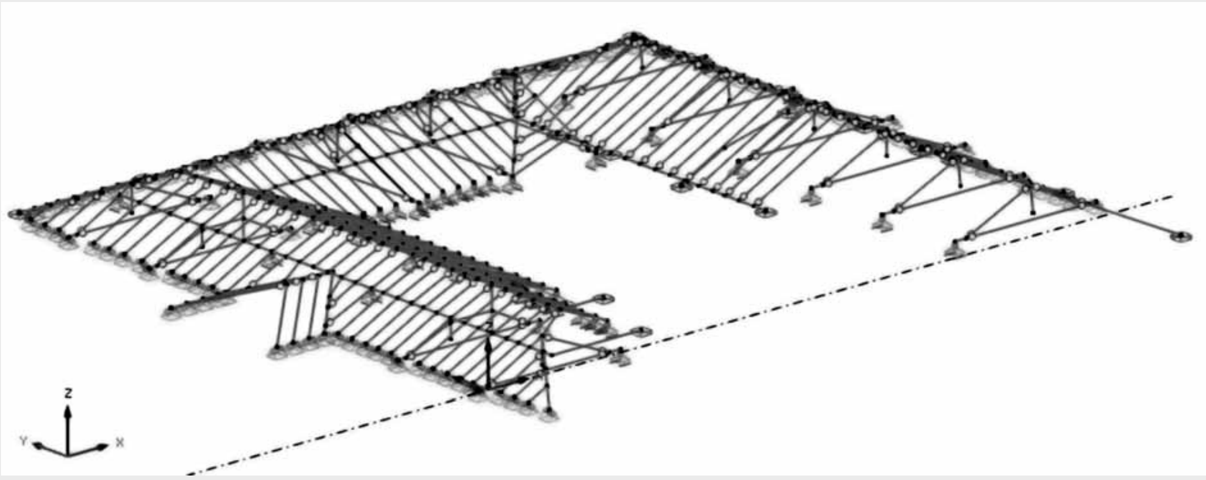

Figure 6: Model for numerical analysis

7. CONCLUSIONS

The application of the seismic vulnerability assessment procedure has resulted capable of indicating clearly and in an organized form the critical aspects of the structure and the interventions necessary for its improvement.

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