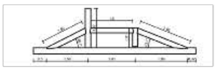
22. STRUCTURAL UNIT nr. 12					
22.1 ANALYSIS of the STRUCTURAL UNIT		Is the structural unit labile?		YES	NO
				x	
		THIS STRUCTURE IS LABILE: IT IS NECESSARY TO MODIFY THE RAFTER-POST- STRAINING BEAM CONNECTION IN ORDER TO AVOID LABILITY.			
22.2 ANALYSIS of STRUCTURAL ELEMENTS   	22.2.1 Rafter			int.	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:			
22.3 ANALISYS of the JOINT	**FOOT JOINT**			int.	ext.
	22.3.1 Rafter - Tie beam	Single step joint		x	x
		Double step joint			
		Reverse step joint			
			notch depth:	Few centimeters. External connection could not be inspected.	
		Tenon and mortise			
		Angle: ~ 23°			
		Decay:			
		Fasteners: heel straps, bolts…			
		other:			
	22.3.2 Tie beam - Wall plate				
		Halving joint			
		Dovetail joint			
		Simply supported			x
		Decay:			
		Fasteners: heel strap, bolts…			

Figure 1. Guided survey form for vulnerability assessment, software version.

Figure 2. Queen-post truss with potentially unstable layout.

Figure 3. Connections between king-post structures.

Figure 4. Irregular cross section of the rafter .

Figure 5. Biotic decay due to insects.

Figure 6. Wedges adopted to recover contact at the rafter (right rafter and purlin).

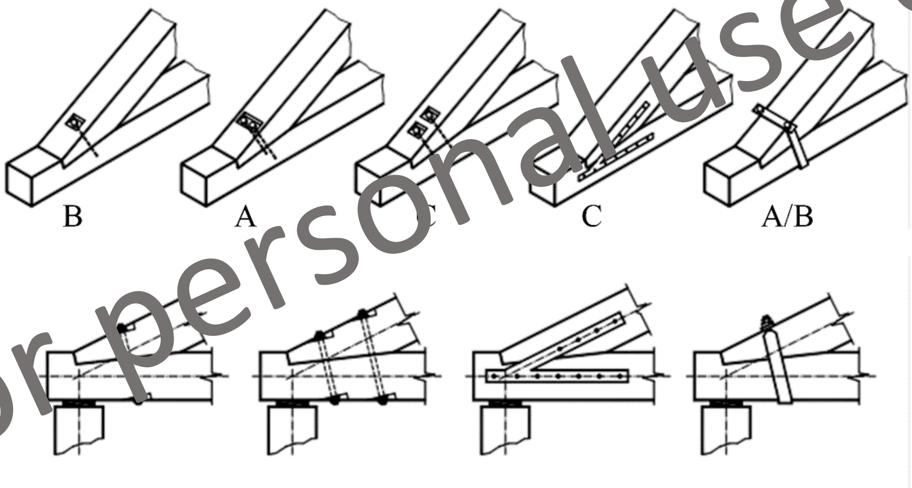


Figure 7 (a) Rafter-tie beam joint. Connection reinforced with metal heel straps. The head of the tie-beam is built-in and cannot be inspected; (b) Different types of joint reinforcements and vulnerability class (modified from Parisi and Piazza 2002).

Figure 8 - Collapse due to massive intervention substituting timber trusses with concrete products at Amatrice, Central Italy earthquake, 2016.

Figure 9. The roof structure analysed: (a) internal view (b) numerical model with main elements

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Figure 10. Detail of the roof structure.

Introduction

Methods for assessing the seismic vulnerability of buildings within risk mitigation programs were first developed in the 1980's, after the occurrence of devastating earthquakes in Europe (e.g. Friuli, 1976, and Irpinia, 1980, in Italy; Vrancea, 1977, in Rumania). Vulnerability studies aimed at sorting out the most significant features that condition the building response and at developing rapid assessment procedures to be applied to a building stock for a first screening of critical cases. Initially, evaluation criteria and practical assessment procedures were developed for residential masonry buildings, which were responsible for a large part of the seismic risk (e.g. Benedetti and Petrini, 1984; Sandi, 1986; Petrovski et al., 1985); later, other typologies have been considered, including cultural heritage assets such as churches and palaces (e.g. Lagomarsino and Podestà, 2004a, 2004b).

Studies and applications of vulnerability concepts have continued to date. In Italy, the recent public campaign for supporting the seismic improvement of the building stock with partial public funding opens new perspectives for vulnerability assessment and needs to be supported by a suitable framework at various accuracy levels. This is a strong motivation for reconsidering and renovating paradigms on which assessment has been based so far.

An important part of vulnerability studies concerns elements that are not strictly part of the building structure, yet may affect its response. The roof structures, which in traditional buildings are usually assemblies of timber trusses, have shown strong influence on the building behaviour. In a seismic event, a favourable outcome may depend on the capability of the roof structure to connect walls enhancing their collaboration, rather than impinge on them and trigger their failure.

In the assessment procedures for different construction typologies, consideration of the roof influence has been very synthetic, and often somewhat superficial, lacking a thorough exam of the roof structure and of its possible interaction with the wall system. Various factors contribute to the vulnerability of a roof structure and should be considered in the assessment. Here, the principal ones are examined and grading criteria are given, in order to supply a general framework for evaluating roof structures per se and in relation to the whole building.

The detail in which a vulnerability assessment may be conducted depends on the final objective and in part also on external circumstances, usually related to the possibility of actually performing a visual analysis more or less in depth. The assessment, for instance, may be performed:

- within a global assessment of a building;
- specifically for the roof structures to decide needs and priorities of intervention;
- to gather information on a specific roof structure as part of a database collection for listed cultural heritage assets;
- prior to planned restoration interventions, in order to shed light particularly on the expected seismic behaviour, which requires considering specific construction characteristics.

Each objective implies a different depth of investigation. The criteria and indications expressed in the following constitute a general basis, in view of formulating assessment procedures at different levels of detail. One such procedure, intended for the second case listed above, has been developed by the authors and is presented here.

The need to formalize specific criteria for the evaluation of timber roof structures stems not only from their constructional characteristics, governed by peculiar mechanical and physical properties, but especially from the fact that such structures were mostly built with reference to vertical loads, including the effect of wind that for common pent inclinations results in an almost vertical pressure or suction. Earthquakes activate structures mainly in the horizontal direction.

A standardized assessment procedure allows a more homogeneous and coherent evaluation among different cases as well as among different survey teams. Assessments may be advantageously supported by the use of pre-organized templates implemented on paper forms or with software systems. The former are a common choice for surveys, the latter allow an efficient organization of collected data and may provide more efficient guidance to the evaluation of the different features related to vulnerability. Some characteristics desirable in a system are outlined in the following, making reference to a developed prototype.

2. Damage and vulnerability in timber roof structures

Post-earthquake damage surveys have been the major source of information on the seismic behaviour of buildings and other structures. The difficulty of reaching roof structures in a seriously damaged building, especially in the presence of large amounts of debris,and the final state of a collapsed roof, which may suffer complete destruction because of brittleness of the material, may not allow to reconstruct reliably the failure path. Moreover, the minor importance that is traditionally attributed to these structures, always seen as secondary and temporary, leads to focus attention on other parts of a damaged building. Consequently, roof damage data have not been collected systematically . Some indications about vulnerability derive from known construction characteristics and material properties. A useful source of knowledge is scientific literature, with studies on structural identification of existing roof structures (e.g. Faggiano et al. 2018a, 2018b) and failure analysis (Tampone, 2016).

The possibility for the structure to resist shaking with little or no damage depends on:

- its structural scheme, a determinant issue for structures not specifically built for horizontal loads;
- the capacity of the cross sections to absorb safely the increase of internal actions that may result from the earthquake.

The structural typology and the member dimensions are, thus, important contributors in the vulnerability definition.

Connection of timber elements was traditionally performed with carpentry joints that skilfully transmit loads by direct contact. Often, they were supplemented with metal devices acting as a safety measure toward exceptional actions that may disconnect the assembly. Joints are a discriminating element in terms of suitable response. Their diversity and their correct realisation may condition significantly the structural behaviour. Joints are, then, another factor that qualifies vulnerability.

A frequent cause of severe damage is the loss of support, when the roof structure separates from the wall, sliding off and often engaging the structures below, slabs or vaults, in a progressive collapse. Therefore, a primary source of vulnerability resides in the design and quality of the supports.

Timber properties are highly susceptible to different conditions of environmental and biological origin. Additional alterations may derive from human action, for instance modifications performed in the lifespan of the structure. The current state of the structure, in its many folds, is another determining factor to be considered.

A vulnerability assessment procedure will necessarily comprise the exam and evaluation of these issues, to an extent that depends on the accuracy level required.

Wood characterization is usually of top importance. Although the determination of the species remains a step to be performed within general assessment procedures, it is not considered a primary factor in seismic vulnerability. It is an indirect one, affecting other issues like cross section adequacy or the behaviour in adverse climate conditions.

3. Definition of an assessment procedure

Vulnerability assessment requires both a thorough visual and instrumental analysis and an elaboration of the observations according to predefined criteria, making use of evaluation scales for classifying parameters, features, and conditions concerned.

Visual analysis is the first step to be performed and it is critical for creating the appropriate basis, in terms of data and information, for the subsequent assessment phase.

Survey sites are often in precarious environmental conditions, with great amounts of trash, dust and droppings, subdued light, and difficulty of access: a state that may hinder regular

operations. For this reason, a prescribed scheme for the operations to be performed should be used to avoid excessive emphasis on some aspects or disregard of others, ensuring a coherent and well balanced survey. A paper form with the sequence of items to be observed and data to be collected has been developed and subsequently implemented in a software version (Parisi et al., 2008, 2017) (Figure 1).
During inspection, all data and general impressions are collected (Cruz et al. 2015, Feio and Machado 2015, Kasal and Anthony 2004, Kasal and Tannert 2010).The proper vulnerability analysis is performed in a second step, because it requires to interpret the collected data with a global vision, evaluating those issues that have been recognized as significant indicators of the capability of seismic response, or vulnerability indicators.
In summary, the procedure amounts to:

- first step, on site: guided survey;
- second step, off-site: vulnerability analysis and classification.

According to section 2, a comprehensive assessment should investigate:

- the conceptual design and its realisation;
- the quality of connections;
- the retaining system, or roof-wall interface;
- the current state of the structure.

These points correspond to the indicators considered in the procedure.
Each of these items may be further subdivided pointing out different issues to be examined. The following sections offer a detailed description and reference criteria for each.

A fundamental question is the choice of a reference scale for grading and comparing the levels of vulnerability. Different choices may apply, depending also on the purpose of the survey, ranging from a yes/no outcome for a rapid decision in emergency, to a global numerical index, which allows to develop statistics from large scale surveys. An intermediate choice, adopted here, is to express grades with a linguistic variable. They may be subsequently transposed into a numerical value, after suitable calibration. Grading criteria are:

- Grades range from A to D through B and C;
- The value A corresponds to the minimum vulnerability of a structure designed, executed and maintained according to best practice, incorporating all the positive features in favour of seismic safety, comparable to a new code-designed structure;
- D corresponds to the highest vulnerability level, that is, a structure with serious deficiencies that should be promptly reduced by suitable interventions;
- B and C represent intermediate levels: B denotes situations not fully satisfactory but not requiring action in a short time; C indicates criticalities apt to evolve into negative consequences, for which an improvement should be considered.

This scale may be applied to the four indicators above, and to the different issues, or partial indicators, considered within them. Grading references and examples are in sections 5 to 8.
Grades highlight the criticalities of the structure and give a measure of their severity. Their plurality supplies a global picture of the seismic quality of the system. If a global index for the structure is needed, different ways of combining partial results may be proposed. These are commented in section 9.

4. The survey

A direct survey carried out simply by visual inspection or with the support of diagnostic tests and instruments is the kernel of any assessment procedure for timber roof structures (Dietsch and Koehler 2010, Riggio et al. 2014).

Before any other issue, a safe access to the structure must be guaranteed (UNI 11119:2004), with a safety check of the actual capacity of the elements to be accessed by inspecting personnel. It detects insufficient cross sections and the presence of decay by fungi, often indicated by wood colouring, which may abate the load bearing capacity.
Often, only a limited access is possible, so the extension of the survey should be indicated in the survey form.

In the spirit of a seismic vulnerability assessment, only simple, indispensable instruments are used. Besides tools to improve vision in dim light conditions, basic implements are measuring tapes and laser distance-meters to trace horizontal and vertical alignments, a camera to record images, a hammer and possibly a hygrometer. When more sophisticated exams are required, a Resistograph and similar devices are needed, considering that a comparison among tests of different type offers a general and more complete vision (Piazza and Riggio, 2008).

In order to organize the collected information, a reference system permitting to identify all the members with progressive numbering must be defined and reported in the form. For instance, for a roof structure covering a church, the direction along and across the nave would constitute a reference, as well as the left and right-hand-side with respect to the nave axis.

The first action is the characterization of the environment in terms of temperature and humidity: even though no continuous measures are usually taken, excessive values at survey time indicate risk of decay. As a reference, to avoid fungi growth, humidity must remain below 80-90%, a rather high value. Yet, the presence of water cumulated on surfaces and in cracks may generate the problem.

The subsequent steps in the survey procedure examine the different elements of the structure related to the indicators.

5 Elements for structural typology analysis

5.1 The layout

Examining the structural scheme, the first element to be considered is the basic structural unit and its connection to other units to form a three-dimensional roof structure. Good seismic performance is possible when stiffness and resistance are equally distributed in the main orthogonal directions: the degree of three-dimensionality is inversely related to vulnerability. In common construction, roof structures are seldom conceived as fully three-dimensional. Usually, a series of parallel trusses are transversally interconnected to form a spatial system.

Instabilities in the structural scheme, usually due to insufficient joint constraints, are identified first. They occur mainly in double-level, queen-post trusses (figure 2), with details probably inspired by examples in classic architectural treatises, which have influenced constructional practice contributing to their diffusion (e.g. Palladio A, 1570). It is worth noting that joints need to be observed accurately to establish the kind and level of constraint they may offer. Insufficiently constrained structures may be capable of supporting symmetrical vertical loads, resorting also to some joint semi-rigidity to respond to minor load deviations. The resisting system, however, is not adequate for asymmetrical vertical loads or for the horizontal forces generated by seismic action. This condition will correspond to a D.

Transversal secondary trusses supply good connectivity, classified with A. (Chesi et al. 2012). Often, the connection between trusses is simpler, with purlins and a ridge plate as in figure 3, sometimes with the addition of transversal struts, or diagonal bracings (Parisi et al. 2016). The most common situation presents two purlins per rafter, which may give satisfactory results if purlins and rafter are well connected: it would be graded up to A in the best conditions. Intermediate situations, mainly related to quality of connection, purlins cross section and regularity, are more difficult to grade and will range between B and C. When only one purlin per rafter is present, or more purlins with insufficient connection, the assembly is deemed too deformable in the transversal direction (C to D).

In the survey form, only the most frequent truss types are currently considered: coupled rafters, couples closed with a tie-beam, simple-post trusses, king-post trusses with struts, and double level queen-post trusses in various shapes. The truss type is usually related to the span it has to cover. Traditionally, up to 6-7 m, closed couple roofs are found; for higher spans, up to about 15 m, a king-post truss with struts is normally adopted; longer spans, up to 25-30 m, often covering public halls, usually require more elaborated systems, like a two-level, queen-post truss. A previous study comprising dynamic analyses of a large series of trusses differing in type, span, members size, quality and stiffness of joints, has shown that the empirical sizing rules of the constructional tradition combine correctly span lengths, minimum cross section sizes and structural layout also with respect to dynamic response (Chesi et al, 2012). For trusses of common size, the study identified three classes of vulnerability, A, B, C, associated to the values of the main design parameters. Classes can be assigned on the basis of geometric dimensions, observable by direct inspection. Table 1 offers guidance, reporting grades for truss schemes compatible with the span length. Trusses with under-dimensioned sections and errors in the conceptual design are classified as D.

Table 1 – Grade examples for structural typology

Three-dimensionality		Dimensions and type					
Structural scheme		Cross-Section	Span [m]				
Trusses in orthogonal directions	A	[cm×cm]	6	9	12	18	24
Parallel trusses with transversal bracings or struts	A-B	15×15	A	B	C		
Parallel trusses with at least 2 purlins per rafter	A-B	20×20		A	B	C	C
Parallel trusses with 1 purlin per rafter	C-D	25×25			A	B	B
Couple roof (no tie-beam)	C-D	30×30				A	A

5.2 Structural elements

The inspection of structural members estimates their adequacy in supplying the bearing capacity required for the increased stress level due to seismic action. Focus is on geometry and material properties. Existing structures often present generously dimensioned cross-sections that may accommodate such increase, yet specific considerations are due.

The strength strictly depends on the mechanical properties of the wood species and moisture content. In order to perform a correct recognition of wood species experience is needed. The investigation may be performed either at macroscopic level, recognising typical characteristics, or by microscopic analysis (Macchioni, 2010). The norm UNI 11118:2004 supplies a useful guide for wood species identification. Lacking this kind of information and for a rapid assessment, other factors like documentation of construction, maintenance reports and at least the species used in the area become a reference. Once the species has been defined, a corresponding strength and service class for new wood may be examined to obtain indicative values. The strength of members in an existing structure may be assessed by testing (e.g. Tannert et al. 2014, Kloiber et al 2015, Riccadonna et al 2019) or by visual grading; when their inspection is possible at least on three sides and one head, indications from UNI EN 11035-2:2010 assign a strength class on the basis of the position, number and dimensions of knots, smooth edges, cracks, slope of grain, and rings size (CEN EN 14081-1:2016). If the inspection requirements cannot be satisfied, an estimation is possible according to UNI 11119:2004, which, based on observed data, supplies allowable strength values and average values of elasticity modulus. Current codes for structural analysis and design (e.g. Eurocode 5:2014) refer to the use of values for limit states. A useful expression permits to pass from allowable stress to limit states values (Riggio et al., 2012).

Evaluation of the bearing capacity of a structural element requires measuring length and cross section, detecting possible irregularities along the length, as in figure 4, in order to identify its minimum cross section area (Lourenço et al 2013, Sousa et al 2014). Only off-site it will then be possible to define loads, perform structural analysis and check structural adequacy.

Wood decay, a major cause of section inadequacy, may be distinguished in biotic decay when caused by insects and fungi and mechanical degradation caused by excessive stress levels. Each wood species is more or less prone to biotic attacks (fungi, insects). The EN 350:2016 norm reports detailed references for the resistance of each species and element service class to borer attacks. Thus, in order to define the effective cross-section, it is necessary to check biotic factors that may reduce the element size (figure 5). The presence of fungi is strictly related to the humidity content of wood. Specifically, in timber elements a humidity percentage of 18-20% or greater constitutes an environment favourable to their development. If humidity is to be measured, electrical hygrometers operate exploiting the electrical properties of wood (EN

13183-2:2003). Their use is rather delicate, because many factors influence measures, from temperature to characteristics of wood elements, (knots, grain slope). More recent methods have been adopted, like infrared thermography and microwaves (Riggio et al. 2015), which along with more traditional ones, may be used also for detecting insects.

Mechanical degradation is intended as the damage produced by excessive stress levels. For an accurate quantification of the residual effective cross section and of the extension and position of the lesion, different diagnostic tools (Resistograph, Pylodin, etc.), together with ultrasonic and thermographic tests may be used.
Excessive deformations, compared to reference values in design, may be associated to various causes, including mechanical degradation. The deflection with respect to the undeformed shape may be measured, possibly with a simple stiff ruler, and compared to the element length.
Excessive deformation could derive from a connection that lost effectiveness. Sometimes the presence of wedges applied in correspondence of a significant deformation indicates an intervention carried out for remediating a lacking connection (figure 6).

6 Traditional carpentry joints

Type, quality and effectiveness may vary strongly in carpentry joints. In seismic conditions, two features qualify their adequacy:

- the capability to maintain the assembly during cyclic conditions, when compression between the joined elements may temporarily decrease;
- the post-elastic behaviour, with the aim at sorting out possible brittle failure modes.

In recent times, considerable research effort has been devoted by different groups to the characterization of carpentry joints and to the definition of suitable retrofitting interventions (e.g. Branco et al 2011, 2017; Moşoarcă and Gioncu 2013, Franke et al 2015, Šobra et al 2016).
Indications for evaluating adequacy for different types of joints have been derived here mainly from a research program on their monotonic and cyclic behavior in the elastic and post-elastic field (Parisi and Piazza, 2000, 2002).

Traditionally, carpentry joints, which commonly transmit forces by compression and friction, were equipped with binding strips or other metal devices to avoid accidental loss of contact. This condition may occur under an earthquake. Unrestrained or ineffectively restrained joints may undergo disassembly; they are at the worse side of the vulnerability scale and are classified as D. Partial degradation or an imperfect realisation of the connection may be associated to intermediate vulnerability levels, indicating the need of an improvement.
Brittle failure modes are equally to be avoided. Reinforced joints with excessive stiffening, like metal cages or cuffs that will limit minor movement and deformation are critical. Experimental testing has shown that risk may derive also from a limited amount of connectors, when they are positioned in a pattern that prevents or limits rotation (figure 7). Identification of possible sources of brittleness requires particular care. Sliding shear at the toe of a rafter-to-chord joint in a truss is another cause of brittle failure. Short toe areas with low rafter and chord skew angle may result in sliding failure under seismic action, incrementing the vulnerability of the assembly. Table 2 gives guidance for the rafter-to-chord connection and may be a reference for similar situations.

Table 2 – Guide for joint assessment

Reinforcement type		class
Unreinforced, no provisions for disconnection		D
Reinforced, with		
	1 bolt	B
	$\geq$2 bolts, small diameter,	
	- Permitting minor rotation	A
	- Blocking rotation	C
	Stirrups	C
	Binding strip	
	- fixed	B
	- adjustable	A
	Steel cuff	D

7 The supports

At the truss-to-wall interface, the chord extremes may be:

- supported at the top of the wall, or within a niche;
- built-in.

The restraint may be assessed by the degrees of freedom that remain unlimited: translation parallel to the tie-beam axis, lateral translation, and rotation of the entire truss around the tie-beam axis, often observed in earthquake damage surveys. The effect of unrestrained or poorly restrained rotation may be counterbalanced by bracings in the longitudinal direction of the roof.

For displacements parallel to the beam axis, tending to drop the truss from the support, examples of good construction techniques may be found, with the beam anchored to the wall base or, according to some constructional tradition, with metal elements nailed to its sides and retained at the wall exterior. When the beam end is enclosed in the wall without possibility of inspection, assessing the extension of the restrained area is impossible and the probability of timber decay due to humidity without ventilation is realistic. The possibility of unseating, and the related vulnerability, must be considered. Table 3 gives tentative grading indications.

Table3 - Classification of supports

Support type	class
No restraint and insufficient extension	D
No restraint, extended support area	C-D
Free rotation without bracings	C
Free rotation, with bracings	A-B
Fixed end, with external restraints, inspectable	A
Fixed end, partially or not inspectable	B-D

8 State of the structure: maintenance and interventions

This vulnerability indicator collects different issues, related to the situation of the timber structure. The main ones may be synthetised in the level of maintenance that affects the current quality of the structure, and in the modifications to the original layout performed in its lifetime.

Poor maintenance plays a significant role. The state of the roof cover should be checked, because rainwater entering from gaps will rapidly deteriorate the underlying structure, even if such effect is not yet observable. The assessment itself would soon loose significance. A possible reference for maintenance grading could be A for good state and frequent, preplanned inspections, D for evident serious lack of maintenance and inspections, with B and C intermediate situations from observation and from information on inspection intervals if available (Table 4).

Table 4 – Grade reference for state of the structure

Item		Class range
maintenance		
	roof cover damage	A none B initial C evident D extended
	general check/ maintenance	A recent/regularly planned B recent/not planned C irregular D none
decay		

	element sections reduction	B-D
	decay of joints	B-D
Previous interventions		
	modification of elements	A (improved), B-D
	With increased loads	C-D

Alterations of the original structure may have been performed for repairs, for change of use of the building, or for eliminating fabrication errors, not rare in construction mostly based on heuristic knowledge. Modifications may reduce or increase the original vulnerability. The variety of situations prevents the formulation of standard classification rules, leaving decision to the sensitivity of the surveyor. Current research is analysing a series of case studies to point out some typical situations also in quantitative terms. In general, it may be stated that strengthening interventions implying a harsh increase of mass and stiffness at roof level induce high seismic vulnerability. For instance, interventions implemented in Italy in the last part of the 20th century to stiffen the roof, casting deep concrete ring beams and laying a brick and concrete slab over the timber structure, or substituting trusses with prefabricated industrial products (figure 8), produced significant damage in recent earthquakes (e.g. Binda et al, 2010). Some cases of milder interventions tending to increase connection without abrupt changes of mechanical properties have yielded positive results.

9. Global evaluation

Statistical or risk management reasons may require a global vulnerability measure.
A translation from linguistic to numerical values has not been studied so far. One way of merging the individual results of the indicators into a global judgement is to considers the effects of vulnerability, in terms of possible damage consequences. If a high vulnerability in an indicator may result in extended damage to the building (e.g. insufficient supports yielding progressive collapse) the global index would be D; C would correspond to the risk of significant damage to the roof, with possible localized damage to the building; B to limited damage to the truss system only. Like for other assessment procedures, for instance in campaigns for seismic damage and building accessibility assessment, the final decision relies on the surveyor, supported by the procedure results. The suggested criterion has appeared useful in tests and examples so far. Yet, for roof structures that are listed as cultural heritage, where a strict conservation requirement holds, a different scale of values may be necessary.
For assigning a grade to an indicator that refers to multiple elements, the frequency of a result for the lot may be considered. For instance, in grading structural elements, or joints, if the grade is B for their majority, except for some C's, a global value of B could be assigned, issuing a warning. Special consideration, however, should go to D values and their consequences.

10. IT extension

Paper forms become cumbersome to bring along and impractical to fill especially for large and complex roof structures. The fast development of computer hardware of small dimensions and weight is overcoming this inconvenience. Mobile technology has been proposed for assessment surveys in other structural cases (e.g. Riggio et al 2015, Riggio et al 2018).

A software tool with the same survey procedure as the paper form has been defined, offering several advantages, including data digitalization directly on site, the possibility of taking and inserting pictures, and in general a more efficient data collection and survey management. A first prototype has been implemented on a notebook, to be completed and transposed to a tablet or smartphone as future development (Parisi et al, 2017).

11. Vulnerability assessment of a 20th century timber roof structure.

The criteria and the assessment procedure have been applied in several cases, also for calibration purposes (e.g. Parisi et al 2010). A recent application concerned the roof structure of a large masonry building, an alpine hotel, dating back to the early 20th century and currently in disuse. The roof structure is composed of 13 trusses with slightly different layout, covering and L-shaped area, according to the scheme of figure 9. Spans range between 7 and 8 m, with spacing between 3.30 and 4.40 m (figure 10). Survey data for structural units, elements and connections have been collected in the relevant forms (e.g in figure 1). The global vulnerability was deemed high, D, because two of the trusses resulted insufficiently restrained to lateral loads (structural typology D). Additionally, a small number of elements had section reductions due to decay, and new metal connectors were needed for most joints to avoid disassembly. A plan of interventions, with their basic design, was proposed to bring the structure to very low vulnerability. A structural analysis carried out in the assumption that interventions had been performed showed full satisfaction of seismic response requirements.

12. Conclusions

A long reseach program on the role of timber roof structures in the seismic behaviour of masonry buildings has highlighted the factors that affect their seismic vulnerability and often that of the entire structural compound. A procedure to assess the seismic vulnerability of roof structures was defined. The procedure, currently suited for structures composed of trusses, will require improvements as well as extension to a larger number of typologies. Still, in applications and case studies performed so far it has proven useful to focus attention on the seismic qualification of these structures, mainly seen, and originally conceived, with regard to vertical loads.

Acknowledgements

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Figure captions

Figure 1. Guided survey form for vulnerability assessment, software version.

Figure 2. Queen post truss with potentially unstable layout.

Figure 3. Connections between king post structures.

Figure 4. Irregular cross section of the rafter.

Figure 5. Biotic decay due to insects.

Figure 6. Wedges adopted to recover contact at the rafter (right rafter and purlin)..

Figure 7 (a) Rafter-tie beam joint. Connection reinforced with metal heel straps. The head of the tie-beam is built-in and cannot be inspected; (b) Different types of joint reinforcements and vulnerability class (modified from Parisi and Piazza 2002).

Figure 8. Collapse due to massive intervention substituting timber trusses with concrete products at Amatrice, Central Italy earthquake, 2016.

Figure 9. The roof structure analysed: (a) internal view (b) numerical model with main elements.

Figure 10. Detail of the roof structure.

Table titles

Table 1 – Grade examples for structural typology

Table 2 – Guide for joint assessment

Table 3 – Classification of supports

Table 4 – Grade reference for state of the structure