Advanced Materials Research Vols. 133-134 (2010) pp 741-746

doi:10.4028/www.scientific.net/AMR.133-134.741

Rehabilitation of Timber Structures and Seismic Vulnerability: a Case Study

PARISI Maria Adelaide[1,a], RIGGIO Maria Paola[2,b], TARDINI Chiara[1,c] and PIAZZA Maurizio[2,d]

[1] Politecnico di Milano, Milano, Italy

[2] Università degli Studi di Trento, Trento, Italy

[a]parisi@stru.polimi.it, [b]riggiom@ing.unitn.it, [c]tardini@stru.polimi.it, [d]maurizio.piazza@ing.unitn.it

Abstract Synthetic methods for the diagnosis of structures and particularly for their vulnerability assessment rely on simplified calculations and visual inspection. Their effectiveness strongly depends on an accurate calibration of the procedure by which data are collected. A recent methodology for the seismic vulnerability assessment of timber roofs in historical buildings has been applied to the Thun Castle during a study for its rehabilitation. The purpose was twofold: testing and calibrating the procedure on a heritage structure and estimating the capability of the roof structure to resist seismic action, as required in a zone of low but not negligible seismicity.

Keywords: Timber roof, timber structure, seismic vulnerability, heritage building, case study

Introduction

Conservation of the timber roof structures that have been traditionally used for covering masonry buildings not only is justified by the desire to preserve the cultural heritage associated with them, but seems also to be in many cases an expedient solution from a technical point of view. It is well known that the radical substitutions of the timber roofs performed in a recent past when refurbishing buildings, often with the intention to upgrade their seismic resistance, have yielded poor results in practice. The new elements, produced with different materials and technology and having generally higher mass and stiffness, enhanced the weakness of the masonry to which they were connected. Often they induced, rather than avoiding, seismic damage or collapse.

This outcome, which had been observed already in foregoing seismic events, has become particularly evident in the L'Aquila, Italy, earthquake of 2009. The roof structures have been very influential on the general response of the building, either acting as a suitable connection between the underlying walls and fostering a unitary response or, vice-versa, generating devastating thrusts and pounding effects. Two aspects were particularly evident,

- the inadequacy of very heavy interventions on roofs, including their inappropriate substitutions,
- the good behavior of many older timber structures, that in some cases had been improved with light interventions in order to eliminate some constructional deficiencies.

These observations further confirm the need to develop methods for assessing the seismic vulnerability of existing timber structures. Recently, one such methodology was proposed (Parisi et al. 2008a) and developed (Chesi et al. 2008, Parisi et al. 2009, 2010). The associated procedure, as customary in synthetic methods for structural diagnosis, relies on visual inspection and simplified analyses. This procedure, summarized in the next section, consists of two steps. The structure is first examined in order to gather data according to a standardized sequence. In a second step, the information collected is used as the basis for evaluating a series of specific vulnerability indicators.

The effectiveness of synthetic methods strongly depends on a clear definition of the field of application, i.e. of the structural typologies for which it is appropriate, and on the possibility and extension of its calibration. The above mentioned procedure focuses particularly on gable roofs supported by truss structures. A number of roof trusses that were of common type and well within the field of application had been examined by the authors as testing cases.

The occasion for applying the procedure to a heritage case study was offered by the rehabilitation now under way of a castle in the Trentino region, Italy. Castel Thun is an imposing building dating back to the 14th century. The timber roof trusses of the Loggia dei Cannoni (cannons loggia), in particular, were to be subjected to a very precise study of the geometry, of the characteristics of materials, of the details and state of conservation of the joints. Although the area where the castle is built is characterized by low seismicity, considering and possibly improving the seismic resistance of the structures would be required during a general rehabilitation program. A vulnerability assessment of the loggia roof structure was, therefore, performed with the double purpose to

- test and calibrate the procedure on a significant case study, and
- define the safety level of the structure toward seismic and, generally, exceptional actions.

Interesting observations stemmed from this work on both these aspects, going beyond the particular case studied. The results are discussed in the following sections.

Vulnerability Assessment Method

A low-vulnerability roof structure should satisfy a series of requirements (Parisi et al. 2008), namely,

- have all thrusts restrained;
- be effectively connected to the supporting walls;
- have a conceptual design capable of standing horizontal loads and offer a comparable capability of response in the different directions;
- be endowed with suitably reinforced carpentry connections that would avoid both disassembling and the development of brittle behaviour,
- be dimensioned with element cross-sections sufficient to accommodate the stress increase due to the exceptional action, and
- be in good maintenance conditions.

The vulnerability assessment procedure consists in two steps:

- The structure layout and details are first examined according to a standardized sequence. Data regarding geometry, details, materials, and state of conservation are collected by filling a form. Guidance for compilation is offered in the form by multiple-choice answers and images. When necessary, each item to be examined is developed in the form in a tree-like structure, with branches detailing different aspects to be considered. The collected information is intended to probe particularly into those features that may affect the seismic response, but gives as well a detailed description of the general conditions of the structure.
- In the second step, this information is used as the basis for evaluating a series of specific vulnerability indicators that express and quantify the requirements listed above (Parisi et al. 2010).

In order to give a measure of the weak points of a structure or of its inconsistencies, a rating is expressed by assigning each examined indicator to one of four classes, from A to D, where A corresponds to the lowest vulnerability, i.e. to a satisfactory condition, and D to a high-risk situation, B and C being the intermediate values. A first version of reference tables has been developed describing the rating for each indicator (Parisi et al. 2010). At present, at the end of the process no general vulnerability value or class is combined or assigned to the structure as a whole, yet a global vision of the situation is obtained by considering the criticalities resulting from the analysis. Once the vulnerability has been analyzed, the detailed information gathered on the structure may be the basis for proposing possible strengthening strategies.

The Case Study: the Thun Castle and the "Loggia dei Cannoni"

The Thun Castle is one of the most remarkable monuments in the Trento province, Italy (Guatelli 1929; Botteri Ottaviani et al. 2007). In the 16th century the original gothic castle was converted into a more comfortable dwelling and, as a consequence of the development of the artillery weapons and of the ballistics science, new defensive walls were built in order to repel cannon attacks. The "Loggia dei cannoni" dates from this period: it was conceived as a covered way, in the innermost wall, for arms shielded from inclement weather. It is a rectangular space measuring 42.5 meters by 8.50 meters, closed, on the northern side, by a stone masonry wall, 110 cm thick, and framed, on the opposite side, by a stone colonnade, as in Fig.1. The Loggia connects the two flanking towers, called "prison towers" (torri delle prigioni). The "escutcheon door" (porta blasonata, year 1541) is the entrance from North, accessible by a drawbridge. A winding staircase leads to a vaulted rock-cut basement. The timber roof was rebuilt in 1926. It consists of ten timber trusses spaced at a mean distance of 4.10 m. The trusses rest on the one side on an architrave, composed by timber plates resting on the stone columns, and, on the other side, directly on the masonry wall, without the interposition of wall plates. Tie-beams are tenoned to the architrave plates. The principal rafters support one purlin at each slope. They are connected to the tie beam and to the post either with plain butt joints or birdsmouth joints assembled with nails. The post is tenoned to the tie beam and, in some cases, iron straps are also present. The timbers used for the trusses are roughly cut, therefore their geometrical features are very variable and irregular. Ranges of cross-sectional size (b x h) are: 15÷25 x 18÷30 cm (rafter), 16÷36 x 21÷41 (tie-beam with rectangular cross section). The wooden species used for the roof are larch (*Larix decidua* Mill.) and spruce (*Picea Abies* Karst.). Because of the technological characteristics of the timbers, many elements are damaged by insect attacks, in the sapwood portions. Some tie-beams are rotten, at the connection to the wall. Mechanical damage occurred in critical areas which were already damaged by biotic attacks. In winter 2009, one of the trusses partially collapsed after an exceptional snowfall. After the accident a comprehensive investigation campaign of the roof was undertaken followed by the restoration design and intervention (Massari et al. 2010).

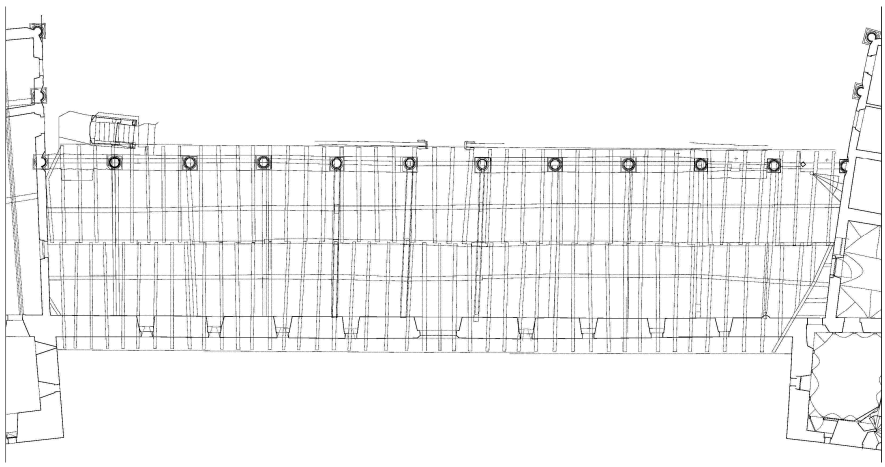

Figure 1: Plan of the Loggia at the roof level

The Local Seismicity

Castel Thun is in the municipality of Ton. The level of local seismicity is low but not negligible according to national seismic regulations. An elastic response spectrum with 475 years return period (Fig. 2), which may be considered an international reference spectrum, was obtained from national seismicity data, assuming a type B soil according to national classifications equal to those in Eurocode 8 (EN-1998-1). The maximum spectral acceleration is 0.173 g. Special rules apply to the castle, being classified as monument. Its condition toward seismic action needs to be assessed, and the effects of possible strengthening interventions need be demonstrated as improvements of the original seismic response, although no compliance to the seismic action to be assumed for newly designed buildings is required.

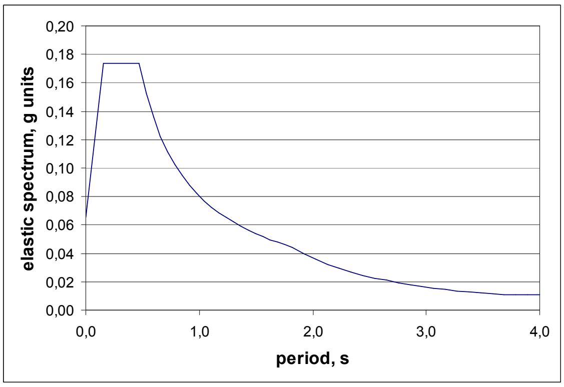

Figure 2: Response spectrum for horizontal acceleration at Ton

Vulnerability Assessment

Fig. 3 shows the structure concerned. The collection of data and information on the structure was the first step in the vulnerability assessment. Being performed by surveyors who were not the original developers of the survey procedure, this operation gave also some interesting feedback on the survey form (Fig. 4) that could be modified accordingly for greater clarity. Additionally, some points that had not been originally considered or sufficiently expanded and would not cover situations that occurred in the case examined stood out and brought to further modification. The most significant additions were related to the irregularity of member profiles varying along their span, the presence and type of previous strengthening interventions, and the need for indicating the quality of workmanship. The structure in exam was affected, indeed, by several irregularities and its quality was rather poor.

Figure 3: The Loggia, from east

Summarizing the results from the exam of the 10 trusses and of the longitudinal members, as to the trusses,

- truss elements had cross sections differing in size, aspect ratio and, at times, shape from truss to truss, but generally they were not insufficient;
- the fabrication of carpentry joints was rudimentary;
- the joints of rafters to tie-beams were mostly of the birdsmouth type; yet some nodes, (Fig. 5), had no indentation and the connection was based only on friction and on a limited number of nails; no other metal connectors had been applied, resulting in an unreliable assemblage;
- a similar situation was found at the connection of posts and rafters;
- a tenon - mortise joint connected the posts and tie-beams; some of the joints were closed with metal straps, loosely connected and intentionally inactive in normal working conditions.

21.2 TRUSS n° 1 - JOINT ANALYSIS				
			l	r
21.2.1Rafter - Tie beam	birdsmouth joint		x	x
	double step joint			
	reverse birdsmouth joint			
	notch depth:	3 cm on semicircular tie-beam		
	tenon and mortice			
	Skew angle: ~ 30°			
	Decay:			
	Metal connectors:	nails		
	Other:			
21.2.2 Tie-beam - Wall plate (left)			l	r
	Half depth		x	
	Dovetail			
	Other: tenon and mortice		x	
	Decay:			
	Metal connectors:			
21.2.3 Post - Tie-beam	Open joint			
		tenon and mortice		x
		stirrup		
		bolted joint		
		laterally restrained within a double tie-beam		
		double tie-beam fixed		
	Restrained	timber keys		
	Other:			
	Decay:			

21.1 TRUSS n° 1 - MEMBER ANALYSIS				
21.1.1 Rafter			l	r
		circular		
		rectangular	x	x
	Section	other:		
	Dimensions (bxh) cm:		20x23	25x21
	Decay:	local from insects, local from mushrooms at the tie-beam right joint		
21.1.3 Tie-beam		circular		
		rectangular		x
	Section	other:		
	Dimensions (bxh) cm:			30x21
	Decay:	extended insect attack in the sapwood		
21.1.4 Post	n°			1
		circular		
		rectangular		x
	Section	other:		
	Dimensions (bxh)cm:			29x37
	Decay:	from insects		

Figure 4: Example of form compilation

At the supports,

- at the northern wall, tie-beams are built-in. The rafter to tie-beam node, however, is at a distance from the support, causing a bending moment on the wall as may be seen from damage in Fig. 5.
- on the opposite side, trusses are tenoned into a timber wall plate, which has a low degree of longitudinal continuity being formed by poorly connected or unconnected parts.

As to other longitudinal elements,

- the ridge beam and the purlins, one per rafter, are, again, of rather irregular shape; above the purlins, common rafters support longitudinal timber plates forming the pent plane. The effectiveness of the connection of all these elements to form a collaborating system with the trusses rather than just loading them is unknown, but very likely modest given the general quality of the assemblage.

For the second step of the procedure, vulnerability indicators related to structural typology, carpentry joints, the condition of the supports, and the current state of the structure have been considered.

For the structural typology indicator, various aspects are rated: no unrestrained thrusts are present (A) and the typology and number of the trusses is correct for the span covered (A); yet, the low number of purlins and the uncertain contribution of other elements in providing connection would make the whole structure deformable in the longitudinal direction and sensitive to such component of ground motion, with a risk of pounding of the ridge beam into the tower walls. The rating for this typology aspect was, therefore, C.

As to carpentry joints, the absence of metal devices preventing disassemblage under seismic action would rate them as highly vulnerable, D, even without need to consider all the other serious deficiencies commented above.

The situation of supports seems particularly critical, because their conditions point to a possible collapse mechanism. In case of loss of support from a column loosing stability under horizontal forces, the segmented wall plate very likely would not be capable of redistributing loads to the remaining columns; one or more trusses, missing one bearing, would suddenly cantilever out of a wall that shows signs of damage already in the current conditions, with almost certain collapse of the truss-wall system. The rating is D.

The current state of the structure shows decay that is mostly localized in different spots and a general state of poor quality and maintenance, corresponding to a C rating.

The study summarized here has shown that the timber structure of the Loggia has a comparatively high level of seismic vulnerability, but has also indicated the critical aspects originating it. These causes of vulnerability could be mitigated with limited but well-addressed interventions.


Figure 5: Truss supports; (left) with wall plate over a column; (right) into the northern wall

Conclusions

The seismic vulnerability assessment of a historical roof structure, performed with a recently proposed procedure, has pointed out critical aspects of the structure that could be reduced with suitable interventions and, at the same time, has given indications for improving the assessment procedure itself. The use of a systematic procedure in the survey has proved useful to focus attention on aspects related to the seismic response of these timber structures that are mainly seen, and were originally conceived, with regard to vertical loads.

Acknowledgements

The authors wish to acknowledge the *Alta sorveglianza Soprintendenza Beni architettonici* P.A.T. (S. Flaim, M. Cunaccia, M. Favero, V. Barbacovi); for the geometric survey the group coordinated by G. Massari (M.C. Bonora, F. Luce, C. Pelegatta, K. Svaldi, F. Avanza, L. Mattei). The second author was supported with a post-doctoral P.A.T fellowship on digital technologies in timber restoration (DIGITimber). Partial support from the Reluis-DPC Project, part 2, is gratefully acknowledged.

References

[1] Botteri Ottaviani, M, Dal Prà, L, and Mich E (2007). "*Arte e potere dinastico. Le raccolte di Castel Thun dal XVI al XIX secolo*", Provincia Autonoma di Trento.
[2] Chesi, C, Parisi, MA, Tardini, C (2008). "Concezione strutturale e risposta sismica delle strutture lignee di copertura," *Ingegneria Sismica*, Patron Editore, 3, 36-45.
[3] EN 1998-1 (2004). *Eurocode 8, Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings*, CEN, Brussels.
[4] Guatelli, E (1929). "Il castello di Thun", *La lettura* XXIX N. 8, 1 August 1929.
[5] Massari GA, Riggio M, and Gadotti F (2010). "Respecting the diversity. The timber roof of the "Cannons Loggia" in the Thun Castle (Italy)," in *Proc. SAHC2010*, Shanghai.
[6] Parisi, M A, Chesi, C, and Tardini, C (2010). "Seismic vulnerability indicators for timber roof structures," in *Proc. of the joint 9th US National and 10th Canadian Conference of Earthquake Engineering*, Toronto, July 25-29, 2010.
[7] Parisi, M A, Chesi, C, Tardini, C, and Piazza, M (2008). "Seismic vulnerability and preservation of timber roof structures," in *Proc. SAHC08*, Bath, 1253-1260.
[8] Parisi, M A, Chesi, C, Tardini, C, and Piazza, M (2009). "Traditional Timber Roof Structures: Seismic Vulnerability Assessment and Preservation," in *Proc. Prohitech09 Conf.*, Rome, 391-396.