Effectiveness of Seismic Improvement of Monumental Heritage

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SUMMARY:
New guidelines for seismic improvement interventions on monuments and heritage buildings were issued in Italy in 2011. Such guidelines are characterized by the introduction of a procedure for evaluating the effects of interventions in terms of the resulting increase of nominal life of the structure. The procedure makes reference to the description of the state of the structure in terms of damage mechanisms. In the work proposed here, the application of this recent procedure to a particular case is the occasion for a study of its sensitivity to the values of the vulnerability parameters adopted. The case examined concerns a church located on a hill crest in the subalpine region of northern Italy, in a low-to-moderate seismic area. The application of the procedure has permitted remarks on the evaluation both of the vulnerability indices associated to the different damage mechanisms and of the reduction of risk consequent to the interventions.

Keywords: seismic improvement, vulnerability, heritage structures

1. INTRODUCTION

Protection of the cultural heritage from seismic damage requires the development and implementation of interventions that are non invasive and effective at the same time. Seismic improvement indicates the case of interventions aimed to generically increase the capability of responding to seismic actions and suitable for the cultural heritage, versus seismic strengthening, pertinent to common buildings and aiming at restoring the same level of response of a new structure. The concept of seismic improvement has now been widely accepted as the correct approach to the problem of enhancing the seismic resistance of the monumental stock.

Guidelines for seismic improvement interventions on masonry monuments and heritage buildings have been recently issued in Italy (2011). Such guidelines are characterized by the introduction of a procedure for evaluating the effects of interventions in terms of the resulting increase of nominal life of the structure. In this way, it becomes possible, through a simple procedure, to express the vulnerability level of the structure by means of a numerical value. The use of such parameters allows, on the one side, to have a comparative view of the situation of a group of buildings in terms of their exposure to the seismic risk; on the other side, it makes possible, for a specific structure, to evaluate the reduction of the vulnerability level following an intervention of seismic improvement.

The new procedure is now undergoing extensive application to different cases; this gives the opportunity to verify its stability and reliability in relation to the definition of the input parameters, which are deeply affected by personal judgement. In this work, the guidelines are applied to the specific case of a country church located in the north of Italy, for which an intervention has been designed, with the purpose of both increasing the seismic resistance and, at the same time, preserving the building historical value. The application provides an example of the new method for the numerical characterization of vulnerability and also a discussion on its sensitivity to the values of the parameters adopted in the study.

Figure 1. Madonna di Monte – Global view

2. VULNERABILITY EVALUATION: BASIC CONCEPTS

From the analysis of thousands of churches which suffered damage from earthquakes in the last few decades, it was possible to recognize that, in many cases, local collapses occur due to the lack of equilibrium of a limited portion of the structure. In this way, it has been possible to define a number of typical local collapse mechanisms, which have provided a reference tool for both the description and the analysis of the seismic damage to churches and palaces. In the specific case of churches, 28 basic mechanisms have been codified, which have been adopted also in the recently issued guidelines for vulnerability evaluation.

In the same spirit of this classification, it has been recognized that local interventions are often suitable in order to achieve seismic improvement. A global vulnerability evaluation can therefore be based on an evaluation of the specific mechanisms before and after the restoration intervention.
The new procedure which is discussed here makes also reference to the concept of the nominal life of the structure which, as it is known, can be put in relation with its seismic safety. In the specific case of monumental buildings, the concept of a reduced nominal life can be introduced, interpreted as a period of time after which a new verification of the structural conditions will be necessary; improvement interventions, not invasive and compatible with preservation principles, might take place as a consequence.

In line with the principles adopted by modern seismic codes, the structure nominal life can be related to the seismic motion intensity through the earthquake return period and the exceedance probability concept. In the case of monumental buildings, the SLV (life protection) limit state, associated to a 10% exceedance probability, is meaningful as it is related to both human and structural safety. In the following, the details of the procedure for vulnerability evaluation are recalled.

3. VULNERABILITY EVALUATION: THE PROCEDURE

In this procedure a vulnerability index is attributed to each mechanism that may be recognized significant for the structure. It measures the current situation of the structure toward developing such mechanism. A global vulnerability index, combined from basic individual indexes, is then associated to a peak ground acceleration value. From this, the relevant return period and finally the nominal life of the structure are computed. The possibility to include the presence of provisions for seismic protection in the evaluation of vulnerability permits to compare the nominal life in the original conditions and after improvement.

Specifically, the procedure goes through the following phases:

1 – Selection of the local collapse mechanisms which are meaningful for the case examined; some of them might be not applicable to the case. Each mechanism is then identified through the number of the elements providing seismic protection and of the vulnerability indicators, extracted from a specific list associated to the mechanism. Both numbers have to be modified by an efficiency factor, ranging from 0 to 3. The mechanism global vulnerability index depends on the difference between the two indexes according to the following expression:

$$i_V = \frac{1}{6}\frac{\sum_{k=1}^{28}\rho_k\left(v_{ki} - v_{kp}\right)}{\sum_{k=1}^{28}\rho_k} + \frac{1}{2}$$

where: ν_{ki} is the vulnerability index, ν_{kp} is the protection index and ρ_k is a weight factor (in the application presented here a value of 1 has been always adopted).

2 – From the vulnerability index the maximum ground acceleration is obtained as:

$$a_{SLV} = 0.025 \cdot 1.8^{5.1-3.44 \cdot i_v}$$

which applies to the Italian territory in relation to the SLV limit state.

3 – The earthquake return period is obtained as:

$$T_{SLV} = T_{R1} \cdot 10^{\log(T_{R2}/T_{R1}) \cdot \log(a_{SLV/}/F_C a_1)/\log(a_2/a_1)}$$

where parameters make reference to the seismic hazard map for the Italian territory.

4 – Finally, the nominal life can be obtained as:

$$V = T_{SLV} \cdot \ln(1 - p\ )$$

where p denotes the exceedance probability for the considered limit state (10%). Through V a safety index can be computed as V / 35 , considering that 35 is the minimum value allowed by the Italian building code for the structure nominal life.

4. CASE STUDY: THE MADONNA DI MONTE CHURCH

The case examined concerns a church located on a hill crest in the subalpine region of northern Italy, in a low-to-moderate seismic area (Fig.1). The stone masonry building dates back to the 13th century and is classified as protected cultural heritage. In Italy, seismic strengthening or improvement of an existing building is enforced whenever it undergoes major renovation or extensive and extraordinary maintenance. This is the case of the church, for which the current conditions of the roof and walls required restoration works. In its history the church never underwent a major earthquake, yet the damage progressively cumulated from a long series of minor events is evident. In its lifetime, other effects of static nature and structural modifications contributed to the general state of decay. In order to design an intervention for rehabilitation and seismic improvement, the new procedure indicated by the code for assessing the effects of interventions with reference to the initial conditions has been applied (Parisi et al., 2011a, 2011b).

The building has a relatively simple shape, with a single nave and without transept. The static and the dynamic behaviour are, however, complicated by the context where the church is located. The church is not isolated, but part of a building aggregate. The presence of a bell tower is particularly important here, because its interaction with the church may have been a cause of damage.

Due to the simple layout of the building, many of the damage mechanisms considered by the procedure do not apply. Namely, only 9 out of 28 possible mechanisms were meaningful in this case. Each of these significant mechanisms is briefly described in the following, explaining the reasons for which it may be considered active, the existing elements providing seismic protection, the vulnerability indicators associated to the mechanism, and the type of intervention proposed. Table 1 enlists, for each mechanism, the efficiency factors assigned to the seismic protection elements and to the vulnerability indicators. In the figures the schemes reported by the norm for each mechanism and some views of the actual situation of the church are shown.

5. ANALYSIS OF THE DAMAGE MECHANISMS

1. Mechanisms in the plane of the main facade: are revealed by the presence of vertical cracks.
Seismic protection elements: steel ties.
Vulnerability indicators: large openings and cracks.
Improvement interventions: increase the effectiveness of existing steel ties.

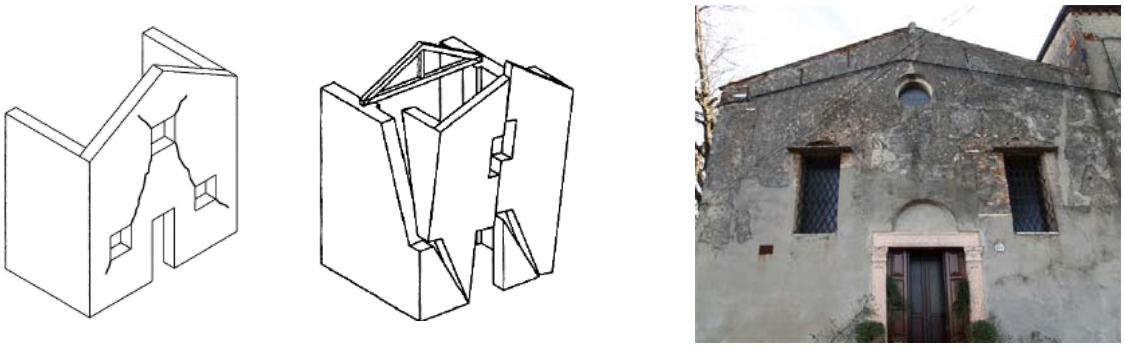

Figure 2. Damage mechanism n. 1.

2. Transversal response of the nave: the presence of this mechanism is revealed by the lateral wall rotation and by the slenderness of these walls.
Seismic protection elements: adjacent structural units.
Vulnerability indicators: slender walls.
Improvement interventions: better connection with adjacent structural units.

3. Triumphal arch: a possible collapse mechanism is related to a system of cracks.
Seismic protection elements: massive lateral walls plus a steel tie.
Vulnerability indicators: interaction with the bell tower.
Improvement interventions: additional steel ties and more effective connection to the bell tower.

Figure 3. Mechanism n. 2

4. Rocking of the Abse: is revealed by the presence of vertical cracks.
Seismic protection elements: reaction by other structural units and external buttresses.
Vulnerability indicators: large openings plus interaction with the bell tower.
Improvement interventions: more efficient connection to the bell tower.

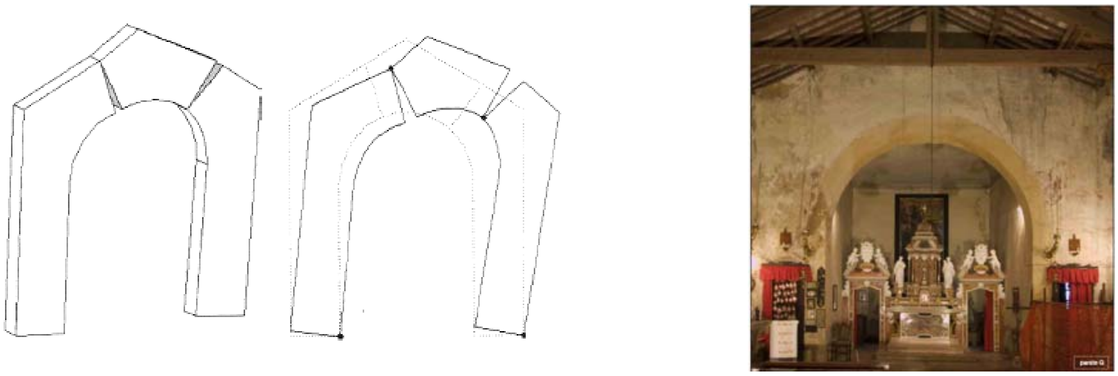

Figure 4. Mechanism n. 3

5. Roof and nave lateral walls: cracks are present at the connection of the timber roof structure with the walls, where relative sliding can be observed.
Seismic protection elements: effective connection of the roof structure well built into the walls.
Vulnerability indicators: thrust from the roof to the wall.
Improvement interventions: light ring beams at the top of walls, better connection of the roof timber structure to the walls, pent bracing, better connections between the roof elements.

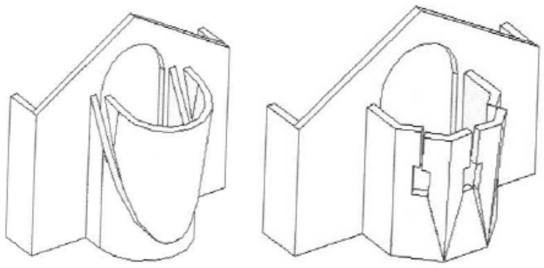

Figure 5. Mechanism n. 4

6. Roof and abse region: cracks are present at the connection of the timber roof structure with the walls, where relative sliding can be observed.
Seismic protection elements: effective connection of the roof structure well built into the walls.

Vulnerability indicators: thrust from the roof to the wall.
Improvement interventions: light ring beams at the top of walls, better connection of the roof timber structure to the walls, pent bracing, better connections between the roof elements.

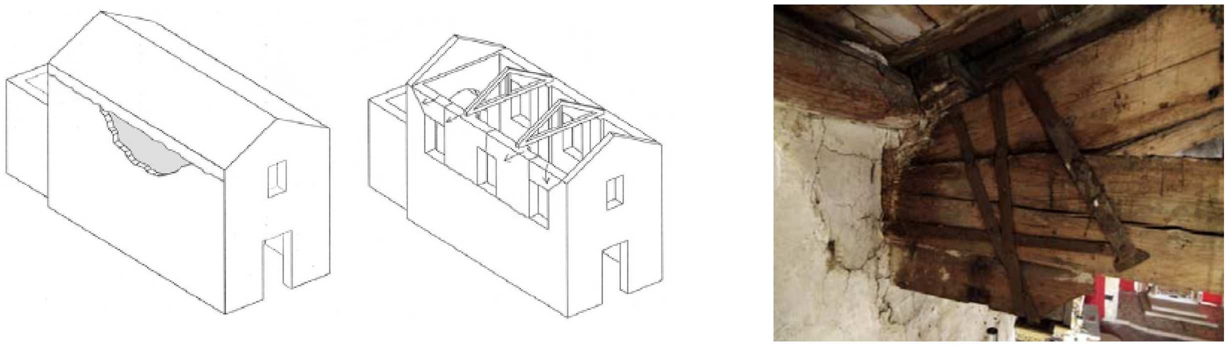

Figure 6. Mechanism n. 5

7. Plan and elevation irregularities: are revealed by cracks at the connection with the adjacent tower building.
Seismic protection elements: effective wall interlocking plus steel ties.
Vulnerability indicators: stress concentration around the connection.
Improvement interventions: increased interlocking between walls.

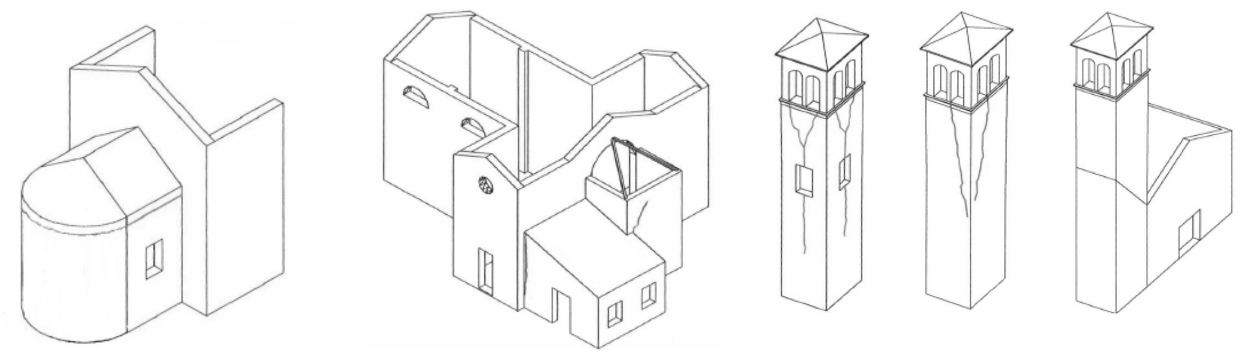

Figure 7. Mechanisms n. 6, 7 and 8

8. Bell tower: vertical cracks are visible.
Seismic protection elements: previously inserted steel ties.
Vulnerability indicators: lack of symmetry at the foundation level.
Improvement interventions: effectiveness check for existing steel ties.

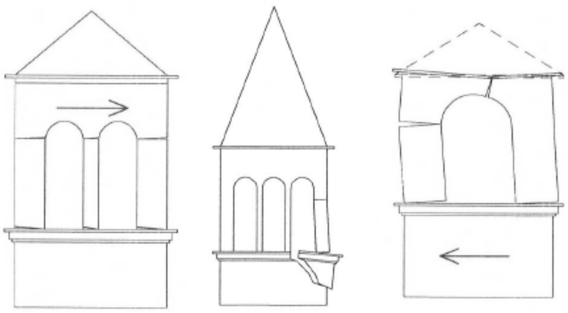

Figure 8. Mechanisms n. 9

9. Belfry: cracks are visible.
Seismic protection elements: previously inserted steel ties.
Vulnerability indicators: heavy roof structure.
Improvement interventions: effectiveness check for existing steel ties.

Table 1: Efficiency factors for the 9 collapse mechanisms in the present situation and after improvement interventions. Values in brackets refer to the alternative solution.

Mechanism type	Present situation		After stregthening	
	Seismic Protection	Vuln. indicators	Seismic Protection	Vuln. indicators
Mechanisms in the main facade plane	1 (2)	2 (2)	3 (3)	2 (2)
Nave transversal response	1 (1)	2 (2)	2 (3)	2 (2)
Triumphal arch	1 (2)	3 (3)	1 (3)	2 (2)
Abse rocking	1 (2)	3 (3)	2 (3)	3 (3)
Roof and nave lateral walls	1 (1)	3 (3)	3 (3)	3 (2)
Roof and abse	1 (1)	3 (3)	2 (3)	3 (2)
Plan and elevation irregularities	1 (1)	3 (3)	1 (2)	3 (3)
Bell tower	2 (2)	2 (2)	2 (2)	2 (1)
Belfry	2 (2)	2 (2)	2 (2)	2 (1)

6. REMARKS ON THE PROCEDURE AND VULNERABILITY EVALUATION RESULTS

According to the code procedure, the number of the seismic protection elements and that of the vulnerability indicators constitute a fairly objective estimate. In the case under study, these have been relatively easy to identify following the indications in the code. The efficiency factors, on the contrary, are necessarily derived from a subjective evaluation. Values attributed to this parameter and reported in Table 1 correspond to a conservative evaluation: in the scale ranging between 1 and 3, values by defect have been attributed to elements with a positive effect on vulnerability, and values by excess were assigned to elements with a negative effect. This criterion has been applied both to the evaluation of the present situation and to the situation after the improvement interventions.

This evaluation brings to the results reported in Table 2 as “basic solution”. The table compares the two situations in terms of vulnerability index, peak ground acceleration and corresponding return period, nominal life for the structure, and safety index intended as ratio between the computed nominal life and a conventional life of 35 years.

Table 2. Vulnerability evaluation parameters

Parameters	Basic solution		Alternative solution	
	Present situation	After stregthening	Present situation	After stregthening
Vulnerability Index	0.722	0.537	0.667	0.389
Peak ground acceleration (g)	0.116	0.169	0.130	0.228
Return period (years)	226	583	298	1324
Nominal life (years)	24	61	31	139
Safety index	0.69	1.74	0.89	3.97

7. SENSITIVITY OF THE PROCEDURE TO SUBJECTIVE EVALUATIONS

It was deemed interesting to examine how the results would vary when obtained according to different criteria in selecting the subjective parameter constituted by the efficiency index. In particular, a less conservative approach has been tried, giving a more positive evaluation to the seismic protection

elements, especially after the interventions, and an evaluation that was only partially pessimistic to the vulnerability indicators.
The global vulnerability index depends on the difference between the vulnerability indexes and the seismic protection elements. The difference may result negative. The three limit values are: 1, in the most negative situation, when no protection elements are present and the worst evaluation is given to the vulnerability indexes; 0, in the opposite case, and ½ in the case of even evaluations. The corresponding peak ground accelerations become 0.066, 0.500, and 0.182 (g units), respectively.

For the case in exam, an optimistic but at the same time realistic evaluation of the parameters (see values in brackets in Table 1) yields the results reported in Table 2 as "alternative solution". The situation appears much more favourable than the one previously obtained as "basic solution".

It seems possible to conclude that, even if the procedure is robust, in the sense that it offers a conclusion for every case, it is necessary to be very cautious in selecting the efficiency parameters, avoiding excessively optimistic evaluations. The variation range of the results is, indeed, rather wide.

8. CONCLUSIONS

The new guidelines for the seismic protection of heritage buildings, issued in Italy in February 2011, indicate seismic improvement as the criterion for interventions. The same guidelines recognize the effectiveness of localized interventions on the basis of numerous observations of partial collapse occurred in heritage buildings and churches during the past earthquakes.

The new aspect introduced by the guidelines concerns the procedure for analyzing the interventions, which permits to compare them by means of a global vulnerability index to be calculated in the original situation and as a result of the intervention itself.

The procedure has been applied in a case study. The importance of subjective evaluations on which the final judgement is based has been highlighted. These analyses, with reference to the case examined, indicate that very optimistic evaluations should be avoided for the situation of the present state as well as for the effectiveness of the interventions planned. Most of all, the procedure appears extremely useful for the comparative evaluation of many different situations, while its use appears more delicate when only one case is considered and the effectiveness of a single intervention needs to be estimated.

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