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THE 31ST OCTOBER 2002 EARTHQUAKE IN MOLISE (ITALY): A NEW METHODOLOGY FOR THE DAMAGE AND SEISMIC VULNERABILITY SURVEY OF CHURCHES

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SUMMARY

This paper describes the new methodology used to assess seismic damage in the churches of Molise damaged by the 31st October 2002 seismic event. In the paper the first results of the statistical re-elaboration of the data collected with the new survey form are presented, which is based on the method used after the 1997 earthquake in Umbria and The Marches (Lagomarsino [1]). The possibility of having a vulnerability survey of the churches through a subdivision into vulnerability indicators and a-seismic devices has allowed us a more accurate evaluation of the seismic behaviour of this kind of building that showed considerable damage, despite the low magnitude of the two main seismic events. The high intrinsic vulnerability of churches, , has, in fact, in many cases been increased by not so effective retrofitting interventions. The new detailed form has allowed us to identify these specific aspects and to give meaningful suggestions for the successive reconstruction phase.

INTRODUCTION

The need for accurate methodologies for damage assessment to buildings certainly represents one of the most important aspects for the management of a seismic emergency. In such a case, it is necessary to evaluate rapidly the usability of the buildings and to define the provisional structures needed to safeguard both people and elements. In the case of monumental buildings this aspect assumes a particular meaning in relation to the artistic and historical value of such buildings. As regards churches (which represent more than 80% of the Italian cultural heritage) the method used has led to the need for a more detailed application on the territory.

The re-elaboration of the data after the recent Italian earthquakes (Umbria and The Marches-1997, Latium-1999, Tuscany-1995, Piedmont-2000) (Lagomarsino [2]; Podestà, [3]) has highlighted how the method used for the damage and vulnerability survey is a valid tool for the appraisal of the seismic behaviour of religious buildings (churches), from which not only useful indications in the first phases can be obtained, but also suggestions during reconstruction. This approach, linked to the identification of the

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collapse mechanisms in the various macro-elements present in the churches, allows us, in fact, to obtain a double aim, on the one hand to correlate the damage pattern to the kinematism induced by the earthquake, on the other, to make the survey quick and easy.
The concept of a macroelement, (Doglioni [4]; Lagomarsino, [5]) a part of the fabric characterized by a prevalent autonomous structural response, can, however, be defective when the damage assessment is carried out before the seismic event highlights in such a clear way the behaviour for parts of the buildings. In particular, the forecast of the damage mechanisms must be evaluated according to a more careful assessment of the vulnerability indicators, of which in the original version of the form (Lagomarsino [1]) there were two for each collapse mechanism; this fact created inevitable approximations and uncertainties during compilation. The presence of large churches, moreover, makes the operation of synthesis so difficult that it generates confusion in attributing the damage that occurred to the correct mechanism. The presence of the damage in an aisle or in a chapel vault does not, in fact, find a correct position, unless it is confused with general damage to the vaults, creating, also for the parameters introduced (damage index), some values that can falsify the final judgement. Such considerations have generated in the authors the decision to produce a new methodology, able to eliminate the weak points of the form used after the Umbria and The Marches earthquake.

Table 1. List of the considered damage mechanisms, in the different macroelements of a church

Damage mechanisms	*Mode of damage*	*Part of the church*
1 - OVERTURNING OF THE FACADE	I	FAÇADE
2 - DAMAGE AT THE TOP OF FACADE	I	
3 - SHEAR MECHANISMS IN THE FACADE	II	
4 – NARTEX	I o II	
5 - TRANSVERSAL VIBRATION OF THE NAVE	I	NAVE
6 - SHEAR MECHANISMS IN THE SIDE WALLS	II	
7 - LONGITUDINAL RESPONSE OF THE COLONNADE	I	
8 - VAULTS OF THE NAVE	I o II	
9 - VAULTS OF THE AISLES	I o II	
10 - OVERTURNING OF THE TRANSEPT'S END WALL	I	TRANPSEPT
11 - SHEAR MECHANISMS IN THE TRANSEPT WALLS	II	
12 - VAULTS OF THE TRANSEPT	I o II	
13 - TRIUMPHAL ARCHES	II	TRIUMPHAL ARCH
14 - DOME AND DRUM	I o II	DOME
15 – LANTERN	I o II	
16 - OVERTURNIG OF APSE	I	APSE
17 - SHEAR MECHANISMS IN PRESBITERY AND APSE	II	
18 - VAULTS IN PRESBITERY AND APSE	I o II	
19 - PART OF ROOF: SIDE WALLS OF NAVE AND AISLES	I o II	ROOF COVERING
20 - PART OF ROOF: TRANSEPT	I o II	
21 - PART OF ROOF: APSE AND PRESBITERY	I o II	
22 - OVERTURNING OF THE CHAPELS	I	CHAPEL
23 - SHEAR MECHANISMS IN THE WALLS OF CHAPELS	II	
24 - VAULTS OF CHAPELS	I o II	
25 - INTERACTIONS NEXT TO IRREGULARITIES	I o II	
26 - PROJECTIONS (DOMED VAULTS, PINNACLES, STATUES)	I	BELL TOWER
27 - BELL TOWER	I o II	
28 - BELL CELL	I o II	

The research took place as an initiative by the Department of Civil Protection with the Ministry of Internal Affairs and the Ministry of Public Building and Works. A working group with the function of developing survey tools for the different typologies of monumental buildings was created in order to be used both in a preventive phase and after a natural calamity.

The recent seismic event that struck the province of Campobasso (31st October 2002) allowed us to use the new method directly, correlating it with the institutional survey proposed by the Ministry of Public Building and Works which, for the section regarding the structural damage, follows the GNDT method used during the earthquake in Umbria and The Marches. In particular, the new method permits us to by-pass the problems encountered in the preceding assessment campaign by increasing the number of damage mechanisms from 18 to 28. The increase, however, does not determine the loss of the applicative and territorial characteristics of the method and allows a more precise description of both the vulnerability and the damage.

The 28 mechanisms, correlated to a revised abacus, also in the already presented parts, allow a more detailed description of the activated kinematisms. They, therefore, furnish the surveyors with a series of extra-parameters also useful for verifying the usability of the fabric. In Table 1 the list of the damage mechanisms taken into consideration is reported. In the two columns on the right-hand side the parts of the church and the damage modes (out-of-plane action are listed: I mode; in-plane action: II mode) connectable to every collapse kinematism. It is clear that certain mechanisms are not easily linkable to a sole damage mode, because this schematisation was introduced to describe the seismic response of a masonry wall; as regards the vaults and the roofs this simplification is meaningless. For such architectural elements, the damage pattern, if it is not connected to a general action, (transversal or longitudinal response of the nave), could be associated to a sole damage mechanism.

THE SURVEY FORM FOR DAMAGE AND VULNERABILITY ASSESSMENT

The form is divided into three parts, which resume, though with some modifications, the seven sections of the previous version used in Umbria and The Marches, in 1997. The first part regards the general knowledge of the church; we consider, therefore, the shape and the main dimensions of the architectural elements as well as the masonry characteristics in the various macroelements.

As regards the dimensional and the typological data we have increased the section that was insufficient to describe large and complex churches. In particular we want to highlight how the analysis of this information (typology, dimensions, masonry quality, recent interventions) could help the surveyors to fill out the second part, in which a judgement of the damage and on the vulnerability must be expressed.

The collected data represent, in fact, the intrinsic vulnerability of the monument. This aspect plays a fundamental role in the structural behaviour, as shown by describing the damage patterns. Moreover, it is important to remember how the subjectivity of the collected data, inevitable in the case of experts of different cultural formations, could be hard to limit if the tools used to collect the information allow the surveyors a quick and easy survey.

The second part concerns the damage and vulnerability survey of the church; the modifications in this section are the most meaningful ones. The original 18 mechanisms have been increased to 28, thus allowing even the analysis of large and complex churches with a proper level of accuracy and without ambiguity. An example is represented by the collapse mechanisms of the roof, which, in the previous version, were grouped together. The diversification into three different mechanisms allows us to indentify and to catalogue the building characteristics with greater precision; in fact, in big churches, made up of different macroelements (apse, transept, nave and aisle), different kinds of roof are sometimes present. The main innovation consists, however, in the survey of the constructive details that play a fundamental role in the seismic behaviour of the church. To this end, the vulnerability assessment considers the survey by means of a double complementary approach: vulnerability indicators and a-seismic devices. For example, the buttresses or the tie-rods could be interpreted as a-seismic devices, able to contrast the activation and the evolution of a particular mechanism in a macroelement; on the contrary, the presence of pushing elements or of lumped masses on a vault is a characteristic that increases the vulnerability. Thus, for each of the 28 damage mechanisms, there is a list of a-seismic devices and vulnerability indicators in the form; moreover, the surveyor may add other indicators, taking into consideration the building characteristics at a regional level or of the specific church. In Figure 1, the section regarding the nave-roof mechanisms is reported as an example.

19 – PART OF THE ROOF: SIDE WALLS OF NAVE AND AISLES				
Presence of the macroelement correlated to the collapse mechanism: Yes ❑ No ❑				
Vulnerability	yes	no	A-SEISMIC DEVICES	
	❑	❑	Presence of light ring-beams (reticular steel ring beam, reinforced masonry)	❑ ❑ ❑
	❑	❑	Presence of connections between roof elements and masonry	❑ ❑ ❑
	❑	❑	Presence of pitch braces (crossing roof baring or metal collars)	❑ ❑ ❑
	❑	❑	Presence of connection between roof elements	❑ ❑ ❑
	❑	❑	………………………………………………………………………	❑ ❑ ❑
	yes	no	VULNERABILITY INDICATORS	
	❑	❑	Statically pushing roof	❑ ❑ ❑
	❑	❑	Presence of reinforced concrete ring-beams, heavy roof	❑ ❑ ❑
	❑	❑	………………………………………………………………………	❑ ❑ ❑
Damage	Cracks next to the heads of wood beams, sliding of wood beams. Disconnections between ring-beams and masonry. Thrusting of the cover. Movements between the main elements of the roof covering		Actual	❑❑❑❑❑
			Previous	❑❑❑❑❑

Figure 1. Survey form relative of the damage mechanism in the roof-covering of the nave.

The filling-out rules are substantially the same as those of the original version. In the first row, there is the name of the collapse mechanism that has to be evaluated; in the row below, it should be indicated whether the macroelement is present in the church under consideration. Moreover, for some damage mechanisms, the surveyor should indicate the weight ($0.5<\rho<1$) that has to be used in the evaluation of the overall damage and vulnerability, due to the importance of the macroelement with respect to the others.

In the vulnerability box, there are both a series of a-seismic devices, able to oppose the activation of the collapse mechanism, and a series of vulnerability indicators, responsible for increasing the damage probability. For each of them, the surveyor must indicate its presence or its absence (yes or no) and, in the right-hand column, judge its effectiveness (a-seismic device) or its importance (vulnerability indicators), graduating the evaluation on three levels: 1 - low; 2 - medium; 3 - high. For example, a longitudinal tie-rod, contrasting the overturning of the façade, may have a different effectiveness in relation to: the position, the value of pre-stress, the dimension and mass of the façade. It is worth noticing that the list of a-seismic devices and of vulnerability indicators is open, in order to consider the specific characteristics of the church.

In the damage box there is a description of the most common modes of appearance of the damage (crack patterns, deformations, etc.) for the specific mechanism; this explanation is supported by some simple and schematic drawings, collected in a table (see http://gndt.ingv.it). The damage assessment considers the 5 typical damage grades, used by the modern macroseismic scales like MSK and EMS98 (Gruntal [6]; Lagomarsino [2]). The survey of the damage is subdivided into two: actual damage, correlated directly to the earthquake, and previous damage, already present before the seismic event (if it is possible to distinguish between them). This aspect is of fundamental importance for ancient structures, most of which have been shocked by historical seismic events or by collapse mechanisms of different kinds. The difficulty of correctly describing, particularly in non-epicentral areas, what is usually listed as a worsening of pre-existing damage, may easily be overcome by the identification of the surveyed damage as the sum of two distinct factors. The actual damage will be evaluated in its complex while a judgement on the level considered already present before the earthquake will be reported in the box of "previous damage", in order to define even the safety judgement of the structure in a better connected way.

Moreover, for some mechanisms, there is the possibility of expressing a value correlated to the maximum level of damage found in the macroelement. This is particularly useful, for example, in the mechanisms of the vaults in the nave. In fact, the case in which one bay suffers severe damage (even leading to complete collapse), with significantly less damage in the other bays, is rather frequent; in this case, the above-mentioned evaluation should represent a mean value, but it is important to record also even the presence of local collapse or severe damage.
The evaluation of the seismic behaviour of the whole building is, as in the previous version (Lagomarsino [1]), obtainable from the calculation of two indices (damage and vulnerability indices) representing the appraisal of the average damage and vulnerability met with during the survey. As regards the damage index, it is shown by a normalized average defined through:

$$i_d = \frac{1}{5}\frac{\sum_{k=1}^{28} \rho_k d_k}{\sum_{k=1}^{28} \rho_k} \qquad (1)$$

where ρ_k is the importance given to each mechanism; d_k is the damage level associated with the k^{th} mechanism (from 0 to 5); N is the number of the mechanisms that might have been activated in the church. In particular, in comparison to the original version, the parameter ρ_k has been introduced in order to better take into account the relation between the different damage mechanisms under consideration. This procedure is partly automatic but, for some kinematisms, depends directly on the surveyor's personal appraisal of the importance of every macroelement in relation to the others. In Table 2, the values of the ρ_k parameter for the 28 damage mechanisms are reported, both those directly assigned and those that can vary in a fixed range. It is clear how, in the case in which the macroelement is not present in the church or the damage mechanism associated with it has not been activated, the value of such a parameter is equal to zero.
The calculation of the vulnerability index in this version is slightly more articulated with respect to the form used in Umbria and The Marches. In fact, the structure of the form allows the distinction in the survey of the constructive characteristics that can directly influence the collapse mechanisms (contrasting or favouring their activation). During the survey these modifications permit a clearer understanding of the building features of the activated kinematisms, of the resources or the weaknesses of the church in relation to the seismic events. The knowledge of the a-seismic devices and of the vulnerability indicators, specific to the macroelement, gives fundamental information also for the final appraisal of both the safety and the usability of the building. This obviously remains a presentation that cannot be subordinated to any analytic algorithm, but depends on the final judgement of the surveyors.
The need to survey a great amount of information in a most detailed way determines a new expression of the vulnerability index, in order to take into account the diversification of the vulnerability survey technique introduced.

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

where: v_{ki} *e* v_{kp} are respectively the score obtained from the survey of the vulnerability indicators (v_{ki}) and of the a-seismic devices, (v_{kp}), according to the criterion reported in Table 3.

Table 2 – List of values of the ρ_k coefficient for each damage mechanism

COLLAPSE MECHANISMS	***Range value***
1 - OVERTURNING OF THE FACADE	***1***
2 - DAMAGE AT THE TOP OF THE FACADE	***1***
3 - SHEAR MECHANISMS IN THE FACADE	***1***
4 - NARTEX	***0.5 ÷1***
5 - TRANSVERSAL VIBRATION OF THE NAVE	***1***
6 - SHEAR MECHANISMS IN THE SIDE WALLS	***1***
7 - LONGITUDINAL RESPONSE OF THE COLONNADE	***1***
8 - VAULTS OF THE NAVE	***1***
9 - VAULTS OF THE AISLES	***1***
10 - OVERTURNING OF THE TRANSEPT'S END WALL	***0.5 ÷1***
11 - SHEAR MECHANISMS IN THE TRANSEPT WALLS	***0.5 ÷1***
12 - VAULTS OF THE TRANSEPT	***0.5 ÷1***
13 - TRIUMPHAL ARCHES	***1***
14 - DOME AND DRUM	***1***
15 - LANTERN	***0.5***
16 - OVERTURNING OF APSE	***1***
17 - SHEAR MECHANISMS IN PRESBITERY AND APSE	***1***
18 - VAULTS IN PRESBITERY AND APSE	***0.5 ÷1***
19 - PART OF ROOF: SIDE WALLS OF NAVE AND AISLES	***1***
20 - PART OF ROOF: TRANSEPT	***0.5 ÷1***
21 - PART OF ROOF: APSE AND PRESBITERY	***1***
22 - OVERTURNING OF THE CHAPELS	***0.5 ÷1***
23 - SHEAR MECHANISMS IN THE WALLS OF CHAPELS	***0.5 ÷1***
24 - VAULTS OF CHAPELS	***0.5 ÷1***
25 - INTERACTIONS NEXT TO IRREGULARITIES	***0.5 ÷1***
26 - PROJECTIONS (DOMED VAULTS, PINNACLES, STATUES)	***0.8***
27 - BELL TOWER	***1***
28 - BELL CELL	***1***

Table 3. Scheme for the evaluation of the vulnerability score of each damage mechanism

Effectiveness judgement	***Number of vulnerability indicators or of a-seismic devices***	***Score***
3	at least 1	3
2	at least 2	
2	1	2
1	at least 2	
1	1	1
0	-	0

In the third part, free-sections are present, in order to put this information, not catalogued in the previous sections, or which can lead to a better diagnosis of the structural behaviour of the church (sketches, drawings, photos). Moreover, we have envisaged a section in which the archive references of historical geometrical relief can be annotated. The possibility of also having a preliminary geometrical survey can be useful if the situation needs a more detailed analysis through the application of mechanical models, which are based on an amount of information that is hard to obtain during an emergency survey.

APPLICATION OF THE NEW METHODOLOGY TO THE MOLISE REGION CHURCHES DAMAGED BY THE SEISMIC EVENTS OF OCTOBER 2002

The survey of the 296 churches damaged by the Molise earthquake has confirmed, yet again, how these monuments represent a typology of building that is particularly vulnerable to seismic actions. The lack of horizontal floors, the presence of slender walls, of pushing elements already in a static condition (vaults, arches, etc.), of particular architectonical elements (dome, etc.) represent a vulnerability source that, also for low intensity seismic events, caused damage levels greater than those surveyed in ordinary buildings.
Table 4 shows the mean damage grades for the whole population of churches, obtained from the previous earthquakes in Italy (Podestà [3]). The set of 296 churches surveyed in Molise has been split, according to the macroseismic intensity (Modified Mercalli scale), into four sets, I_{MMI}= IV, V, VI and VII-VIII (the last two intensities are considered together, in order to dispose of a number of churches which could be considered a statistically significant set). The damage probability distributions are shown in figure 4, while the corresponding values of the mean damage grade μ_D are reported in table 4 (Lagomarsino [7]). The comparison with the values obtained from the previous earthquakes (Lagomarsino [8]) confirms the confidence and robustness of the methodology used.

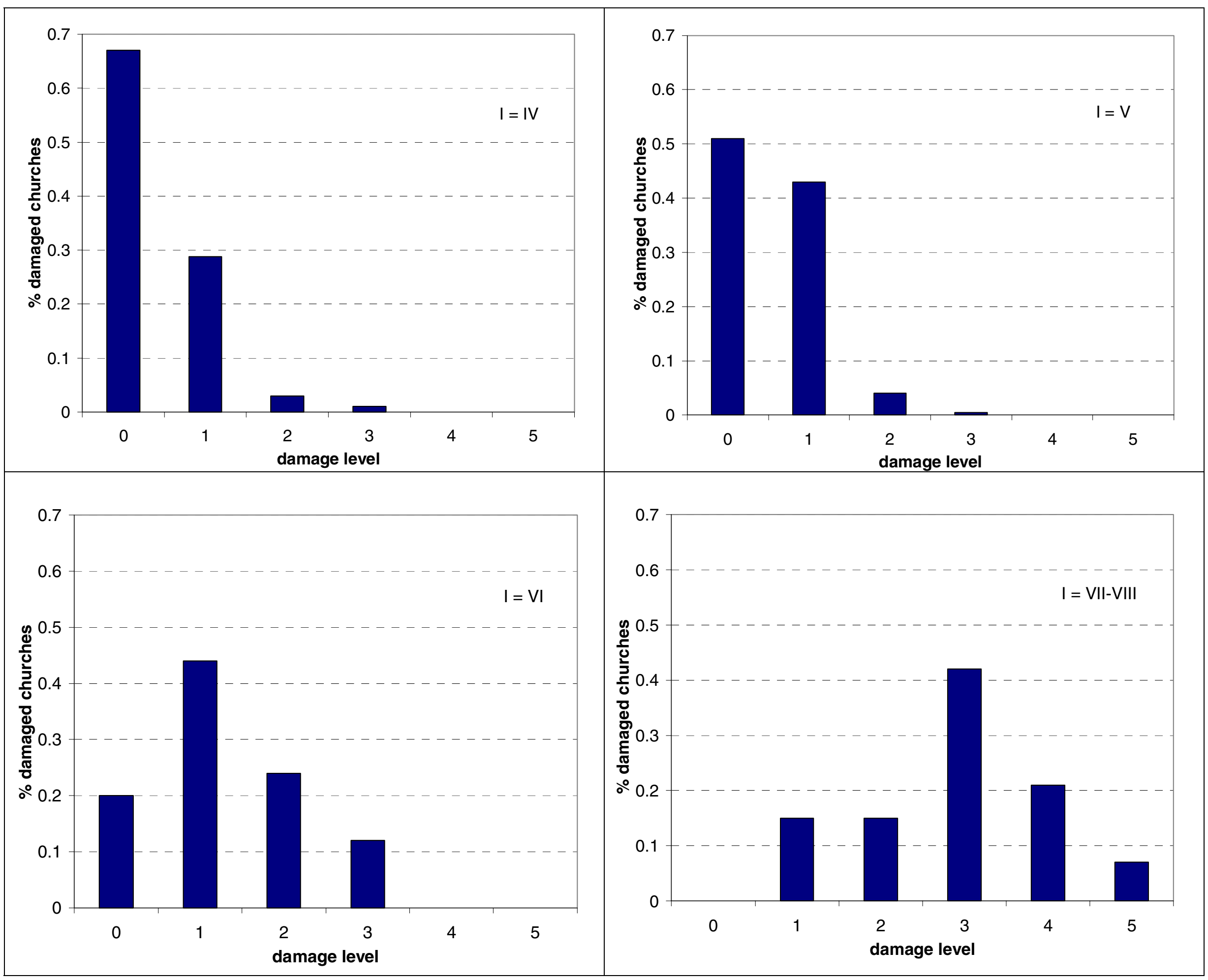


Figure 4. Damage histograms of Molise churches.

Table 4. Binomial coefficient (μ_D - mean damage grade) for the DPM of churches.

	Macroseismic Intensity (MCS)				
	IV	V	VI	VII	VIII
Previous earthquakes	-	1.025	1.385	2.015	3
Molise	0.4	0.54	1.28	2.9	

Among the damage surveyed, the most frequent found is: 1) cracking and collapse of the vaults (owing to their limited thickness and the lack of tie rods); 2) damage due to the crushing and shearing of the masonry pillars in the churches with more than one nave (because of the increased weight after the intervention with reinforced concrete in the roof and over the vaults, but also as a consequence of the high energy content of the vertical component, measured in some historical centres on ridge or crest topographic configuration - Lagomarsino [9]; Cevasco [10]); 3) damage connected with the sliding or overturning of the spires over the bell towers (when rebuilt with heavy and rigid reinforced concrete slabs); 4) out of plane failure of the gable of the façade or in the apse (again in the presence of roofs reconstructed with reinforced concrete).

Figure 5. - Three examples of crushing damage in masonry pillars

The macroelements that experienced the major percentage of severe damage (damage grade 4 or 5), in the total sample of the surveyed churches, are reported in table 5; the most severe damage occurred in vaults, arches (due to lack of tie-rods, very rarely used in Molise) and in the bell tower, while less frequent are the collapse mechanisms connected to the out-of-plane action, which are, generally, the most vulnerable for historical masonry buildings.

Table 5. Perceptual of the activation in some damage mechanisms

DAMAGE MECHANISMS	% CHURCHES SEVERLY DAMAGED
1 - OVERTURNING OF THE FACADE	0.06
8 - VAULTS OF THE NAVE	0.15
9 - VAULTS OF THE AISLES	0.14
13 - TRIUMPHAL ARCHES	0.12
27 - BELL TOWER	0.13
28 - BELL CELL	0.07

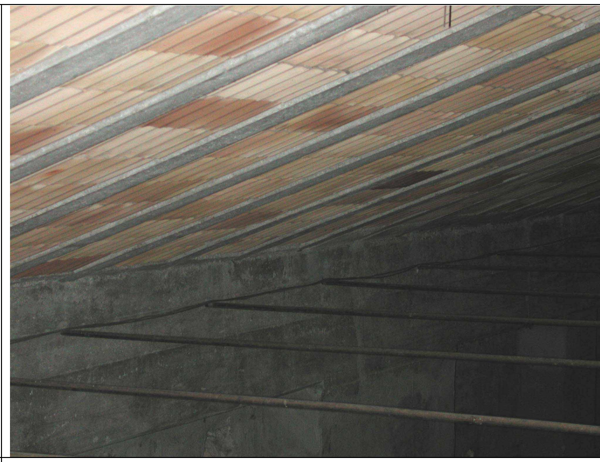
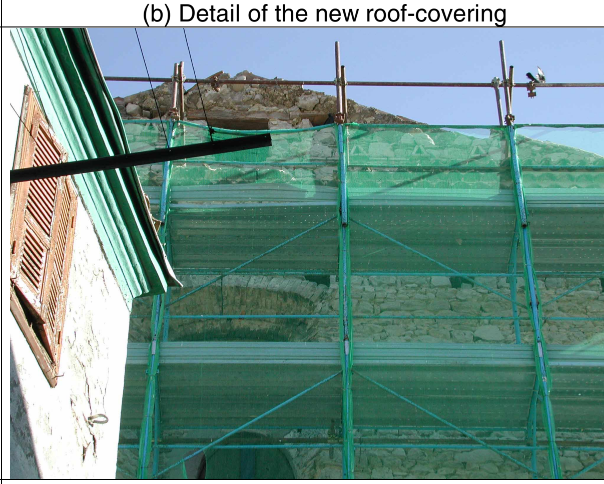
An emblematic case is that of S. Helen's church in San Giuliano di Puglia (Table 6). Although the structure was not complex and traditional buttresses were present, the damage pattern raises serious doubts about the effectiveness of the retrofitting intervention (reinforced concrete roof and reinforced concrete tie-beam in the side walls), carried out in 1970. The hammering action induced by the roof caused the collapse of the gable of the façade and the expulsion of the external curtain of the lateral masonry walls, risking the total loss of the monument. It is worth noticing that the belfry is now placed on the roof, highlighting the fact that the collapse of the gable was induced by an impulsive action from the rigid roof. Moreover, it is interesting to observe the characteristics of the reinforced concrete ring beam (in photos "c" of Table 6); it was only placed over the internal leaf of the lateral masonry wall and did not tie the façade, because it stopped at the lateral wall. The different stiffness of the new reinforced concrete elements (tie beam and roof slab) with respect to the masonry walls (lateral and façade with the gable) is the main cause of the masonry collapse.

Table 6. S. Helen's church in San Giuliano di Puglia.

	
a) The church before the earthquake	b) The church damaged by the earthquake
	
(c) Detail of the reinforced concrete tie-beam	

Instead, in Table 7 is shown some of the damage suffered by, in Colletorto. This church is in the historical centre and has been extensively retrofitted in recent years; in particular, rehabilitation was in progress at the time of the earthquake, regarding the retrofitting of the lateral wall of the church. In the seventies, the bell tower and the roof were strengthened, substituting the original wooden roof with a new reinforced concrete structure, connected to a heavy reinforced concrete tie-beam (80 cm height), at the top of the lateral wall. On 31st October 2002, the earthquake induced a hammering action of the roof that caused a different damage pattern. In proximity of the façade, the rigid constraint due to the presence of the bell tower caused the collapse of the first part of the roof-covering, while, in correspondence with the apse, the seismic action caused the out-of-plane of the masonry gable.

Table 7 - St. John the Baptist church – Colletorto (Italy)

	
(a) Bell tower of the church	(b) Detail of the new roof-covering
	
(c) Damage in the first part of the roof-covering	(d) Overturning of the gable of the apse-wall

FINAL REMARKS

Any rehabilitation of historical structures must be made only if one has a complete mastery of the various choices, in which the repercussions on the structural behaviour of the whole fabric need to be taken into account.

Learning from an earthquake, through a careful diagnostic observation of the damage to buildings, is an important tool to understand complex seismic response (perhaps one of the most complicated actions to be described and analysed), in particular in the case of masonry buildings. These represent a very difficult typology to model, both because of their technological and constructive complexity, and because of the non-linearity of the mechanical behaviour of the masonry “material”. This empirical approach has to be carried out bearing in mind that the past retrofitting interventions were the result of an incomplete knowledge, and that they were suggested and sometimes imposed by technical rules. But, nowadays, we are aware of the aforesaid concepts and we need to try out different ways, taking into account that some

traditional interventions, even if abandoned after the introduction of the modern concepts of structural safety, are still useful.
The idea of a "*unicum architectonicum*" that characterises each monument has to be analysed within a multidisciplinary approach. This is not perfectly associable to the strict observance of the technical prescriptions or the code of practice suggestions. In fact these are calibrated through specific cases or through the mean value of a statistically significant (more or less) sample.
Only through the recognition of the intrinsic vulnerability causes in the fabric is it possible to point out, in each situation, the most suitable retrofitting intervention in order to obtain an effective a-seismic improvement. The vulnerability sources, which mean constructive and technological deficiencies, have to be correlated to the damage mechanism that could be activated by the earthquake.

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