16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

DAMAGE EVOLUTION IN CHURCHES DUE TO REPEATED EARTHQUAKE SHOCKS

Maria A. PARISI[1], Claudio CHESI[2], Gessica SFERRAZZA PAPA[3]

ABSTRACT

Many ancient masonry churches reported considerable damage in the earthquakes that occurred in Italy in the last decades. In order to protect this heritage, dedicated research projects collected the effort of a large research community, producing methods for vulnerability assessment and damage classification, and criteria for seismic improvement. Considerations deriving from different surveys carried out by the authors on churches damaged in the recent Central Italy, 2016, earthquake are reported here. The surveys have been performed in the Region Marche at different times. Some churches inspected at the beginning of October 2016, after the first strong earthquake shocks, could be revisited in Spring 2017 after the strong events at the end of October and in January 2017. These surveys offered the opportunity of observing the evolution of damage and to assess some effects of the structural improvement interventions that had been carried out prior to the earthquake. In summary, the seismic events that arrived after the first surveys increased the damage on these already weakened structures, developing further the damage mechanisms that had been identified. In some instance the situation evolved into localized collapse, but in most cases the global stability was maintained. While further investigations including numerical modeling are in progress, observations confirmed that simple and low-impact interventions are effective in limiting some damage typologies; in some of these cases, however, damage developed moving to different elements, most likely for a higher level of action.

Keywords: churches; cultural heritage assets; seismic damage observation; seismic improvement; strengthening interventions

1. INTRODUCTION

In the Italian cultural heritage, churches are usually the assets that suffer most extensive damage during earthquakes. Their geometric and structural characteristics result in high vulnerability, making them a category particularly at risk.

Many ancient masonry churches have reported considerable damage and even collapse in the earthquakes that occurred in the last decades. In order to protect this heritage, research projects dedicated to the various aspects of this problem collected the effort of a large research community, producing ad-hoc methods for vulnerability assessment and damage classification of churches, for their numerical analysis, and for their seismic improvement. A very rich literature concerning observed damage, repair and strengthening interventions on churches and cultural heritage assets and case-histories from recent earthquakes is available (e.g., Lagomarsino & Podestà 2004a, 2004b, 2004c, Da Porto et al., 2012, Sorrentino et al., 2014, Cescatti et al., 2017).

In this context, some considerations deriving from different surveys carried out by the authors on churches damaged in the recent earthquakes and particularly the earthquake of Central Italy, (Centro Italia) 2016, are reported and discussed in this work. The surveys have been performed in the Region Marche at two different times. Some churches were examined at the beginning of October 2016, after

---

[1]Associate Professor, Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milano, Italy, maria.parisi@polimi.it
[2]Professor, Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milano, Italy, claudio.chesi@polimi.it
[3]Doctoral Student, Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milano, Italy, gessica.sferrazza@polimi.it

the earthquake shocks that started in the area near Amatrice, Regione Lazio, and before the shocks that arrived at the end of October and in January. The latter were particularly strong and with epicentre much closer to the area concerned. A subsequent visit in the same location in Spring 2017 permitted to examine other churches, but also to observe or receive information on those churches already inspected in the previous visit. Some considerations on damage evolution became possible. This aspect is of special interest when considering that most of these churches had been subjected to repair and seismic improvement interventions after the Umbria-Marche earthquake that hit the area in 1997. While further investigations including numerical modeling are necessary, first considerations in relation to the effectiveness of improvements were possible and are reported in the following.

2. METHODOLOGICAL BASES

Research carried out in Italy in the last decades on damage to masonry buildings and particularly to churches has brought to a systematization of the damage modes that were found to recur most frequently. Churches may be seen as an assembly of parts, or macro-elements, like the façade, the bell-tower, the apse etc. Since damage tends to occur in such elements in recurring patterns, the main macro-elements and the relevant damage typologies have been defined and classified, becoming a reference in two different operations:

1) the assessment of damage after an earthquake,

   and in a perspective of prevention,

2) the rapid assessment of vulnerability, in which the presence of initial damage and other unfavorable conditions in the macro-elements are sorted out and classified as they may trigger damage or collapse in a seismic event.

These evaluations are usually performed by visual inspections, based on suitable reference scales. If the masonry quality is sufficient, damage, and eventually collapse, develops with the formation of compact blocks delimited by fracture lines and the limit situation of collapse may be represented by the formation of a kinematic mechanism. As a consequence, this scheme offers the possibility of estimating the limit capacity of the structure for that mechanism in terms of limit equilibrium.

The first definition of church macro-elements was given as an interpretation of damage developed in the Friuli, 1976, earthquake (Doglioni et al., 1994). The experience acquired in subsequent earthquakes brought to formulate an abacus of 28 damage mechanisms that make reference to the main macro-elements.

This set is reported in the official survey form A-DC (MiBAC, 2006) to be adopted in Italy for damage recognition operations. Church damage surveys after the earthquakes of L’Aquila, 2009, of Pianura Padana emiliana, 2012, and Centro Italia, 2016 have been performed according to this form.

3. THE EARTHQUAKE OF CENTRO ITALIA, 2016.

The Centro Italia, 2016, earthquake, or seismic sequence of Amatrice-Norcia-Visso, started in August 2016 and lasted several months, with events of comparable magnitude covering an area that involved four different Regions. Figure 1 reports part of the Italian hazard map with the area where the earthquake occurred and fig. 2 shows the epicenters and highlights the main events. Specifically, two events of M5.4 and M6.0, respectively, occurred on August 24, 2016, with epicenter in the southern area in the figure, while at the end of October the northern area was hit by events of magnitude M5.4 and M5.9 on October 26, and M6.5 on October 30. Additionally, a strong shock arrived again in the southern part on January 10, 2017. These dates are of interest here, because the surveys were conducted in the Region Marche at different times. First surveys were carried out at the beginning of October 2016, before the occurrence of the new series of strong events at the end of October, which had epicenters closer to the surveyed areas. A subsequent visit to the area took place in Spring 2017, during which churches not seen before have been visited. At the same time, it has been possible to visit churches that had been inspected in the former survey or, in some case, to collect information on their outcome in the recent events, making it possible to follow the evolution of damage. A timeline of seismic events and surveys is in Fig. 3.

The earthquake of Colfiorito Umbria-Marche, of 1997, occurred approximately in the same area. Most of the churches had undergone repairs or improvements after this earthquake. It was, therefore, particularly interesting to focus attention on the effectiveness or possibly on the inadequacy of such interventions.

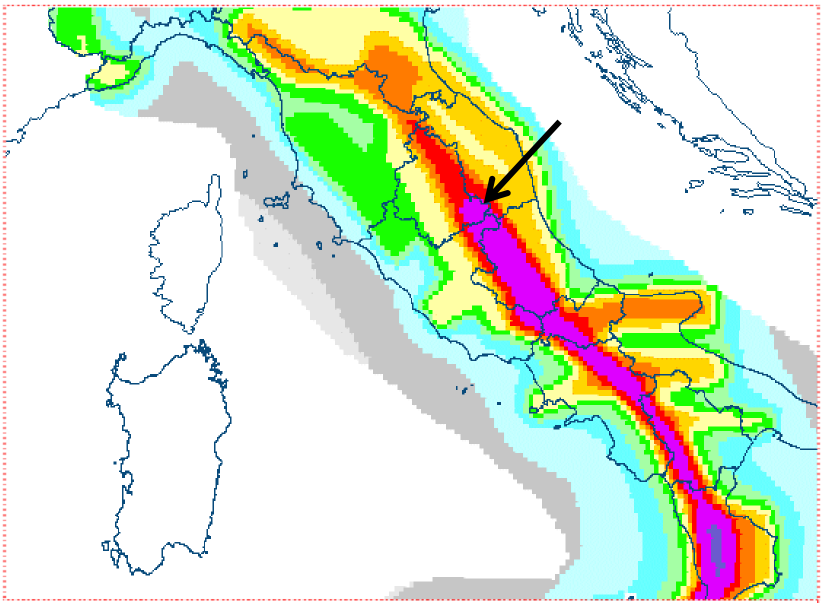

Figure 1. Italian hazard map; the epicentres of the Central Italy earthquake were located in the area indicated by the arrow; the four Regions involved, delimited by blue borderlines, are clockwise from top right, Marche, Abruzzo, Lazio, and Umbria.

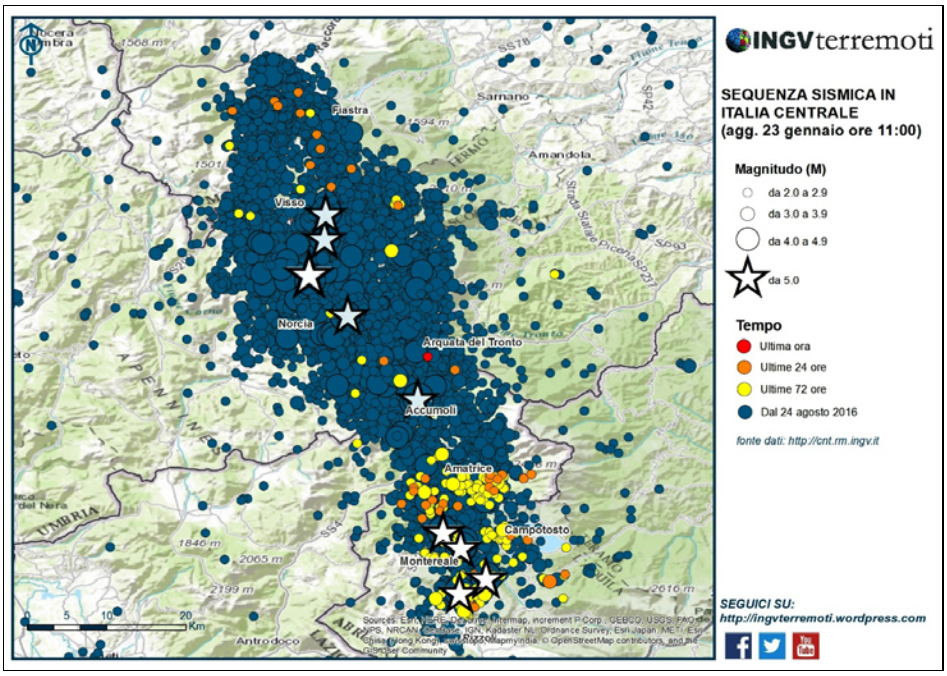

Figure 2. Seismic sequence in Central Italy (INGV, 2017) till January 23, 2017; white stars indicate events with magnitude greater than M5.0; the dark area indicating the cluster of epicentres has a length of over 60 km.

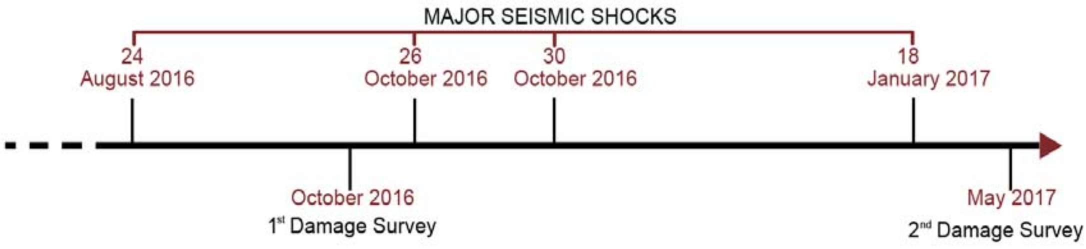

Figure 3. Timeline of seismic events and surveys

4. CONSIDERATIONS ON OBSERVED DAMAGE

Reference to the macro-elements composing the church building and to the mechanisms that may develop in each is an effective way of describing the seismic response and classifying the observed damage in a standardized, homogeneous form. Cases of damage are organized and interpreted here according to this method. Figure 4 shows some examples from the abacus of mechanisms.

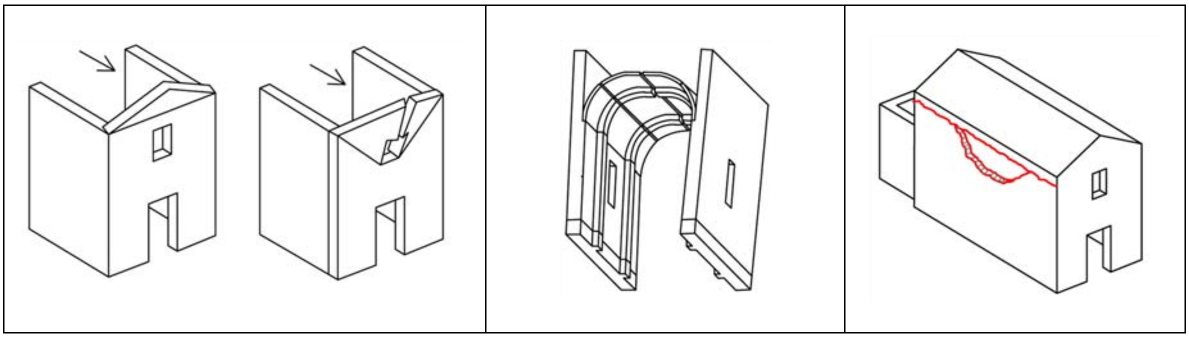

Figure 4. Damage mechanisms of the façade (left); out of plane mechanism of the nave walls from interaction and thrusts from the vaults (centre) and from the roof (right), as represented in the survey forms.

4.1 Mechanisms of the façade

Façade mechanisms are extremely frequent: the conditions for their occurrence and their evolution have been studied in detail (e.g. Casolo, 2017). This damage condition has been found in many of the churches examined. Signs of detachment and incipient rotation were visible. None, however, had developed to an advanced state, also thanks to the presence of favourable conditions. In one case, steel ties had been inserted to improve the façade connection to the lateral walls shortly before the earthquake.

In fig. 5 the exterior of a church in the province of Macerata shows damage progression with subsequent events (Parisi & Sferrazza Papa, 2017). Initially the crack pattern was modest, but it expanded at the end of October, requiring provisional interventions. Figure 6 shows the interior in correspondence of the façade. Scaffolding that had been mounted before the earthquake in order to perform restorations of the stuccos supplied a means to reach the upper part of the church for inspection after the event. Pictures in fig. 6 were taken in the same days as those in Fig. 5. Damage was already significant in the first survey, with detachment of the end wall from the vault and deep cracks at the centre of the panel, but it was much more advanced later, as may be seen along the border.

Other mechanisms had begun developing in the same church; these are presented in the next sections; yet, it is important to point out how considering their association it is possible to give a comprehensive interpretation of damage evolution.

Figure 5. Damage to a façade, progressing with subsequent shocks.

Figure 6. Interior damage to the same façade of fig. 6.

Figure 7. Façade with rectangular tympanum.

In the church in fig. 7 the upper portion of the façade, slender and with a rectangular shape that leaves top corners rather unrestrained, suffered some rotation with the shocks of October 26 and 30, with a maximum at the left corner. Comparing this case to the previous one, the influence of the architectural typology on the outcome is evident. This church, in a village closer to the Abruzzo region, recalls in the façade the Romanic churches of Abruzzo, with a typical squared aspect. This type of façade has shown to be particularly vulnerable during the earthquake of L'Aquila, 2009. An example has been the collapse of the right side of the façade of the church of Saint Peter in Coppito.
Façade vulnerability toward out-of-plane collapse had been in some cases recognized and reduced, with positive results. In the church of St Gregory, in fig. 8, a tall pointed tympanum had been restrained with a metal strut in the back that anchored it to the body of the church. As a result, no damage was observed.

Figure 8. Pointed tympanum.

Finally, no significant damage was observed to the façade of the church of San Salvatore in Acquapagana that had been repaired and improved after the damage occurred in the 1997 Umbria-Marche earthquake. At the time, this church had suffered extended damage, with the collapse of the upper part of the tympanum and of the left corner of the façade; severe shear cracks appeared from the tympanum to the lower corner of the façade; the upper part of the lateral walls collapsed together with some portions of the buttresses. Figure 9 compares the two outcomes.

Figure 9. The church after the 1997 earthquake (left) and the 2016 sequence (right).

4.2 Out-of-plane mechanism of navy walls

In the series of 28 reference mechanisms developed for churches, the out-of-plane failure of the upper part of nave walls may be triggered by a thrust from the vaults or by horizontal forces coming from the roof structure. The schemes of both cases are shown in Fig. 4. This damage mechanism has been the cause of several failures during the Pianura Padana Emiliana earthquake of 2012. It was facilitated by the geometry of the 18th century churches with much higher walls in the central nave that were rather deformable laterally; often a progressive collapse took place, starting from the wall tops followed by the roof, which fell and in turn drew down vaults and ceilings below (Parisi et al., 2015).

The typology of churches in the Marche Region very likely reduced the risk of this total failure.

The same church of figures 5 and 6, for which damage in the façade area had occurred, showed an important response in the upper part also in the transversal direction, with damage corresponding to this mechanism. In this case, the ribbed barrel vault over the central nave tended to open, with a longitudinal crack and some lowering of the central part of the arches. The crack line is visible in Fig. 10. Both effects were found increased in the second survey.

Correspondingly, crack lines were present in the nave lateral walls. Indeed, the full development of the mechanism has been prevented by the presence of steel ties at the base of the arches. The effective contribution of the ties in stiffening the system and retaining the walls and vault is demonstrated by the rupture of the central tie that occurred in August 2016 and by the subsequent ruptures of two more ties with the two main shocks that arrived in October. The steel tie broken during the August 2016 event is shown in Fig. 11.

After the ties failed, the church was promptly secured by repairing the broken ties and inserting additional ones to increase lateral capacity.

Most likely, also the interventions that had been performed in the roof area before the earthquake in order to improve the seismic behaviour have contributed to preserve the building. The timber roof structure, needing replacement, was substituted with a new timber one with glulam trusses; a good connection between wall tops and roof was obtained with a low-mass steel truss as ring beam.

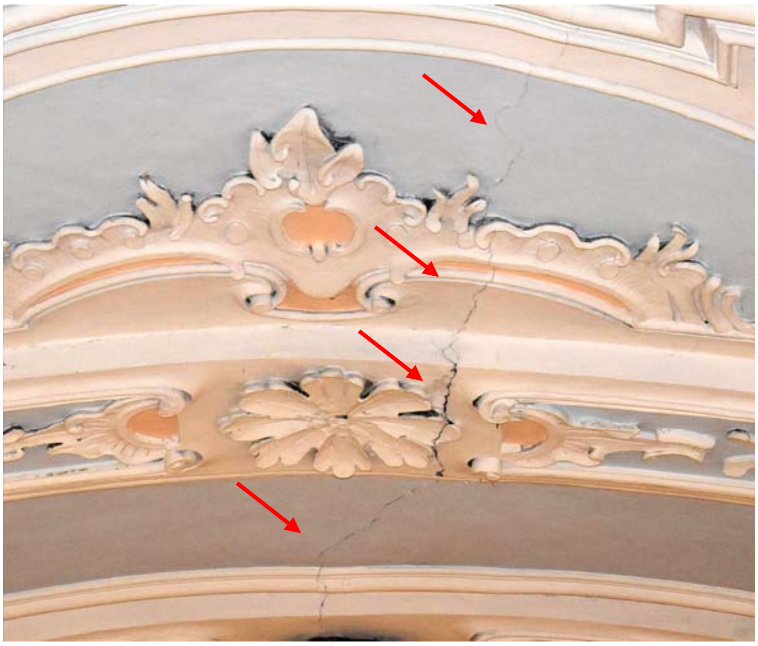

Figure 10. Longitudinal crack in the vault.

Figure 11. Steel tie failure.

4.3 Damage to the vaults

The vaults resulted among the most damaged elements in the group of surveyed churches. Damage was often serious, with some cases of total collapse. Considering two of the cases examined, progression of damage due to accumulation of events may be seen.
The first case is a church with circular plan, which presented serious cracks at first survey time. Cracks were located in the four semi-circular vaults holding the drum and the dome. These last two elements have not reported serious damage in the entire earthquake sequence. On the contrary, damage to the vaults increased with the following events, bringing one of them to collapse limit.
In order to explain such behaviour, the presence of a steel plate hoop confining the drum must be considered. This reinforcement protected the top elements according to the intentions, but the damage occurred in the inferior vaults, which were more difficult to protect with limited interventions. Figure 12 shows the initial cracking and then the advanced damage in one vault.

Figure 12. Damage progressing in a semi-circular vault.

The progression of damage was extreme in the case of fig. 13, where part of the vault had collapsed after the first strong shock and a complete collapse occurred with the following one. This was a case of thin layer vaults, where the bricks are laid flat, resulting in a thickness of only a few centimetres. This kind of vaults is very common in Central Italy and it has shown its high vulnerability in this as well as in other earthquakes. Research programs are in progress to characterize these elements and identify effective interventions to improve their behavior (e.g. Borri et al., 2014). Strengthening may also be based on advanced materials, in order to keep the vault light. In the figure, through the opening due to local collapse the first picture shows a detailed view of the composition of the vault structure. The second image shows the situation after the global collapse and puts into evidence the timber roof structure, which has maintained a good connection with the walls and very likely helped in the global response of the church.

Figure 13. Local and global collapse of a thin brick vault.

4.4 Damage to non-structural elements: the lanterns

Lanterns were present in numerous churches in the area and often showed damage or incipient damage from torsion, as expected according to the relevant reference mechanism, in fig. 14.

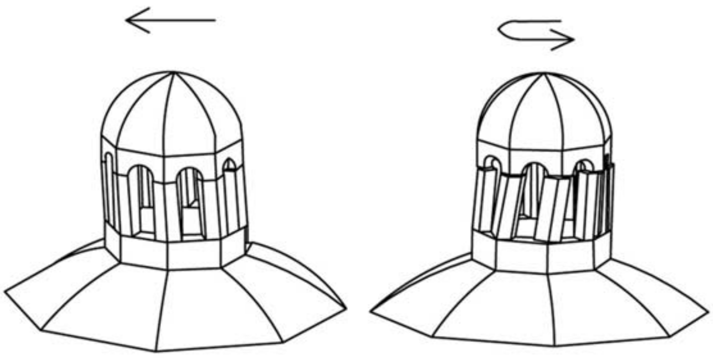

Figure 14. Lateral and torsional response and damage of the lanterns.

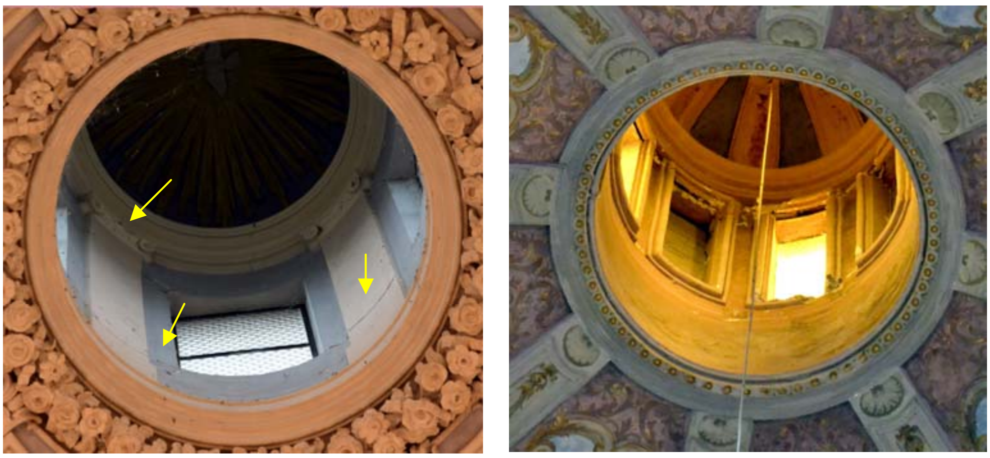

Figure 15. Damage to lanterns.

Figure 15 shows two cases where cracking at the base and on top of the openings had appeared. For the lantern at the left in the figure, during the first survey, no other damage was observed in the dome underneath. Yet, the possibility of further damage that could bring to the collapse of the lantern in the circumstance of a strong aftershock induced to prevent access to the public for the church until repairs were performed. This church could not be re-inspected during the subsequent inspection campaign, but the information came that severe damage to the lantern had actually occurred as foreseen.
It is worth noting that the damage from rotation due to torsion occurred in these lanterns, as well as in the façade in fig. 7, has been observed in many other cases, like belfries and in a tower that is part of a historical palace.

5. INDICATIONS ON INTERVENTIONS

The cases reported above were selected as particularly significant especially for the damage typology and for the considerations that could be derived on the effects of interventions. While for some of these cases an in-depth quantitative analysis is in progress or planned, some general remarks are possible.
In general, all the churches that have been surveyed had undergone some kind of interventions for repair and improvement after the Colfiorito Umbria-Marche earthquake of 1997. Results were different from what observed in other areas and earthquakes. In the L’Aquila earthquake of 2009 where mostly massive and highly stiffening interventions had been performed also on heritage buildings, the response had resulted mainly unsatisfactory. In the current case, projects apparently were careful in avoiding excessive increases and concentrations of masses and stiffnesses, obtaining altogether better results. The above-mentioned case of light ring beam was not the only one found; the extended use of tie rods to improve connections and simple, low-impact interventions seemed to really avoid or limit the effect of the mechanisms for which they were intended. In some cases, however, damage developed in other parts of the building and according to other mechanisms, very likely for a higher level of action. In general, interventions permitted, in spite of some local damage, to preserve the building as a whole. This issue is being further investigated by suitable analyses.

6. CONCLUSIONS

Surveys performed in two different periods to assess the state of damage of churches in the Region Marche after the earthquake sequence of 2016-17 offered the opportunity of observing the evolution of damage for subsequent events and to investigate some effects of the interventions that had been previously carried out for structural improvement. In summary, as could be expected, the seismic events that arrived after the end of the first surveys increased the damage on these weakened structures, developing further the mechanisms that had been recognized. In some instance the situation evolved into localized collapse, but for most of the cases examined the global stability was generally maintained.
In general, simple and low-impact interventions appeared effective in limiting some damage typologies; in some cases, however, damage developed moving to different elements and locations, most likely starting at a higher level of the excitation.

ACKNOWLEGEMENTS

Research performed within the Reluis-DPC (Network of University Labs for Earthquake Engineering-National Civil Protection Agency) Program 2014-18.

REFERENCES

Borri, A., Castori, G., Corradi, M. (2014) A new method for strengthening tiled vaults: “Reinforced Catalan vaulting”, *Proceedings 9th International Masonry Conference*, Guimarães, Portugal.

Casolo S. (2017). A numerical study on the cumulative out-of-plane damage to church masonry facades due to a sequence of strong ground motion, *Earthquake Engineering and Structural Dynamics*, pp. 1-22, published on-line, DOI: 10.1002/eqe2927.

Cescatti, E., Taffarel, S., Leggio, A., da Porto, F., Modena, C. (2017). Macroscale damage assessment of URM churches after the 2016 earthquake sequence in Centre of Italy, *Proceedings ANIDIS Conference*, Pistoia, Italy.

Da Porto F., Silva B., Costa C., Modena C. (2012). Macro-scale analysis of damage to churches after earthquake in Abruzzo, (Italy) on April 6, 2009, *Journal of Earthquake Engineering*, 2012, 16(6), pp. 739-758, doi: 10.1080/13632469.2012.685207.

Doglioni F., Moretti A., Petrini V.(1994). *Le chiese e il terremoto*, Lint Press, Trieste.

INGV (2017) https://ingvterremoti.wordpress.com/2017/01/23/sequenza-in-italia-centrale-aggiornamento-del-23-gennaio-ore-1100 (on Dec. 20, 2017)

Lagomarsino S., Podestà S. (2004a). Damage and vulnerability assessment of churches after the 2002 Molise, Italy, earthquake, *Earthquake Spectra*, 20(S1), pp.S271-S283, doi:10.1193/1.1767161.

Lagomarsino, S., Podestà, S.(2004b). Seismic vulnerability of ancient churches: part 1. Damage assessment and emergency planning, *Earthquake Spectra*,2004b, 20(2), pp.377-394.

Lagomarsino, S., Podestà, S.(2004c). Seismic vulnerability of ancient churches: part 2. statistical analysis of surveyed data and methods for risk analysis, *Earthquake Spectra*, 20(2), pp. 395-412.

MiBAC, PCM-DPC (2006). Scheda per il rilievo del danno ai beni culturali – Chiese, modello A-DC.

Parisi M.A., Chesi C., Cattaneo S., Falconi C. (2015). Seismic Interaction of Timber Roofs and supporting Walls. *Proceedings. 3rd International SHATIS Conference*, pp. 716-723, Wroclaw, Poland.

Parisi, M.A, Sferrazza Papa, G.(2017). Chiese nel terremoto del Centro Italia; Confronti e Osservazioni, *Proceedings IFCRASC Conference*, Milano, Italy.

Sorrentino L., Liberatore L., Decanini L.D., Liberatore, D. (2014). The performance of churches in the 2012 Emilia earthquakes, *Bulletin of Earthquake Engineering*, (12), pp. 2299–2331, doi 10.1007/s10518-013-9519-3.