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Collapse mechanisms of churches: typical recurrence rates and damage levels from the analysis of field data after the 2012 Emilia earthquake

Briselda Calliku[a], Alice Festa[a], Stefano Barbò[a], Anna Maria Basso Bert[c], Claudio Chesi[b*]

[a]*Politecnico di Milano, SSBAP, P.za Leonardo da Vinci, 32 – Milano 20133, Italy*
[b]*Politecnico di Milano, DABC, P.za Leonardo da Vinci, 32 – Milano 20133, Italy*
[c]*SABAP – BS, Via Gezio Calini 26, Brescia 25121, Italy*

Abstract

Within the context of fast procedures for the evaluation of seismic damage, an interesting tool is given by the special form in use for churches. The procedure implemented in this form is based on the set of 28 local collapse mechanisms which have been identified as meaningful to deal with the typical Italian configuration of churches; for each mechanism, a damage level from 0 to 5 has to be specified and a global damage index is therefore computed. An interesting application of the above procedure has been possible for a wide group of churches in the province of Mantua, which suffered damage from the 2012 Emilia earthquake. Specifically, it has been possible to access data and analyze 159 forms. Through a detailed analysis of them, it has been possible to define, for each different collapse mechanism, the recurrence rate and the corresponding distribution of damage levels. In this way, it clearly appears, on the one side, which mechanisms are likely to be activated and, on the other side, in which cases high damage levels can be easily reached. This kind of analysis has resulted into a clear picture of the architectural typologies and construction techniques in use in the region; moreover, suggestions have come in terms of seismic prevention, as clear evidence has been given to the damage mechanisms which are more likely to be activated.

Keywords: church; seismic damage; Emilia earthquake 2012; collapse mechanisms.

* Corresponding author. Tel.: +39-02-23994335; fax: +39-02-23994220.
E-mail address: claudio.chesi@polimi.it

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1. Introduction

Within the context of fast procedures for the evaluation of seismic damage in historical buildings, an interesting tool is given by the special form which has been developed in Italy for the specific case of churches and has been now in use for several years; see MiBAC, PCM-DPC (2006), Lagomarsino and Podestà (2004), Lagomarsino (2012), Giovinazzi and Lagomarsino (2001). The procedure implemented in this form is based on the set of 28 local collapse mechanisms which have been identified as meaningful to deal with the typical Italian configuration of churches; for each mechanism, a damage level from 0 (no damage) to 5 (collapse) has to be specified and a global damage index is therefore computed. This is typically a fast procedure which can therefore be applied extensively to a wide set of churches, thus providing a meaningful database for a statistical evaluation of the earthquake damage.

An interesting application of the above procedure has been possible following the earthquake occurred in 2012 in the north of Italy, see Tertulliani et al. (2012). The epicentre for the 5.8 magnitude seismic event was in the Emilia region, but many buildings in the neighbouring Lombardy region were also seriously affected, mainly in the province of Mantua. Several collapses were reported for industrial and monumental buildings, while the damage level was lower for the residential ones; in the case of the architectural heritage, damage was very serious in general, mainly with reference to churches, towers, and bell towers, see Sorrentino et al (2014), Milani and Valente (2015). One third of post-earthquake field inspections was dedicated to churches; in the Lombardy region, specifically, out of a total of 653 surveys, 212 were relative to churches, 188 of which belonging to the Mantua province.

This group of churches, therefore, provided an interesting sample for the application of the special damage inspection form, allowing for the implementation of a wide database and consequent statistical analyses. From these, interesting considerations have come in terms of activation and progress of possible collapse mechanisms, as discussed in the following.

Observing high levels of seismic vulnerability for this group of churches is not surprising. From a general point of view, indeed, several construction details are not in favour of safety, like global size, height of façade walls, intersecting vaults, lack of steel ties, poor level of connection between walls. In this specific case, however, a major contribution to vulnerability comes from the construction technique in use for brick masonry walls; mortar mechanical properties, indeed, are very poor due to the prevalent use of clay rather than lime.

2. Data acquisition

Results from post-earthquake field inspections, in terms of damage forms, were available for consultation at the Seismic Archive of the SABAP office for the cities of Brescia and Bergamo. A large quantity of interesting documents is stored in the archive, including the design of both provisional safety interventions for the emergency phase and restoration works as well. Within a time period of ten years after the occurrence of seismic events, damaged structures have been repaired almost entirely; a wide set of documents is therefore available, providing both description and interpretation of damage as well.

As already mentioned, documents available for consultation correspond to a total of 212 churches; for the purpose of the present work, all of the 188 churches belonging to the Mantua province have been considered. By the end, a set of 159 churches was defined, corresponding to the cases for which the special damage forms, filled during the post-earthquake field surveys, were available.

3. The damage form for churches

As already recorded, the damage form is based on a list of 28 local collapse mechanisms, which have been identified as a complete set for the description of common seismic damage situations and collapses in churches. As a result of the field survey, a damage index is associated to each mechanism, in the range between 0 (no observable damage) to 5 (full collapse); a global index is then defined for the church, based on the average of single values. Several interesting considerations can be done on this procedure (see Binda et al. (2007)).

Clearly, after surveying several cases and filling the relative forms, a global damage map comes out for the inspected region; results are meaningful, as the form is based on well-defined and widely accepted references: the list of mechanisms and the damage evaluation scale. Even if the global damage index may not be meaningful in some cases, as coming from the average of the values assigned to all the possible mechanisms, clear indications are given in terms of priority for safety or repair interventions; see Carvelli et al. (2011). No consideration can be developed for the real safety levels, as the procedure which is implemented in the form is typically based on a qualitative approach; all the same, the procedure allows for the comparison of different situations, both in the sense of different churches, and different intervention phases in the same church.

Beyond such operational goals, which apply to the post-earthquake emergency phase, the damage form for churches provides an interesting tool for the evaluation of the recurrence rate and severity of collapse mechanisms which are likely to be activated by the seismic motion. As already mentioned, indeed, each single damage index, being referred to a specific case, may have a limited interest; however, where a wide set of analyses is available covering a well-defined region, statistical considerations are possible and interesting information can be highlighted on both the relevance of single collapse mechanisms and typical construction quality in the region as well. This topic has been widely debated by Calliku and Festa (2022) for the Mantua province in relation to the 2012 seismic event; a summary of main conclusions is given here.

In the following the list of mechanisms is recalled; they are grouped on the basis of the “macro-elements” to which they refer. By “macro-elements” the typical structural blocks which are assembled into the global church structure are intended (see Fig. 1).

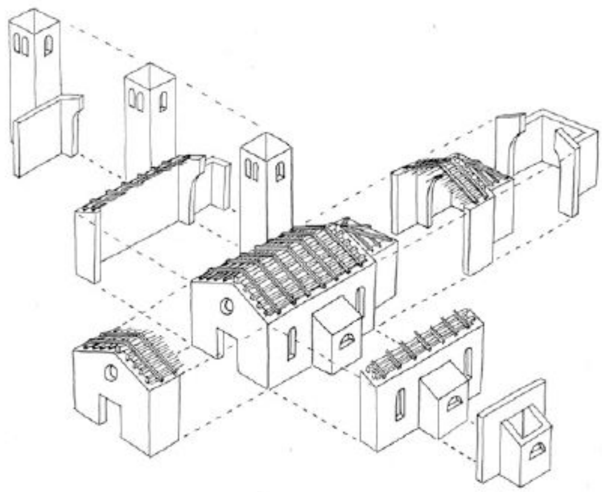

Fig. 1. Subdivision of the church building into macro-elements.

- “Facade” macro-element (4 mechanisms): global façade overturning, top portion overturning, in-plane mechanisms, “protiro” and “nartece”
- “Main room” macro-element (5 mechanisms): transversal response, shear mechanisms in lateral walls, longitudinal response of colonnade (more naves are present), main nave vaults, lateral nave vaults
- “Transept” macro-element (3 mechanisms): overturning / shear mechanisms in end walls, vaults
- “Triumphal arch” macro-element (1 mechanism): in-plane mechanisms
- “Dome” macro-element (2 mechanisms): dome shell, lantern
- “Apse” macro-element (3 mechanisms): global overturning, shear mechanisms, vaults
- “Roof system” macro-element (3 mechanisms): main nave, transept, apse
- “Lateral chapels and annexed blocks” macro-element (4 mechanisms): chapel overturning, chapel vaults, structural interaction due to irregularities, belfries – pinnacles - statues
- “Bell tower and cantilevered portions” macro-element (3 mechanisms): tower main body, top cell.

4. A territorial view

To the purpose of a first global representation of results from the damage forms, values of the damage index, ranging between 0 and 1, have been assigned to 8 different sub-ranges corresponding, in the graphical representation, to a color scale from green to violet, see Fig. 2. In this way, a territorial map has been developed (Fig. 2), which shows all the examined churches on a shake map reproducing the variation of PGA over the territory (2012 Emilia earthquake, second main shock, May 29th). Colors of triangular symbols corresponding to churches indicate to the damage level.

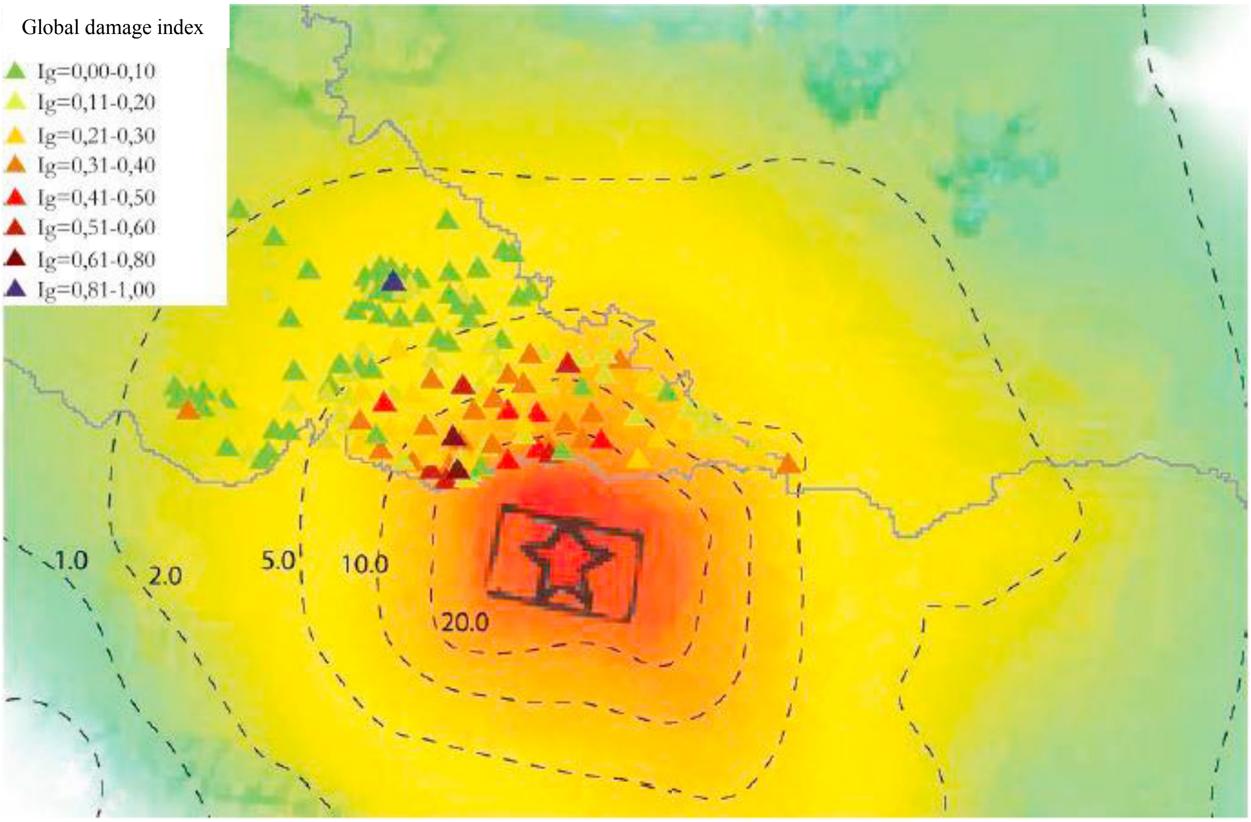

Fig. 2. Shake map for the 2012 earthquake and damage levels for churches in the Mantua province (PGA values as % of g).

As a global comment, the damage is progressively decreasing as the distance from the epicenter increases; this trend looks very regular, with a limited number of exceptions, clearly suggesting that the construction quality of churches is constant over the territory. In general, the value of the damage index is in the range 0.3–0.8 for PGA values ranging between 5 and 20 % g.

Explanations can normally be easily provided for cases not in line with this trend. This applies typically to the case of the Santa Barbara cathedral in Mantua, for which a damage index of 0.9 is specified, although very distant from the epicenter. A local collapse, indeed, took place in the cathedral, affecting the lantern in the bell tower; the damage form was filled with reference to the bell tower only, considering two mechanisms in total.

In other cases, the damage index is very low at locations close to the epicenter. This happens for some churches along the border between the Emilia and Lombardy regions, where damage forms were filled for chapels belonging to cemeteries; these are clearly simple structures, not comparable to normal churches.

In general, many factors can be considered to explain anomalous cases: construction typologies, maintenance level, local soil conditions.

5. Recurrence rates of collapse mechanisms

When damage data are available for a wide set of churches, it is possible and clearly of interest to monitor the occurrence of different collapse mechanisms. This could be done considering, for each of the 28 mechanisms, the ratio between the number of cases when the mechanism was activated (damage index greater than 0) and the total number of cases in the data set (159 in this analysis). This approach, however, does not lead to meaningful results in the case of mechanisms affecting macro-elements with a limited occurrence. It was decided, therefore, to refer to the ratio between the number of activations and the number of real occurrences of the macro-element. Results are shown in Fig. 3 for both the approaches, with orange columns for the first and blue columns for the second one.

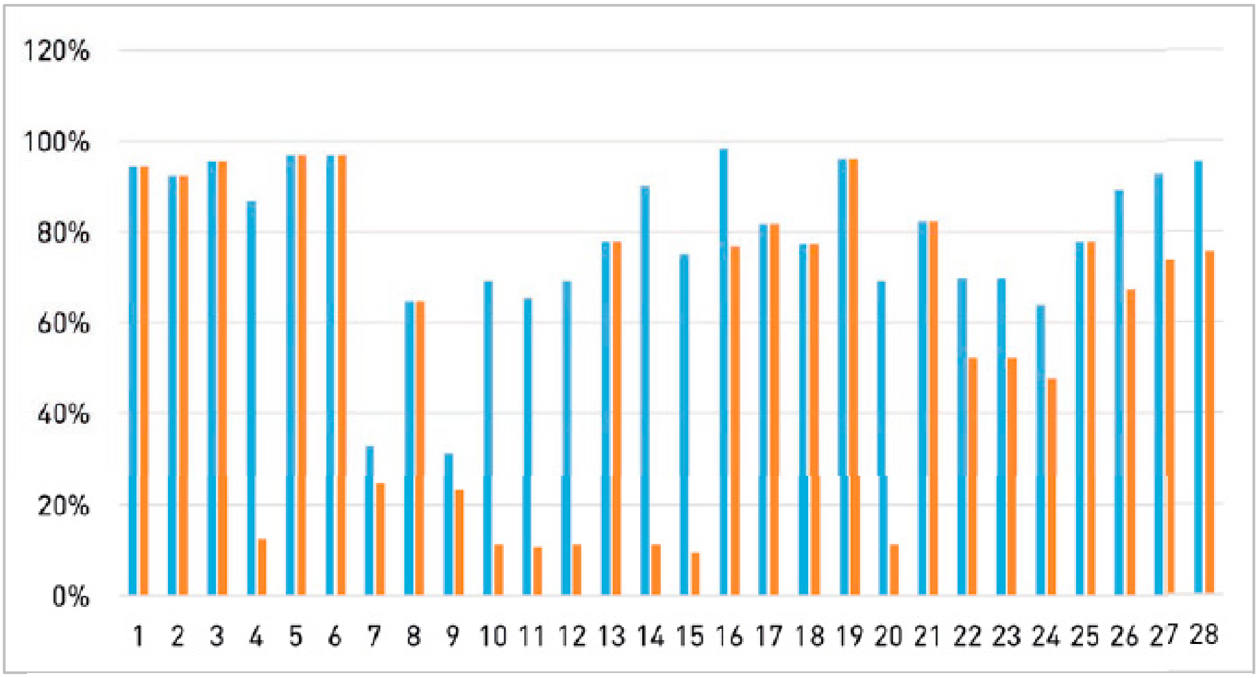

Fig. 3. Occurrence rates of collapse mechanisms.

With this kind of representation of results, no consideration is given to the damage levels; all the same, interesting indications are given in terms of the church elements where damage is more likely to occur due to an earthquake. To this purpose, it is convenient to group results, referring to macro-elements rather than to single collapse mechanisms, as above detailed at point 3. The outcome of this is shown in Fig. 4, where recurrence rates are given for the different macro-elements, from higher to lower recurrences.

From this data representation it clearly appears that:

- mechanisms affecting the façade, the bell tower and all cantilevering elements are the most common, with an occurrence rate over 90%;
- mechanisms affecting the apse, the dome and the roof system occur in about 80% of cases;
- triumphal arch, chapels and connected structural blocks mechanisms are activated in about 70% of cases;
- the transept and the church main room undergo activation of mechanisms in about 60% of cases.

All the above considerations provide a general classification, of a very simple nature, with no consideration of the real complexity of the structural complex and of specific construction details. In the following, a deeper insight into the problem is achieved looking at the damage levels.

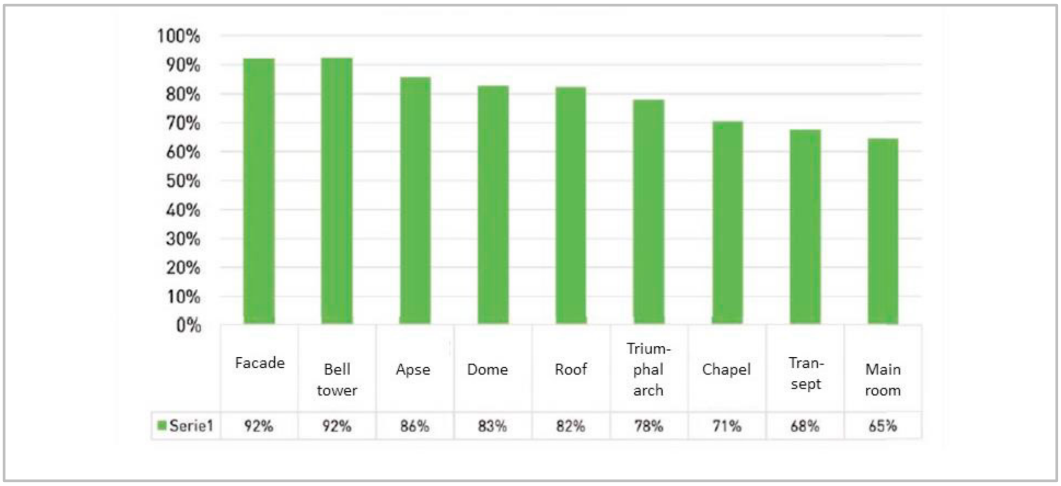

Fig. 4. Mechanism occurrence rates with reference to macro-elements.

6. Damage progress.

Previous considerations on the occurrence rates of single collapse mechanisms need to be integrated considering the real damage levels reported in the field analysis. Obviously, distinction has to be done between the cases when a mechanism has just been activated with a low level of damage and cases when accumulation of damage is in progress and a collapse condition might be reached. In other words, the level of danger associated to mechanisms has to be considered. To this purpose, the diagram in Fig. 3 has been converted into the one in Fig. 5, where each column, corresponding to the mechanism occurrence rate, also reflects the occurrence of the different damage levels through a color scale.

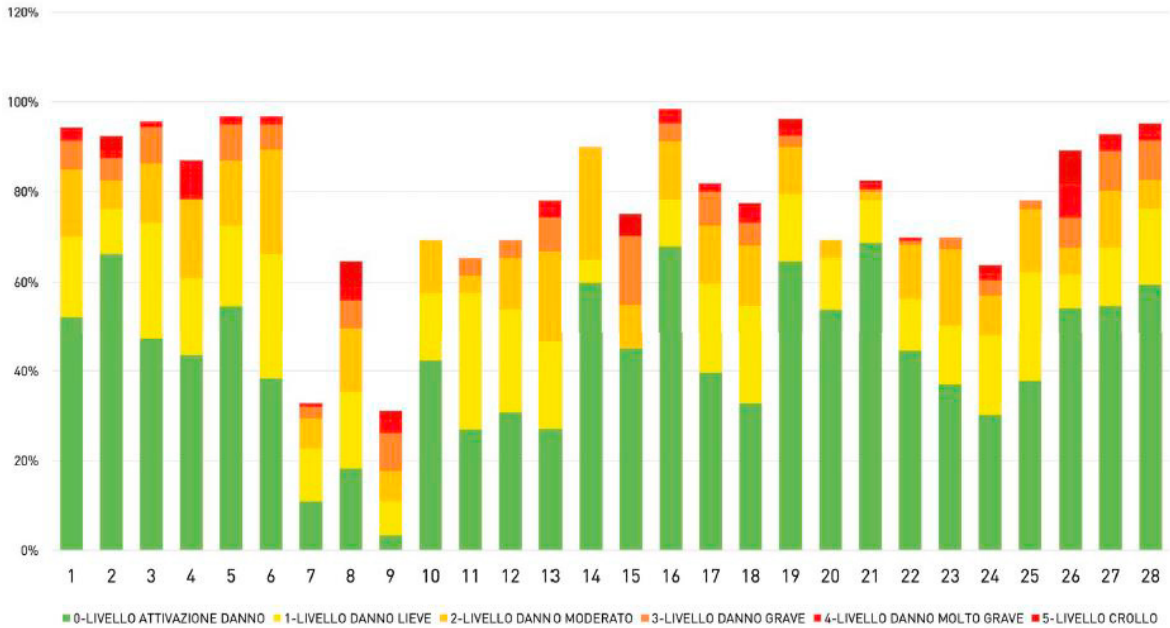

Fig. 5. Occurrence rates of single mechanisms with indication of the damage level.

This kind of analysis provides important indications from the point of view of the progress of damage, allowing for the distinction among different situations. A more global view of the problem, therefore, becomes possible, based on three aspects: occurrence rate of mechanisms, damage evolution properties, occurrence of serious damage levels or even collapse. In the following, an example is given, looking at typical situations (see Fig. 6). A general discussion can be found in Calliku and Festa (2022).

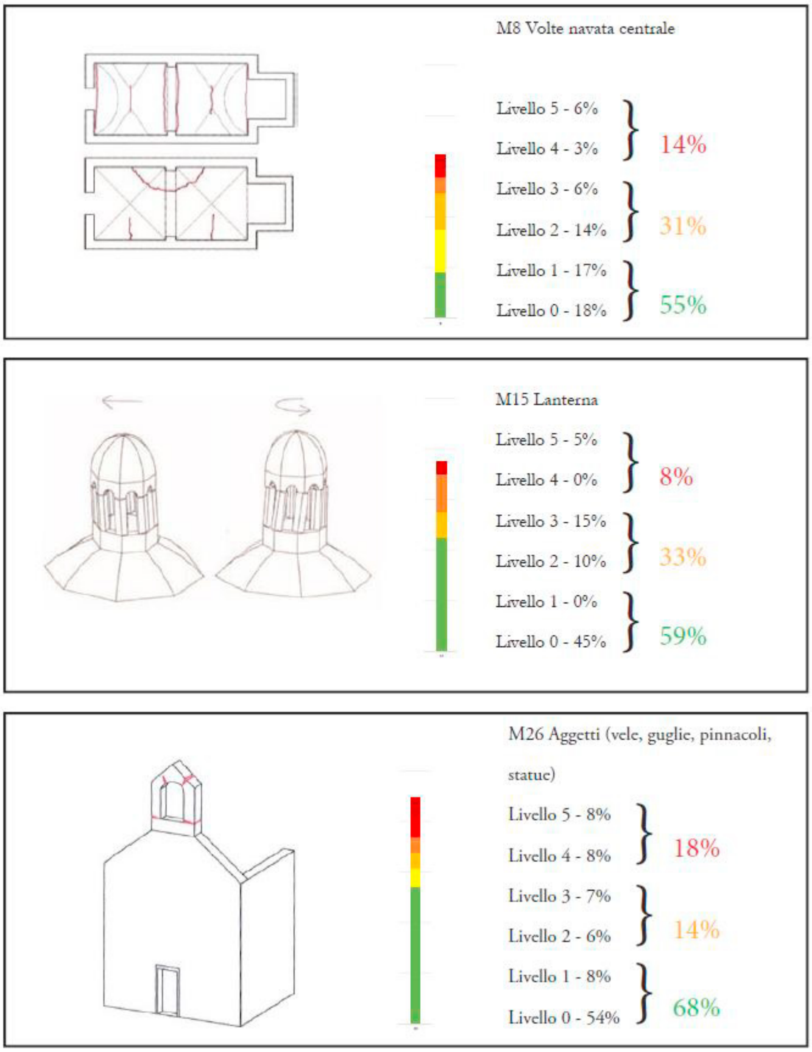

Fig. 6. Different situations from the point of view of the progress of damage.

Collapse mechanisms in Fig. 6 are characterized by high recurrence rate, fast damage progress and serious levels of maximum damage; collapse is possible. Specifically:

- Main nave vaults: occurrence rate is moderate (65%); the damage progress is fast, from low and medium to medium and serious; the percentage of collapses is high.
- Lantern: occurrence rate is high (75%); in most cases (59%) damage is light but, if activated, it has a fast progress to moderate, serious, very serious, collapse.
- Cantilevering elements: high probability of activation (89%); in most cases (68%) damage is light or non-existent but, as it appears, the progress is extremely fast, with high probability of collapse.

7. Conclusions

This work was suggested by the possibility of accessing a wide database including the damage forms relative to churches in the province of Mantua which suffered damage after the 2012 Emilia earthquake. As expected, interesting conclusions have come from the availability of a complete and extended set of data. On the one side, the effectiveness of the damage form for churches has been confirmed, showing that the wider is the sample, the deeper is the interpretation of seismic effects. On the other one, an interesting evaluation was possible for the construction quality and details which are typical of the region, providing useful suggestions for seismic upgrade interventions. A high level of uniformity has been clearly shown for the local building tradition.

Conclusions are partially of a general nature but, in many cases, related to the specific construction properties which are typical of the region. All the same, the procedure here employed for the analysis of data could be applied to other cases; the possibility of extending it to other structural typologies could also be considered.

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