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How the 1976 Friuli earthquake prompted research into the seismic behaviour of historical buildings and the formulating of effective and tailored seismic improvements

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ABSTRACT Cultural heritage constitutes a fundamental resource for a country, both in terms of cultural identity as well as tourist attraction. This is particularly true for Italy, where earthquakes have severely damaged monumental buildings and historical centres in the past, causing huge losses and requiring great efforts for the interventions. The 1976 Friuli earthquake was the starting point for a new, observational-based approach to the vulnerability analysis of historical buildings, and in particular to churches and bell-towers. This new approach enabled interpreting the mechanisms of damage and identifying the weakness points for a more effective and focused intervention of retrofitting. This paper presents a brief overview of how the 1976 Friuli earthquake experience contributed both to the knowledge of seismic behaviour of historical buildings and to the formulation of tailored safety upgrading projects.

Key words: 1976 Friuli earthquakes, historical buildings, knowledge improvements, tailored safety upgrading, seismic behaviour.

1. Introduction

In 1984, after the disastrous earthquakes of 1976 in Friuli (north-eastern Italy) and 1980 in Irpinia (southern Italy), Gavarini and Angeletti (1984) published a paper entitled “Seismic vulnerability of existing buildings. The state of the structure and future development of research in Italy”, in which they highlighted how vulnerability of existing buildings is one of the most important problems in evaluating seismic risk. At the time, plans for mitigating risk were in progress in the United States and in Japan, with different levels of analysis according to the operative scale, and with an assessment of vulnerability in terms of damage and/or victims based on different approaches (subjective, experimental, theoretical-mechanical). Nevertheless, Gavarini and Angeletti (1984) pointed out the differences and complexity in the case of application to Italian urban areas, and in particular to historical centres, and stressed the fact that a scientific approach for assessing seismic risk had not yet been achieved, evidencing the necessity for future research developments and implementation programs.

In the same year, Benedetti and Petrini (1984) proposed a method to evaluate the vulnerability of masonry buildings, subsequently used for assessing public buildings in a specific program of the Italian National Council of Research program (CNR, 1993). Successively, Grimaz (1992, 1993) proposed an extension of the above method for evaluating the vulnerability of masonry building in historical centres, also taking into account the influence of the structural context. *A posteriori* studies were carried out to define the fragility curves by analysing the data of the historical centres of Venzone and Tarcento (both in the Udine province) damaged by the 1976 Friuli earthquake in north-eastern Italy, and of Barrea (L'Aquila province) damaged by the 1984 earthquake in central Italy (Grimaz *et al.*, 1997). In these researches, the damage data collected after the 1976 Friuli earthquake played a decisive role.

At the end of the 1980s, studies were carried on the buildings of the historical centre of Castelvetere in Calore (Avellino province) in southern Italy (Giuffrè *et al.*, 1988) and on the historical neighbourhood of Graziella of the Ortigia Island (Syracuse province) in Sicily (Giuffrè, 1993). Giuffrè (1988) proposed a code of practice as a guide for operating improvements coherently with the historical fabric. The approach was based on the analysis of the typology of construction, constructive techniques, and conservation state of the building. The vulnerability analysis was identified as a preliminary study that permits an evaluation of the potential mechanisms of damage in case of an earthquake, but also to define a contextualized approach of intervention for risk mitigation.

From 1988 to 1998, a specific program of research of the CNR/GNDT (National Research Council/National Group for the Defence from Earthquakes) addressed the study of the vulnerability of historical buildings. The research activity aimed at developing an observational method for assessing the seismic vulnerability of buildings and ancient building aggregates, with a particular focus on monumental and cultural buildings. Furthermore, the studies intended to obtain correlations between vulnerability and damage. In practice, the seismic vulnerability of historical buildings was assessed through *a posteriori* observations and analysis of real cases. The studies were carried out as an "anamnesis", i.e. evaluating and classifying the construction features of the buildings, their transformations through the time and the state of damage caused by previous earthquakes. In this systematic work, the 1976 Friuli earthquake played a fundamental role, the approach being conceived and developed on analysing a large set of churches damaged by the 1976 Friuli earthquakes of 6 May and 11 and 15 September (Doglioni *et al.*, 1994).

In the following sections, we summarise the innovations and enhancements in the damage analysis of historical buildings, highlighting the contribution of data from the 1976 Friuli earthquake. Furthermore, we underline how those innovations contributed to formulating a new approach aimed at upgrading the safety of historical buildings by considering the history of the building and the conservation requirements. Finally, we note the lessons learnt from the studies based on the data of the 1976 Friuli earthquake, which played a key role in the progress made after that experience.

Other studies carried out on existing buildings (not specifically focused on monumental buildings and churches) using the data of damage collected after the 1976 Friuli earthquake are presented in Carniel *et al.* (2001), Di Cecca and Grimaz (2008), and Grimaz and Malisan (2018).

2. The innovative approach of Friuli earthquake damage studies

The 1976 Friuli earthquake marked a turning point in the knowledge of seismic behaviour of historical buildings (Slejko *et al.*, 2018). The innovations can be summarised by the following main aspects:

a) the series of powerful earthquakes that devastated Friuli in 1976 (Slejko, 2018) seriously damaged the medieval historic centres and a large number of churches and bell-towers in the affected area;
b) photos of the pre-earthquake condition as well as photos immediately after the seismic events (see e.g. Briseghella *et al.*, 1976) were available for most of the churches (Fig. 1) and bell-towers;
c) as a fundamental choice for the Friuli reconstruction, it was decided to privilege the repairing of existing buildings as much as possible rather than constructing new ones.

These aspects, for the historical and monumental built heritage, implied the collection and organization of all the available pre- and post-seismic documentation. In this way, for the first time in Italy, a mass of information about the seismic behaviour of masonry buildings was compiled. This huge amount of data constituted the premise for carrying out a systematic study using an *a posteriori* approach based on damage analysis. The approach aimed at identifying the characteristics and the causes of damage, as well as the criteria for designing effective repair interventions. At the same time, the way was paved for studies on seismic vulnerability of the built heritage on the basis of systematic objective evidence diagnosis. These studies significantly increased the ability to understand, from a technical viewpoint, both the historical heritage construction characteristics and the previous damage.

As a result, two main innovations were introduced:

a) better knowledge of the seismic behaviour of masonry buildings, allowing the development of more efficient intervention techniques for historical buildings;
b) the introduction of evidence-based criteria to carry out interventions focused on reducing buildings vulnerability, even if they have not yet been affected by earthquakes.

In the following, we illustrate the key concepts related to the abovementioned innovations.

Fig. 1 - The church of Santa Maria degli Angeli in Gemona del Friuli (Udine province) before and after the earthquake of May 1976.

2.1. Damage analysis based on the concepts of macro-element and mechanism

The huge availability of data induced researchers involved in the CNR research program to create a specific photographic archive with the aim of documenting the status of each monument before the earthquake, after the first main shock of May and after the main shocks of September 1976. The complete sequences found allowed the researchers to document the evolution of the damage process and to study the kinematic development of the damaging processes, also taking into account the conditions before the earthquake.

In particular, the systematic collection of graphic and photographic documentation enabled the researchers to introduce an "epidemiological" approach that could "read the pathologies", considering also the "damage history" of the building before and after the earthquakes of 1976.

Researchers prepared a form with the specific purpose of comparing the vulnerability and damage conditions, respectively before and immediately after the earthquake. The form was applied on about 350 churches and the analysis was based on two main key concepts.

The first key concept is the "macro-element". The macro-element was defined by the researchers as "a constructively recognizable and complete part of the building that can coincide with an architectural or functional part" (Fig. 2). Usually, it is composed of multiple walls and elements connected to each other, so that it constitutes a single part standing by itself and, in some cases, volumetrically defined, although it is usually connected and not independent of the construction complex. The partition of the church into macro-elements was introduced for a systematic analysis, description, and classification of the damage and to facilitate its understanding.

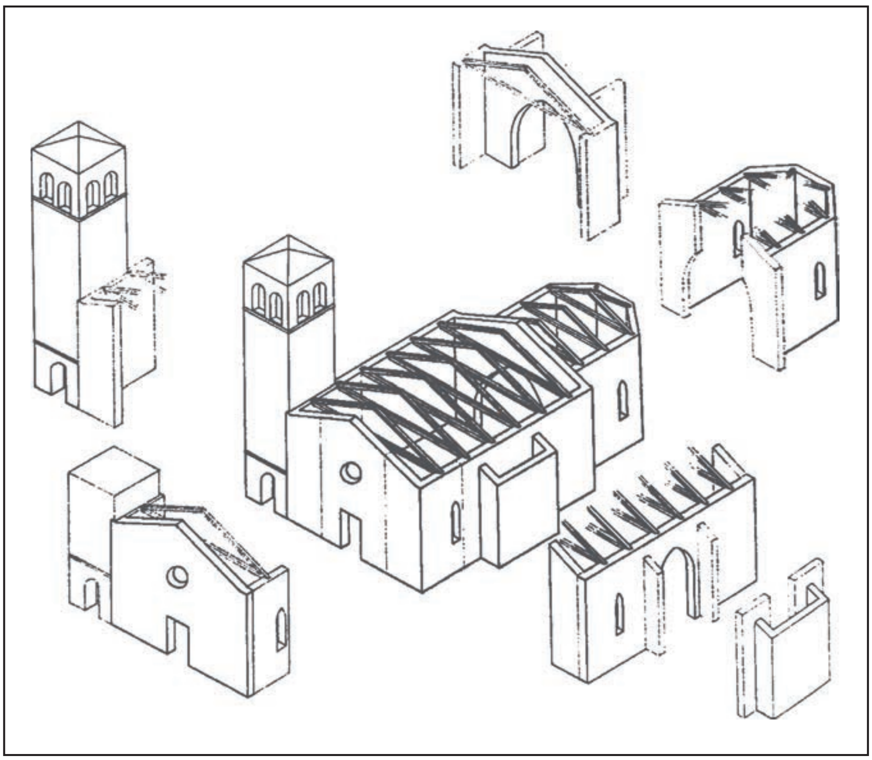

Fig. 2 - Macro-elements of the Santo Stefano Church in Valeriano (Udine province) (from Doglioni *et al.*, 1994).

The second key concept is the "mechanism". The mechanism is the kinematic representation used to interpret and describe both the behaviour of a unitary structural part (macro-element) during an earthquake and the consequent related characteristics of damage (Figs. 3 and 4). The mechanism is necessary both for the dynamic and mechanical interpretation of the damage that already occurred and for predicting further damage, since the future behaviour can be interpreted as a progression of the mechanism.

In practice, the seismic behaviour of the churches was studied by separating the macro-elements of each church, and recognizing for each of them an almost autonomous seismic behaviour. For each macro-element, researchers carefully interpreted the damage to identify the already mobilized mechanisms or those that could be activated. This research on damage highlighted the repeatability of certain cracks and/or deformation phenomena in specific architectonical parts, thus providing an initial series of expected damage on macro-elements identified in buildings belonging to similar architectural types. This evidenced the possibility of using these data for characterizing the vulnerability of buildings, by identifying the typical potential mechanisms correlated to specific architectonical features of the macro-element.

The damage analysis of churches and bell-towers in Friuli, therefore, became a significant source of knowledge both for vulnerability studies and for the definition of "problem-specific" safety upgrading interventions.

2.2. *A posteriori* vulnerability characterization

From the numerous examined cases, a very close connection emerges between the construction architectonic features, the transformation processes, the previous damage (building history and damage history) and the type and extent of the damage sustained after the earthquakes of 1976.

The *a posteriori* analysis enabled the researchers gather some important information in terms of seismic vulnerability, namely the "predisposition of a building to be subjected to damage due to an earthquake". Considering that the damage derives from the activation of a mechanism in each macro-element, the vulnerability could be associated to the potential activation of a mechanism. This permits recognising three types of vulnerabilities:

- typical vulnerability: this concerns the insurgence of damage mechanisms strictly related to the conformation of the macro-element;
- specific vulnerability: this is linked to factors and situations that facilitate and/or drive the progression of the damaged associated with the activated mechanism (i.e. weaknesses or discontinuities linked to the construction history, enlargements, structural modifications, previous damage, etc.);
- endemic vulnerability: this relates to materials and/or building techniques used in a certain geographic and cultural area. It is a type of vulnerability introduced after the comparison among the distinctive modalities of damage observed after earthquakes in different areas.

The peculiar constructive characteristics of a building, considering also its original state and transformations, allow forecasting the potential damage that could result as the progression of the activated mechanism. This approach led to introducing a new concept of structural improvement, as a set of interventions directly aimed at inhibiting the mechanism activation or progression.

The results of this intense research activity are illustrated in detail in the book of Doglioni *et al.* (1994), which constituted the fundamental reference point for subsequent research and improvements in the sector.

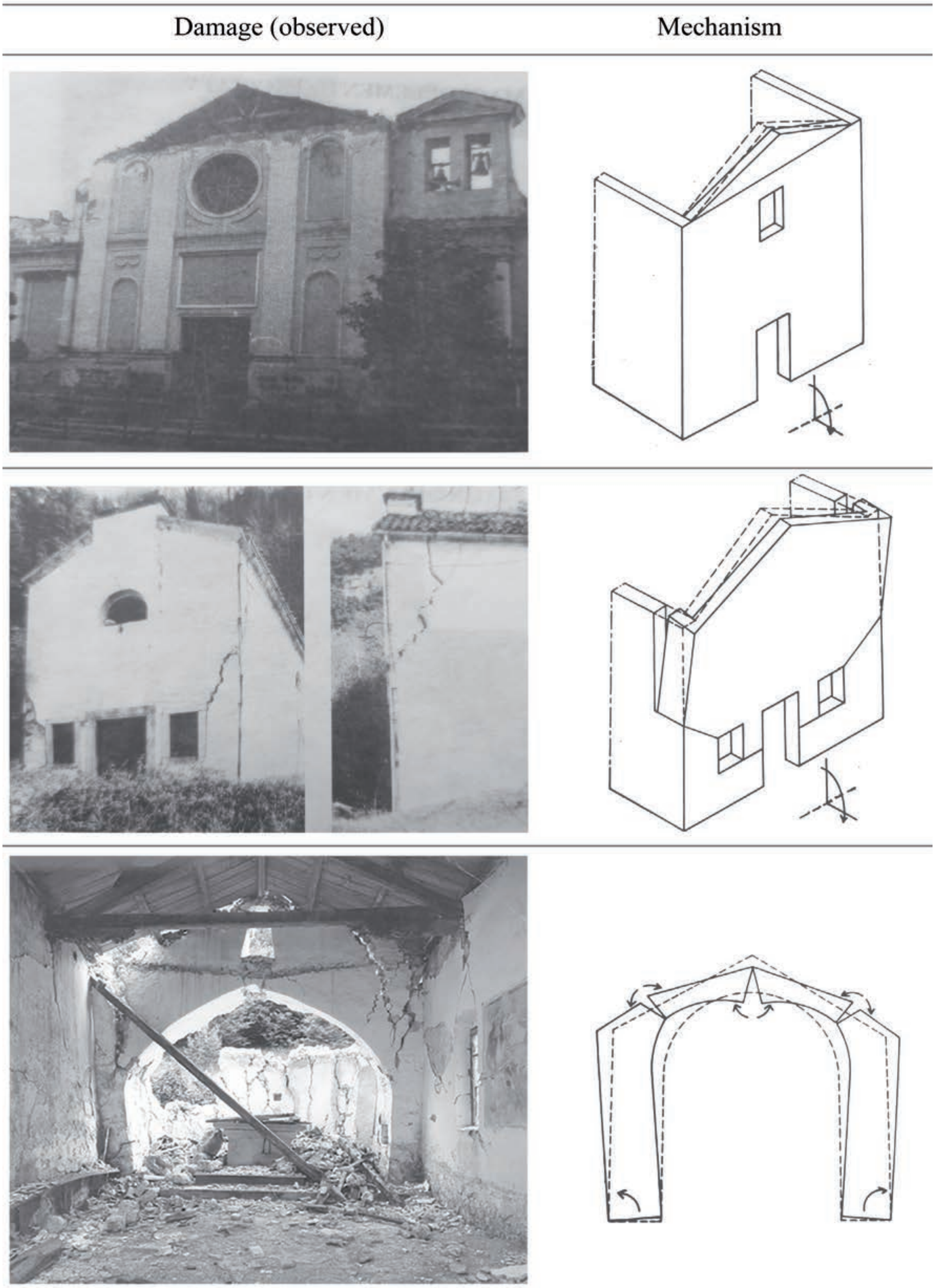

Fig. 3 - The damage on churces and the related mechanism scheme (modified from Doglioni *et al.*, 1994 and Doglioni, 2000).

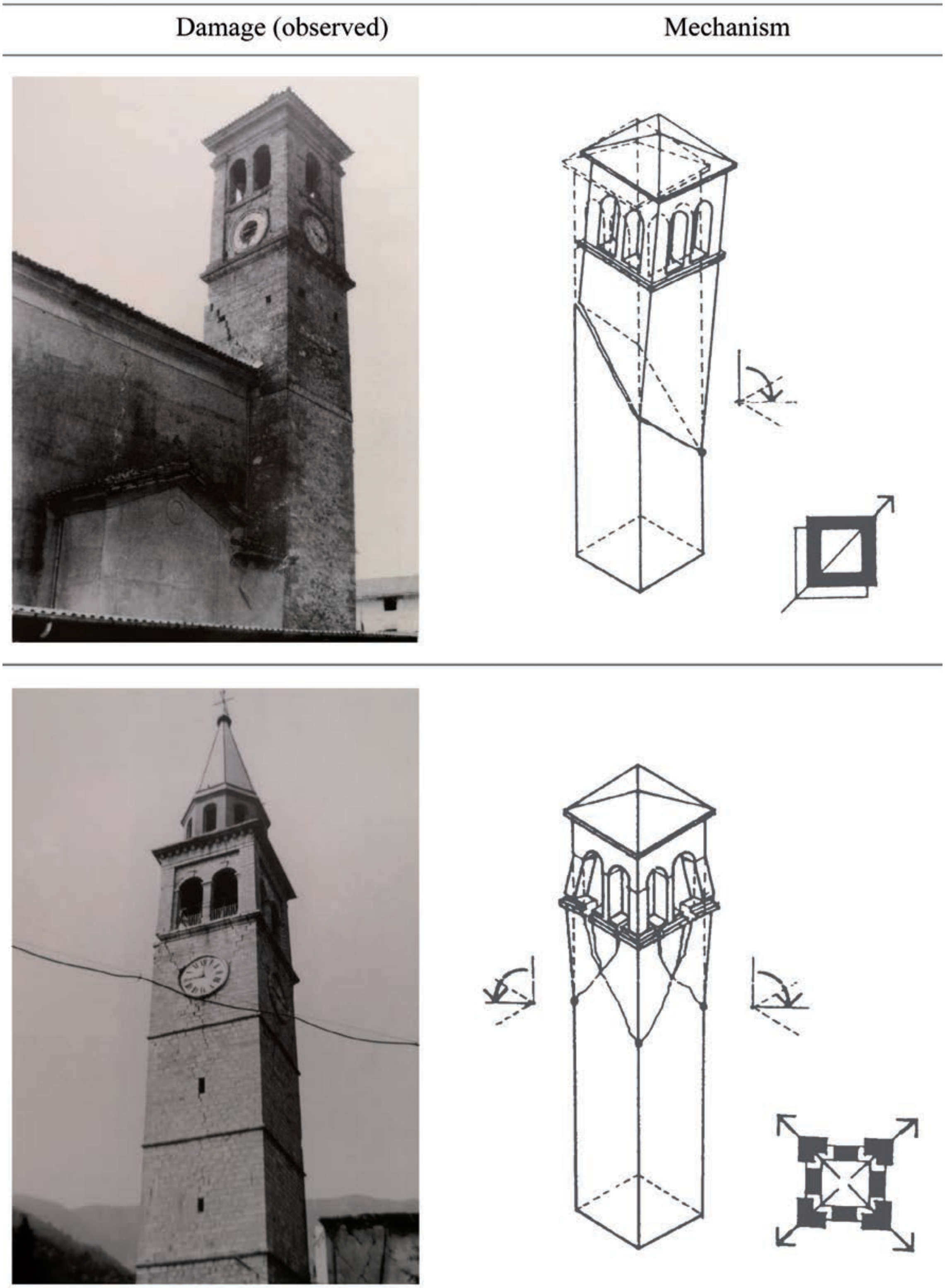

Fig. 4 - The damage on bell towers and the related mechanism scheme (modified from Doglioni *et al.*, 1994 and Doglioni, 2000).

2.3. Progression of damage

The massive and systematic acquisition of pictures from the very first moments after the 6 May earthquake allowed beginning to recognise the evolution and progression of damage. The damage progression is an effect of the aftershocks or of new earthquakes. Observations highlight that the damage progression is closely linked to the evolution of the mechanisms already activated by the first shock. This aspect is particularly evident when observing the consequences of the shocks of September 1976 in Friuli. Fig. 5 shows the progression of damage in the cathedral of Venzone, which was almost completely destroyed after the September events. The effects of damage progression were further recognised also in the subsequent Italian earthquakes in Irpinia (1980), Umbria-Marche (1997), Aquila (2009), Emilia (2012), and central Italy (2016) (Grimaz and Malisan, 2017).

In the following, section 3 summarises the main improvements based on the studies on the data of the 1976 Friuli earthquake.

3. Enhancements in historical buildings safety based on Friuli studies

The studies on Friuli earthquake damage introduced new concepts which led to enhancements, especially in the systematisation of interventions on damaged structures. The analysis of seismic damage permitted establishing the basis to define evidence-based criteria for implementing interventions. Furthermore, the experience enabled establishing the methodologies for a systematic damage survey aimed at the definition of interventions.

3.1. Code of practice for a "problem-specific" safety improvement

The methods and concepts introduced through the researches on the 1976 Friuli earthquake have been used to develop the vulnerability and damage data sheets used after the earthquake of Umbria Marche (1997) by the Italian Ministry of Cultural Heritage and the Italian Civil Protection Department. In particular, starting from the results of the researches on Friuli data (Doglioni *et al.*, 1994), a Code of Practice was developed to manage the intervention on historical buildings. This code also allowed defining restoration and preventive safety upgrading interventions that could be used both for buildings constructed using traditional techniques and for the architectonical heritage.

The Code of Practice of Marche Region (Doglioni, 2000) was based on the definition of a contextualized plan of actions aimed at improving the seismic response of the specific building.

In particular, it is based on:

- researching and finding all forms of typical vulnerability that could be present in a building (recognised on the basis of the damage in similar buildings);
- recognising the signs and other directly observed elements, such as pre-existing damage, discontinuities, weakening due to deterioration and transformations, etc.;
- conceiving the intervention as a systematic counteraction to all the recognized vulnerabilities and damage: this is done by studying the correspondence between each type of vulnerability, the mechanisms (both activated or that could be activated), and one or more interventions suitable to avoid the activation and progression of mechanisms.

Fig. 5 - Progression of damage (modified from Doglioni *et al.*, 1994): the cathedral of Venzone a few days after the earthquake of 6 May 1976 (top) and after the events of September 1976 (bottom).

More broadly, the Code of Practice introduced a “problem-specific” approach for repairing or for upgrading safety conditions of the historical building in seismic-prone areas, capitalizing on all the previous studies and in particular the studies on the churches and bell-towers in Friuli. This approach ensures that for the intervention all the structural elements already present in the building interact during an earthquake, with each other deactivating the potential mechanisms. The goal is reachable using specific solutions, such as the introduction of metallic connections between trusses of the roof and the external walls in order to counteract their out of plan mechanisms.

The key criterion of interventions is to inhibit the activation or progression of the potential mechanisms (especially for mechanisms that overturn front walls) without radically altering the physiology of the structure. It is fundamental that the intervention avoids introducing significant differences of stiffness or mass increase, especially in the upper part of the building. A possible solution is to use tie rods and metallic connections (Fig. 6) together with reinforcements on vulnerable points (such as angular windows). Rigid and heavy structures such as reinforced concrete tie beams, or concrete structures for the roofs or slabs should be avoided, since the post-earthquake analysis of damage showed that these elements often introduce specific vulnerabilities (Fig. 7). In order to achieve this objective, it is preferable to adopt solutions that work in traction, which usually have a limited weight and are generally metallic or made of wood (Fig. 8). Furthermore, vulnerability is greatly reduced with interventions that counteract the upending

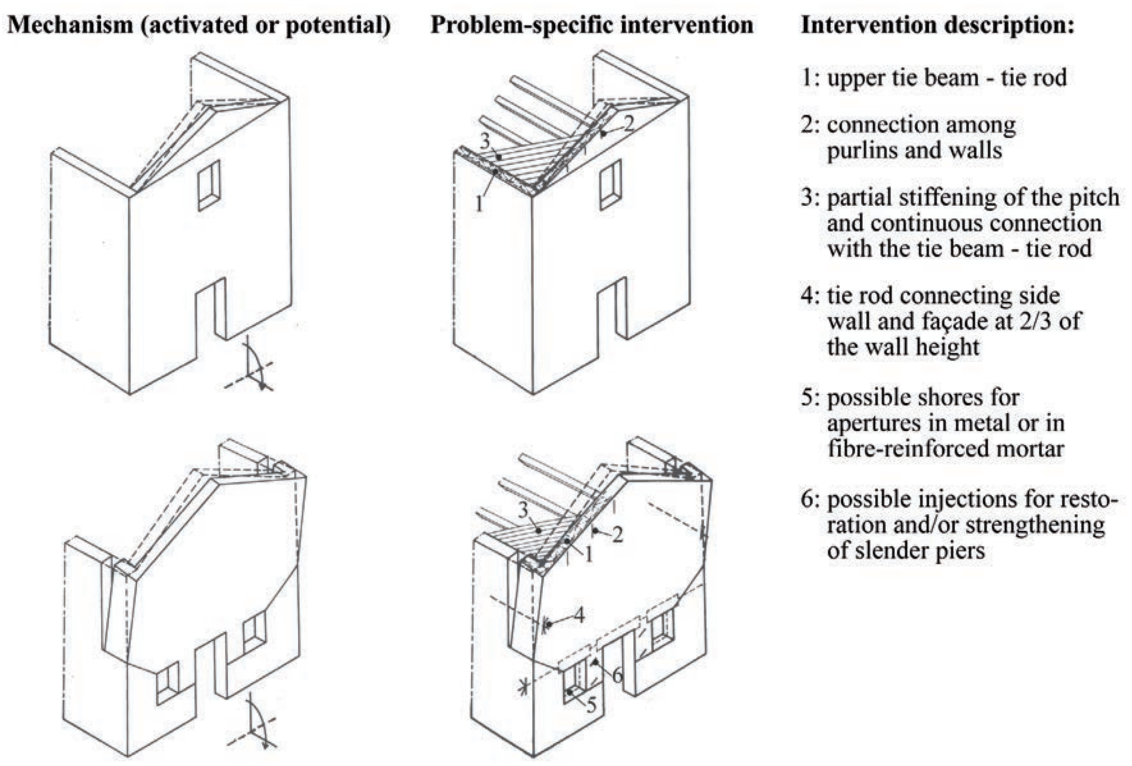

Fig. 6 - Tailored approach: problem-specific intervention is conceived with the goal of inhibiting the activated or potential mechanism (modified from Doglioni, 2000).

Fig. 7 - Church of Santa Giuliana, in San Pellegrino, Norcia (Perugia province, central Italy). The heavy beam supporting the roof is an intervention that introduced significant differences of stiffness or mass increase in the upper part of the building.

Fig. 8 - Example of problem-specific interventions based on Code of Practice criteria. Tailored solutions defined for the roof of the church of Beata Vergine Maria in Ostiglia (Mantua province) damaged by the 2012 earthquake in Emilia (northern Italy).

mechanisms of *façades* or perimeter walls; these mechanisms are activated even with medium-energy earthquakes. In order to oppose shear mechanisms of inside walls, which collapse only with much stronger earthquakes, widespread and invasive tightening interventions are needed, which are consequently much more expensive.

The purpose of the intervention suggested by the Code of Practice does not consist in preventing the occurrence of the local damage, but in limiting movements leading to the collapse. Following this tailored approach, the seismic behaviour of the building is, paradoxically, more controllable than the behaviour of a building subject to a radical modification by using different structural schemes and materials.

Even if this new tailored approach has a qualitative origin, in recent years structural models have been developed for a quantitative evaluation of the effectiveness of the interventions. These models are based on linear and nonlinear kinematic analysis; their use is suggested by recent standards (NTC2018, 2018) for the quantitative evaluation of the seismic safety of existing buildings and of seismic improvement interventions.

3.2. Short-term countermeasures on damaged heritage buildings

The studies on the Friuli earthquake damage provide a starting point for considering the effects of the progression of damage caused by aftershocks, as well as their potential implications in first response. The observations stressed the necessity to focus on the problem of safeguarding heritage buildings, to stop the activated mechanisms, and avoid the progression of damage in the short-term after the earthquake.

On occasion of the 2009 L'Aquila earthquake, the concepts of mechanism and the problem-specific interventions were used to support the Italian National Fire Services in defining short-term countermeasures for securing severely damaged historical buildings (Grimaz, 2011; Grimaz *et al.*, 2016, 2018). A technical handbook and a vademecum of solutions (Grimaz *et al.*, 2010a, 2010b) were compiled and adopted by the Italian National Fire Services for securing damaged historical buildings in the post-earthquake emergency phase. In order to avoid the collapse during the aftershocks, the rapid interventions were conceived with the goal of inhibiting the activated mechanism using predefined standardized solutions (Fig. 9).

3.3. Lesson learnt from applications

After the 1997 Umbria-Marche and the 2004 Garda Lake earthquakes (Italy), the authors of this paper were extensively involved in monitoring and supervising safety improvement projects at regional scale. Immediately after the 2012 Emilia earthquake, they were also engaged in designing intervention on cultural heritage buildings. These wide-ranging supervision and design activities, directly related to applying the principles and approach introduced by the Code of Practice, allow us to define a number of lessons learnt in terms of advantages and limitations of the tailored approach.

The following aspects summarize the advantages of the tailored approach for seismic improvement:

- the behaviour of the whole building does not change, since it does not introduce stiffness gaps or localized extra weights that could unbalance the response of a part of the construction;
- the devices aimed at inhibiting the mechanisms can be applied gradually and/or for parts, enabling to steadily reduce the vulnerabilities, working building by building or on portions of a

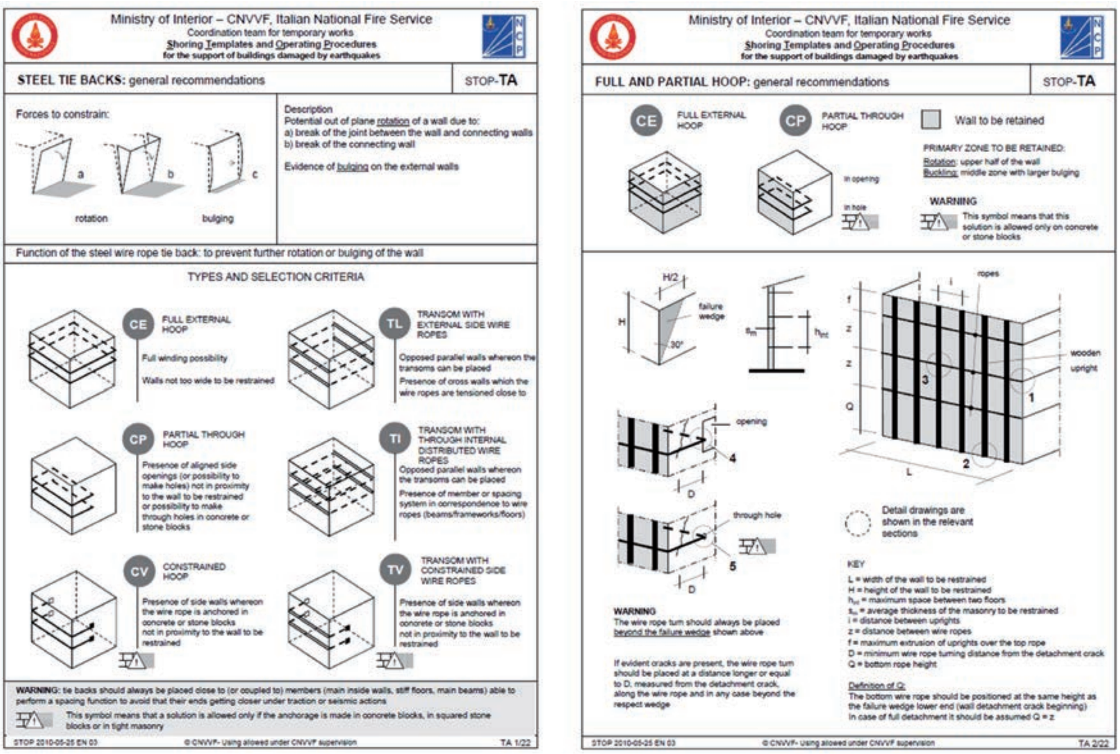

Fig. 9 - Shoring template and operating procedures. Steel tie back to prevent or counteract collapse mechanism (rotation and bulging of walls). Extract from the Vademecum STOP (Grimaz *et al.*, 2010b).

building. In this way, it is possible to reduce the problems deriving from the fragmentation of the buildings of historical centres with large blocks or aggregates.
- most interventions have a low or medium-low physical impact on the building, as most of them are localized and do not need extended actions; for this reason, no extensive demolitions of plasterwork and roofs with following new finishes (e.g. plasterwork and flooring) need to be made; this radically lowers the overall costs;
- most of the solutions are compatible with the owner's requests to reduce the time in which they have to leave their houses;
- these interventions can be made together with extraordinary maintenance works of roofs, doors, and windows, reducing in this way the overall and construction site costs; they also have the highest compatibility with old city centres and historic buildings.

Nevertheless, practical experiences also highlight the following limits and disadvantages:

a) the method cannot be applied to some cases or situations:
  - buildings that had already been restructured with different materials and techniques and through the integration of roofs and concrete tie beams; in these cases, a choice must be made between stiffening the building, if it is isolated from other constructions, or substituting the current elements;
  - buildings already highly damaged or deteriorated;
  - buildings with irregular ground plans or height;
  - buildings made of walls with extremely low-quality construction and mechanical

characteristics. They can indeed undergo disintegration of walls before the prevention mechanisms are activated. In these cases, a choice has to be made between strengthening through injections or substituting the walls;

b) the method does not define precisely the collapse limits, in particular with earthquakes that release a lot of energy.

Considering advantages and limits, the practical experiences highlight how this approach allows reaching a reasonable compromise between the costs of intervention, safeguarding cultural heritage, and seismic vulnerability reduction.

4. Final considerations and conclusions

The huge amount of documentation on the damage caused by the 1976 Friuli earthquake, in particular to churches and bell-towers, was studied with an innovative epidemiological approach. These studies, carried out from the middle of the 1980s until the 1990s, introduced the new method of analysis based on reading and interpreting seismic damage with a diagnostic objective, also taking account of the sings of the history of the building. This opened the way for studies on seismic vulnerability of the built heritage, based on systematic objective evidence and significantly increased the ability to understand, from a technical perspective, the construction characteristics belonging to the historical heritage and of previous damage.

On the basis of these studies, after the 1997 Umbria-Marche earthquake, a Code of Practice for guiding the seismic improvement of historical buildings was drawn up and used as a key tool in the process of repair and reconstruction. The purpose of the Code of Practice was seismic prevention; assessment was conceived as the first step for the consequent identification and realization of the interventions focused on risk reduction through the reduction of buildings vulnerability.

The applications highlight that the a posteriori analysis and the vulnerability characterization can be fruitfully used as a preventive tool to improve the safety of buildings with similar features and that have not yet been affected by earthquakes. The evidence, confirmed also by recent earthquakes, suggests that for historical centres and for most of the architectural heritage, it is better to proceed with a systematic improvement based on qualitative standards, also taking into consideration the damage history before proceeding with improvements based solely on a structural calculation. Moreover, the lower costs of problem-specific solutions will allow to quickly expand the prevention to a greater number of buildings of the architectural heritage.

The philosophy of the improvement, especially for historical buildings, is also to safeguard as much as possible the original physiology of the building. This consideration played a leading role in the definition of the Code of Practice and in particular in the introduction of the "problem-specific" approach based on the analysis of the mechanism of collapse and in the recent and current Italian national seismic codes.

The strategy of inhibiting the activated mechanism lies at the roots of the short-term countermeasures applied by Italian National Fire Services for securing historical buildings in the post-earthquake emergency phase.

Finally, we can affirm that work carried out in the wake of the 1976 Friuli earthquake has proved fundamental, both to the knowledge of seismic behaviour of historical buildings and to the formulation of effective and tailored improving interventions. Indeed, it started a new era in the approach to seismic improvement of existing buildings, which, today, also characterizes the more advanced seismic codes.

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