STRUCTURAL INTERVENTIONS ON HISTORICAL MASONRY BUILDINGS: REVIEW OF EUROCODE 8 PROVISIONS IN THE LIGHT OF THE ITALIAN EXPERIENCE

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ABSTRACT
The paper presents a critical review of Annex C, section 5, of the Eurocode 8 Part 3, which focuses on the structural interventions for existing masonry buildings. The considerations herein drawn up are developed in the light of the Italian experience after recent earthquakes, and refer particularly to the Codes and Guidelines currently in force, which are also based on the results of extensive experimental researches carried out in Italy and Europe. The limits and the deficiencies of Eurocode 8 Part 3 (Annex C.5) are pointed out following the logical structure of the Italian norms, that are organized by defining the objectives and the performance requirements to be achieved through the strengthening interventions. Suggestions for reviews and improvements are given, considering the significance of this document and the need for general and shared rules to be applied, in the field of seismic strengthening of masonry buildings, at an European level.

KEYWORDS
Eurocode 8, structural interventions, masonry buildings, architectural heritage, restoration.

1 INTRODUCTION
Safeguard of historical buildings from the seismic risk is a difficult task regarding first the prevention, and then the whole process from building assessment through design and execution of interventions. It is essential that targeted methodologies, which allow applying the general concepts of seismic engineering to the particular case of historic buildings and are being recently developed, are applied at a larger scale and become available and viable for designers.

As an example, the adoption, for historical masonry buildings, of the same classes of predictive models developed for new constructions can mislead about the real behaviour of the structures (Binda et al., 2005; Magenes, 2006), and can bring to the choice of useless or even harmful interventions for their seismic protection (Modena et al., 2009). The most recent seismic events (Lunigiana and Garfagnana, 1995; Reggio Emilia, 1996; Umbria and Marche, 1997; Piedmont, 2000; Molise, 2002; Piedmont, 2003; Salò 2004, Abruzzo 2009) confirmed limits and consequences of some type of interventions, concurrently corroborated also by extensive experimental researches, but also the effectiveness of new methods based on the use of both traditional and innovative materials and techniques.
From observation and study of structural faults of original and repaired structures, not only information on the effectiveness of various strengthening interventions could be drawn, but it could be also highlighted that historical buildings cannot be assessed through “standard” methods. On one hand, these methods are far from understanding the real seismic behaviour of constructions and, on the other, they can lead to invasive interventions which modify permanently the cultural value and the structural behaviour of the buildings, in conflict with necessary preservation requirements. It has been also clarified that the knowledge of the typical features of each historical building, regarding, for example, the constitutive materials (i.e. masonry typology and arrangement), the structural type (common building, isolated/in aggregate, churches, towers, palaces), etc., is essential for the definition of suitable interpretative models. In addition, the preliminary diagnosis of the building, regarding history, geometry, materials, connections, etc., should constitute the basis for all safety evaluation and intervention planning (Giuffrè, 1991; Giuffrè, 1993; Doglioni et al, 1994; Binda et al, 1999). Hence, the assessment process should be considered a multidisciplinary task, taking into account also qualitative evaluations and involving different specialists to take a joined decision, with the structural engineer, about the safety level to confer to the historical construction and the type of intervention to be undertaken, as recently reasserted also by the draft version of Annex I (Heritage Structures) to ISO 13822 (2006).

In the next section, some aspects of how the topic of structural interventions on existing masonry buildings is treated by the recent Italian codes (OPCM 3431, 2005; NTC 2008) are discussed. Subsequently, some recent developments and results from researches and post-earthquake survey observations are reported, with reference to the different approach adopted in the corresponding European norm (EN 1998-3, 2005).

2 PRINCIPLES OF ITALIAN NORMS AND GUIDELINES

Since the D.M. 24/01/1986 was adopted, the concept of “seismic improvement” was introduced in Italy. As a consequence, in the case of minor interventions that do not significantly alter the overall structural behaviour, it is not necessary to undertake the “seismic upgrading”, i.e. the increase of seismic performances to the level required for new constructions. At the same time, in the Italian norms it was possible to avoid the safety checks required by standards prescriptions. Reasserted in the D.M. 16/01/1996, this concept was then applied to the assessment of cultural heritage buildings, since it was considered compatible with their preservation needs. These norms also listed some strengthening techniques to be adopted for improvement and upgrading interventions, which reflected the knowledge and state of art of the years when these were issued. From that moment onwards, the consequences of various earthquakes, listed in the introductions, led to a critical review of the technical content of these documents. The calibration of safety level to the need of an existing structure is also proposed by international standards (ISO 13822, 2006), and can be based on the concepts of minimum total expected cost, comparison with other social risks, importance of the structure, possible failure consequences and socio-economical criteria, although its influence on the type of intervention to be adopted is not clearly defined in other norms. These efforts, through the OPCM 3274 (2003) and OPCM 3431 (2005), have led to the documents currently in force: the NTC 2008 (D.M. 14/01/2008) and the Guidelines issued by the Ministry of Cultural Heritage. In this context, a significant step ahead was moved first with the drawing up of the OPCM 3431 (2005), which enhanced significantly the entire process by defining the knowledge levels and introducing new procedures of analysis and assessment and new criteria for the intervention on existing structures. In addition, this norm
stated again that there is no need of carrying out common safety checks for seismic improvements, but required the designer to calculate the higher safety level reached by means of these improvement. Hence, the OPCM 3431 limited some of the uncertainties prior connected to the application of seismic improvement, which did not need any demonstration of their real need and effectiveness.

A second step was moved when the Guidelines (2007) for the application of the above seismic standards to cultural heritage buildings was issued. This technical document, including and extending the principles already contained in OPCM 3431, was specifically drawn up to delineate a methodology fitted to the need and features of cultural heritage. Several features in this technical document are related to the specificity of cultural heritage buildings. The innovative aspects of these guidelines emerge from the multidisciplinary approach that they propose. The outcomes of the process of assessment and reduction of seismic risk for cultural heritage buildings is thus a compromise between seismic protection requirements and respect of cultural and artistic values, according to the preservation criteria asserted in the various issued charters for the restoration of historic monuments (Athens Charter, 1931; Venice Charter, 1964) and recommendation for structural restoration of architectural heritage (ICOMOS/ISCARSAH, 2003).

In this context, it should be pointed out that the EN 1998-3 (2005), which introduced some of the concepts that have been further developed in the Italian norms (e.g., the definition of knowledge levels, see Binda and Saisi, 2009), is currently lacking some reference values in order to make the methods applicable by the designers. In other fields, such as the definition of the seismic safety levels for existing structures (Borri and De Maria, 2009) and the methods of analysis and assessment (Magenes and Penna, 2009; Lagomarsino, 2009), the Eurocode 8 is not updated with the latest findings and methods introduced in Italy. Even the established concept of “seismic improvement”, which has a significant influence on the design of interventions, is not yet recalled by the EN 1998-3 (2005).

When going more in detail to the types of intervention, some others significant differences are found between the Italian and the European norms. First of all, the Italian norms give some general principles to select and apply the interventions, which are valid regardless the specific technique being employed. One of these criteria is that interventions should be applied as much as possible regularly and uniformly on the building, so to avoid uneven distributions of strength and stiffness. Eventual increase of these factors on limited portions of the building must be carefully evaluated. In addition, particular care must be paid to the execution phase. These simple criteria derive, obviously, by the observation of damages on buildings that had been retrofitted in recent times, but have already sustained new earthquakes. The surveys indeed demonstrated that interventions carried out without paying the due attention to the above criteria were useless and even harmful.

The improvement of the building seismic performances may be achieved using traditional methodologies but also adopting innovative techniques and materials. The choice of the most appropriate approach depends on the results of the previous evaluation phases, thus the interventions listed in the Italian norms should not be considered as prescriptive and to be applied in any case, but should be targeted to the specific problem. Conservation of both materials and functionality of the structure is the main objective, therefore interventions should avoid significant alterations to the original structure and provide compatibility to the largest extent. It should be pointed out that these simple concepts have not been included in the Eurocode 8.

Strengthening interventions are grouped following a performance-based scheme in Italian norms, while EN 1998-3 does not have a consistent outline. In the Italian code, there has been an effort to understand the behaviour and the typical faults of masonry buildings, and thus
proposing classes of interventions that can improve or solve specific problems. Some classes of interventions listed by NTC 2008, that will be discussed in the following, are: intervention aimed at improving the structural connections, interventions aimed at reducing horizontal diaphragm deformability, intervention to increase masonry strength, interventions on vaults and arches, interventions on pillars, etc. At this regard, the structure of EN 1998-3 is not coherent as it sometimes follows a rational path but some other times mixes or simplifies the approaches. As an example, in annex C of Eurocode 8 a sub-section is devoted to the repair of cracks. This is quite limited, if one thinks that being cracks the symptoms of more complex structural problems, say inadequate masonry strength under in-plane shear, or activation of kinematic mechanisms on vaults and arches, or presence of sustained dead-loads on pillars, etc., the solution should be aimed at solving the basic problems. In this context, the interventions listed by the Italian norms, according to the current knowledge, cover all the main aspects of masonry building behaviour, but is not deemed to be exhaustive in terms of materials and techniques. The same norm, indeed, states that other materials and techniques, when proved to be viable for the solution of a specific problem, could be adopted by the designers. In the next section, the main strengthening techniques, grouped by purpose as in NTC 2008, are presented and compared to similar interventions suggested by EN 1998-3 (2005).

3 STRUCTURAL INTERVENTIONS

3.1 Interventions to improve connections

One of the first aspect to be taken into account when dealing with the seismic behaviour of existing masonry buildings, is the lack of good connections between structural elements. Hence, to allow the structure to manifest a satisfactory global behaviour, it is necessary to improve the connections between masonry walls, and between walls and floors and walls and roofs (Tomaževič and Weiss, 1994; Tomaževič and Lutman, 1996). This goal may be achieved inserting ties (Figure 1), confining rings (Figure 2), and tie-beams at the top of the building (preferably in reinforced masonry or steel, also in r.c. but with restrictions, Figure 3). An effective connection between floors and walls is useful since it allows a better load redistribution and applies a restraining action towards the walls’ overturning. In the case of wooden floors, a satisfactory connection is provided by fasteners anchored on the external face of the wall (Figure 4). Conversely, introduction of tie-beams in the masonry thickness at intermediate storeys should be definitely avoided, due to their damaging effects on perimeter walls, often causing also uneven load redistribution among masonry leaves and/or pounding effects on the external masonry leaves in case of seismic excitation. The Eurocode 8 treats the problem of wall to wall intersections in sub-section C.5.1.2. The three techniques reported there are “construction of a reinforced concrete belt”, “addition of steel plates or meshes in the bed-joints” and “insertion of inclined steel bars in holes drilled in the masonry and grouting thereafter”. No mention is made to the wall-to-floor and wall-to-roof connection within this paragraph. It is well known that the first solution should be carefully considered, as it may worsen the overall behaviour of the structure, while the third one should be avoided in most cases, and is actually advise against in the Italian norms, because of its detrimental effects observed after recent earthquakes. Indeed, this technique has raised many doubts due to its invasiveness, to the durability issues raised by the insertion of steel bars into masonry, and to the scarce effectiveness, related to both the execution procedures and the absence of adequate experimental investigation.
Further strengthening techniques, tie-beams and addition of steel ties, are presented in C.5.1.4 and C.5.1.5. Also in this case considerations about effects and feasibility of these techniques are omitted, and some indications, like the provision of adding tie-beams if not existing in the original structure, should be reviewed taking into account the current state of art.

3.2 Interventions to increase the masonry strength

Interventions, aimed at increasing the masonry strength, may be applied to re-establish the original mechanical properties of materials or to improve their performance. Techniques, employed with caution, should make use of materials with mechanical and chemical-physical properties similar to the original ones (Valluzzi, 2008).

The local rebuilding (“scuci-cuci”) methodology (Figure 5) aims to restore the wall continuity along cracking lines (substitution of damaged elements with new ones, reestablishment of the structural continuity) and to recover heavily damaged parts of masonry walls. The use of materials that are similar, in terms of shape, dimensions, stiffness and strength, to those employed in the original wall is preferable. Adequate connections should be provided to obtain monolithic behaviour. This intervention, which is detailed in such a way in NTC 2008,
is also suggested by the EN 1998-3 (sub-section C.5.1.1), only to stitch cracks by means of elongated bricks or stones, without any other specification, besides those regarding the use of heterogeneous materials, such as metal clamps, plates, or polymeric grids to enhance the intervention effectiveness.

An extensive research has recently focused on the used of non cement-based mortar grouting (Valluzzi, 2000; Valluzzi et al. 2004) to increase the strength of multi-leaf masonry walls, and brought to the requirement of compatibility, in terms of chemical-physical and mechanical properties between grout admixture and substrate wall, which is currently asked for by the norms. This technique (Vintzileou and Tassios, 1995) consists in the injection of mixture through a regular pattern of drilled holes (Figure 6), for increasing the connection between masonry layers. Studies (Valluzzi, 2000; Valluzzi et al, 2003) demonstrated (Figure 7) that injections do not significantly change the stiffness of walls, differently from RC jackets, improving at the same time the strength and consistency of walls provided with voids and/or irregular morphology. The EN 1998-3 mentions the injection technique to strengthen multi-leaf walls (sub-section C.5.1.6) and to repair cracks (sub-section C.5.1.1), suggesting the use cement-based materials or, in some cases, epoxy grouting, without taking into account the most recent research findings about chemical compatibility and effectiveness of low-strength grout injections (Vintzileou and Miltiadou, 2008).

Insertion of small-sized tie beams across the wall, supplying a connective function among the wall leaves (Figure 8), is mentioned in sub-section C.5.1.6 as a supplemental solution for the injections. This intervention permits to reduce transversal deformations and local problems of out-of-plane buckling or overturning due to lack of connection. In addition, the combination of these techniques can provide a larger increase of the overall strength of the wall, permitting to carry higher loads (Valluzzi et al. 2004).

A wide research, studying the dynamic behaviour of injections and transversal ties, is in progress. Two scaled masonry structures were built using three leaves masonry stones and tested on the shaking table (Figure 9). First results (Mazzon et al., 2009) confirmed that the overall stiffness of the injected model does not significantly increase with respect to the original one. In addition, higher values of seismic input can be reached, thanks to a monolithic performance due to the connection effect provided by mixture. Several compression, shear-compression and out-of-plain test complete the investigation, and allow to understand the mechanical behaviour of strengthened structures (Figure 10).

The mortar bed-joint repointing is another technique to improve deteriorated joints (Figure 6), that consists in the replacement of degraded mortar (Corradi et al., 2008). If steel bars are inserted within the joints to limit the opening of vertical cracks, this modified method is
known as structural repointing (D’Ayala, 1998; Valluzzi et al., 2005). Laboratory tests and numerical models show that it is possible to use new materials as FRP laminates instead of steel, to ensure compatibility and removability as well as the control of creep deformations (Garbin, 2008). This kind of intervention is described also by EN 1998-3 sub-section C.5.1.1, although no further details, for example on the effectiveness of the intervention in relation to the masonry thickness, are given there.

Masonry strength can be also increased by means of the insertion of “diatoni” (masonry units disposed in a orthogonal direction with respect to the wall’s plane), substituting damaged stones or introducing new elements to provide transversal connections between external layers of wall (NTC 2008). Other methods are mentioned in the EN 1998-3, such as the use of RC jackets or the insertion steel profiles (sub-section C.5.1.7) and application of polymeric grids jackets (sub-section C.5.1.8). A lack of critical evaluation about the proposed techniques is observed also in these cases: the suggested systems have to be carefully evaluated, since the suitability and the effectiveness should be demonstrated case by case. For instance, an incorrect application of RC jackets could easily worsen the structural behaviour because of an excessive stiffness and mass increase of portions of the structure (Modena and Bettio, 1994),
or they can even be ineffective because of incorrect execution procedures or because of durability problems.

3.3 Interventions to reduce flexibility of floors and their consolidation

Interventions aiming at enhancing the in-plane stiffness of existing floors must be carefully evaluated, since it changes the redistribution of horizontal seismic action to the load-bearing walls, and this is seldom the objective of structural interventions. The role of diaphragms in the dynamic behaviour of masonry buildings consists in transferring seismic actions to the walls parallel to the earthquake direction (Tomaževič, 1991); therefore, an effective connection between floors and walls has a large importance as this can limit undesirable overturning of walls.

![Figure 11. Different strengthening interventions using: (a) rotated double planking; (b) orthogonal double planking with wooden diagonal; (c) orthogonal double planking with steel diagonal. (d) Steel frame used for laboratory tests (Valluzzi et al., 2008).]

Providing a further layer of wooden planks is a limited intervention, that does not modifies the overall behaviour and the force redistribution, and increases the wooden floors stiffening (Parisi and Piazza, 2002b). Some studies focused on the analysis of the double planking method (Valluzzi et al, 2008), as the application in orthogonal or inclined direction and the use of tongue-and-groove joints and nails or screw as connectors (Figure 11). This technique may be adapted (Figure 12) by using only wooden connectors instead of metallic ones (Modena et al. 2008). In addition, the use of metallic belts or FRP strips, disposed in a crossed pattern and fixed at the extrados of the wooden floor (Figure 13), or the use of metallic tie-beams bracings, may improve not only the stiffening effect (Corradi et al., 2006), but also the wall to floor connections.
Similar techniques are listed in the EN 1998-3 (sub-section C.5.1.3), underlining the importance of a correct connection between horizontal and vertical structures. However, the application of an overlay of concrete reinforced with welded wire mesh is proposed without pointing out the considerable increase of diaphragm self-weight and stiffness that it produces. In the same paragraph, it is correctly recommended to brace and anchor the roof trusses to the supporting walls (Piazza and Candelpergher, 2001; Parisi and Piazza, 2002a).

3.4 Interventions to reduce thrust of vaulted arches and their strengthening

Among the structural components in masonry buildings, arches and vaults deserve particular attention for being widespread in European historical centres; therefore, their preservation as part of the cultural heritage is a topical subject. These structures can suffer several types of damage, due to many causes (such as earthquakes, age, etc.). Hence, the contribution of strengthening materials and repair techniques is often required to re-establish or enhance their performances and to prevent a brittle collapse of the masonry in possible future hazardous conditions.

The EN 1998-3, differently from the Italian norms, does not provide any information concerning the interventions on this type of structures. Strengthening methods (Oliveira and Lourenço, 2004) may be applied by using the traditional techniques of tie-rods to compensate the thrust induced on the bearing walls. In addition, to absorb thrust of vaulted arches, the possibility of realizing buttresses or reinforced transverse vertical diaphragms should be considered, whilst jacketing the extrados using concrete, reinforced or not, should be avoided. Composite materials, such as FRP (Barbieri et al., 2002; Valluzzi, 2008) or SGP/SRG (Borri et al., 2008) could be a suitable option in some cases (Figure 15). In recent years, experimental researches focused on the behaviour of masonry vaults strengthened by new composite materials, as carbon or glass FRPs, placed at the intrados (inner surface) or at the extrados (outer surface) of the structure (Figure 14) (Valluzzi et al, 2001; Panizza et al, 2008). A multilayer system of adhesion based on epoxy adhesives and designed to provide a support as homogeneous as possible for the fibers has been adopted.

4 CONCLUSIONS

The Italian norms have introduced since a long time ago the concept of ‘seismic improvements’ which is a viable solutions for those buildings, where the requirement of satisfying current safety level adopted for new buildings would imply an excessive use of
strengthening measures and the complete loss of the original building concept and value. Nevertheless, this concept has not been yet defined into the European norms.

Going more in details, the recent Italian seismic norms, OPCM 3431 and NTC 2008, provide sound criteria for the application of interventions and group the strengthening techniques following a performance-based scheme, while the EN 1998-3 does not show a consistent outline, as it mixes lists of interventions collected by purpose, such as wall intersections or horizontal diaphragms, with descriptions of single techniques, without providing any general concept on how the intervention should be conceived, designed and executed.

In addition, many interventions suggested for masonry buildings are obsolete, as the past ten years of earthquakes have demonstrated their ineffectiveness. Concurrently, many experimental researches have also been carried out. However, these state of the art knowledge has affected only the Italian norms. In this context, and considering the continuous technological development, the Italian norms are open to new types of interventions and materials, that may emerge after the drawing up of the norms, provided that some simple criteria are respected and that the effectiveness of the new materials and techniques is not only asserted, but also demonstrated.

Conversely, the provisions of Eurocode 8 point out specific aspects, for instance materials to be used, but are lacking of information concerning effectiveness, feasibility, suitability, and compatibility, under the chemical-physical and mechanical point of view, of each kind of intervention. Many important aspects that would complete the description of structural interventions on historical masonry buildings are totally disregarded, such as the strengthening of columns and pillars, the interventions on arches, vaulted structures and foundation systems, etc.

Furthermore, the Italian system of seismic norms is also provided with specific Guidelines (2007) for the application of the above criteria to cultural heritage buildings, following a methodology for the application of the seismic standards which takes into account the requirements of preservation.

In conclusion, the Eurocode 8 does no deal with the topic of interventions on masonry buildings in a sufficiently consistent and organic way. Starting from these above mentioned considerations, the way to improve the document could be based on more general principles, matched with a substantial review of all the other aspects, included in the European norm, which concern the seismic assessment and improvement of existing masonry buildings, and with the explicit description of the specific features of the seismic behaviour of masonry buildings. This approach would avoid the a priori exclusion of technical solutions not explicitly mentioned, could simplify the update and the integration of the document and improve its suitability for application on historical structures.

5 REFERENCES


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