Codes of Practice for Architectural Heritage in Seismic Zones

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ABSTRACT: The acknowledgment from the scientific community that the buildings belonging to the cultural heritage can not be evaluated with regards to the seismic action according to standards that are fitted for newly constructed buildings, indicated a new way to undertake in the seismic assessment of such class of buildings. In particular, it was accepted that the balance between structural safety and architectural preservation must take into account both exigencies, on one hand not fully complying with the seismic actions defined by the standards if this would lead to interventions that can alter in a significant manner the cultural and architectonical essence of the building, on the other even changing the use of a specific building, in order to make it able to withstand the seismic action. Safety evaluations must then involve a multidisciplinary, qualitative/quantitative approach.

1 FOREWORD
1.1 Background

The seismic assessment of existing structures can be considered a difficult task for several reasons. Research carried out in the last decades, following the 1976 Friuli and 1980 Irpinia earthquakes, showed in fact that while in case of new constructions the behavioural models proposed by different international seismic codes, based on thorough analytical and experimental bases can be satisfactorily used, for what concerns buildings that belong to the cultural heritage the adoption of the same class of predictive models can be misleading with regards to the real response of the buildings. This is essentially due to the fact that existing constructions were built according to traditional rules that were far from the present day building process, and that the continuous modifications experienced by the building over the time produced several uncertainties in the model definition, besides the generally unsatisfactorily level of knowledge on the structural layout and on the mechanical properties of the constituting materials (Binda et al. 2005).

At a European level (EC8, part 1.4) an attempt was made to define principles and general considerations that can take into account the diversity of the historical respect the new buildings, even if the document seems not to be fully conscious of the particularities and preservation needs of such class of structures. Since 1986 (D.M. 24/01/1986) in Italy there was the introduction of the concept of “seismic improvement” rather than seismic upgrading, that allowed, in case of minor interventions that did not alter in a significant manner the overall behaviour of the structure, to avoid the verification according to the standards prescriptions. Reasserted in 1996 (D.M. 16/01/1996), such concept was then connected to the assessment of cultural heritage buildings of monumental character, since it was considered compatible with their preservation exigencies.
It was then emerging the evidence that historical buildings are a particular and heterogeneous class of buildings that generally can not be assessed through “standard” methods, which on one hand are far from the comprehension of the actual seismic behaviour of the fabric and on the other may lead to invasive interventions that modify in a permanent way the building, in conflict with necessary preservation requirements. It was also becoming clear that the peculiar characteristics of each historical building were essential in the definition of suitable interpretative models, as their constitutive materials (i.e. masonry typology and arrangement), their structural type (common building, isolated/in aggregate, churches, towers, palaces, etc.), and that a preliminary diagnosis (history, geometry, materials, connections, etc.) of the building is the base for any safety evaluation and intervention planning (Giuffrè 1991, 1993, Doglioni 1994, Binda et al. 1999).

This process, evolved through research activities, observation of the performance of historical buildings struck by the earthquake, and the evaluation of the inadequacy of standard strengthening interventions provided to buildings, led to a more conscious approach, considering more suitable interpretative models and more respectful methods of interventions, taking also advantage of the improvement of techniques and materials. The assessment process is furthermore considered a multidisciplinary task, involving also qualitative evaluations and the involvement of the stakeholders in the decisional phase, taking a joined decision with the structural engineer about the safety level to confer to the historical construction.

In the following paragraphs, the indications of recent seismic Italian codes and technical regulations will be outlined.

2 PRINCIPLES AND METHODS, EXISTING BUILDINGS

The Italian seismic code of recent adoption (OPCM 3274/2003 and successive supplements and modifications) comprehend a specific section for the existing buildings, expressly denouncing the fact that generally such class of buildings were designed according to the state of the art at the period of their construction and that usually it is not easy to estimate conceptual and technical deficiencies connoted in the building. In fact, past earthquakes and different actions experienced by these buildings may have provoked non evident defects; by consequence, safety evaluations and the design of interventions are usually affected by a different degree of uncertainty respect the new buildings.

On one hand this admissions leads to the adoption, in the seismic assessment, of appropriate safety factors related to the completeness and reliability of the available information; on the other, peculiar safety evaluation procedures have to be taken into account, with different models adopted to define the collapse modalities. Any strengthening intervention must be then carried out according to defined general methodologies, bearing in mind that in any case the objective situations are rather different from each other and that it is generally not possible to foresee specific and detailed rules for each case.

The concept of seismic improvement is reasserted relatively to interventions that do not alter in a significant way the overall behaviour of the structure. For such class of strengthening interventions it is hence possible to skip the verifications imposed by the standard but the quantification of the seismic improvement obtained thanks to the intervention has to be provided by the designer. A crucial point regarding the cultural heritage buildings is the fact that for such class of buildings it is always possible to consider seismic improvement interventions, in the sense that they do not have compulsorily to withstand the seismic forces defined by the standard. It is however necessary to define the PGA values related to the damage and ultimate limit state prior and after the foreseen structural intervention.

3 PRINCIPLES AND METHODS, CULTURAL HERITAGE BUILDINGS

A step ahead was moved with the establishing of a work group for the definition of the guidelines (latest version, 2006) for the application of the seismic standards (OPCM 3274/2003) to cultural heritage buildings. The technical document, comprehending and overtaking the principles already contained in the seismic standards for existing buildings, was specifically drawn up
to define a path concerning the knowledge, the seismic assessment and the design of possible interventions fitted to the exigencies and particularities of the cultural heritage, with the aim of expressing in the best achievable objective way a final judgement on the safety level and preservation exigencies attained with the seismic improvement intervention.

Several features are present in the technical document, related to the specificity of the cultural heritage buildings. The originality of the document emerges from the multidisciplinary approach that was considered in the definition of the different technical aspects. In particular, people belonging to different areas, as scientists, executives of the Civil Protection Agency, of the Ministry of Culture and Public Works were involved in the document editing and approval, and then the outcomes can be considered a pondered compromise between the seismic protection of the heritage buildings and the respect of their cultural and artistic value.

Between the main innovations there is the adoption of a further limit state: the reference limit states are not only related to the Ultimate and Serviceability conditions, but the so called Artistic Limit State was introduced, aimed at the protection of the artistic apparatus of the building (frescos, stuccos, mosaics…) and conceptually connected to the quasi linear response for the portions of the structure whose preservation is crucial, where only a very limited damage is allowable. Moreover, the acceptance of the qualitative aspect of the final safety judgement, even if based on thorough analytical and experimental basis. This arises from the fact that i) there exist objective difficulties in defining an univocal safety assessment procedure as in the case of the ordinary buildings, since their typological variety and the uniqueness of each “monument” do not allow to individuate an a priori reliable and well defined analytical and interpretative strategy; ii) it is often more appropriate to accept a higher seismic risk for such particular buildings respect the ordinary constructions, rather than to provide strengthening interventions that are manifestly in conflict with the preservation criteria of the cultural heritage (Athens charter 1931, Venice charter 1964, ICOMOS- ISCARSAH Recommendations 2005).

This is conceptually not far from the probabilistic approach used for the definition of the safety margins for the new constructions, considering that, besides the primary exigency of protection of the human beings, the definition of the limit states is not made on the basis of the repair of construction costs, but on the bases of the preservation of the intrinsic cultural aspects of the building. It is in any case always necessary to quantitatively evaluate the acceleration that leads the building to the collapse, prior and after the strengthening intervention, and to compare it with the site demand, a very important issue in the effort of preserving such class of buildings from excessive interventions. It is furthermore considered the possibility to delocalize the functions conferred to specific buildings in cases where the seismic protection is the main concern (Civil Protection Agency offices, Fire brigade headquarters, hospitals…).

Finally, the so called Importance Factors, used in the seismic standards (OPCM 3274/2003) to increase the seismic demand in case of buildings of particular importance (γI, from 1.0 – ordinary buildings - to 1.4 – hospitals, fire brigade headquarters…), were re-defined for the cultural heritage buildings, according to their artistic relevance (defined by the Ministry of Culture) and their use. It is stressed here that in this case such factor can also reduce the seismic demand (i.e., for a limited relevance and an occasional use, as can be the case of a rural church, γI, corresponds to 0.5).

Table 1 : Importance Factors, guidelines for the application of the Italian seismic standards (OPCM 3274/2003) to cultural heritage buildings (2006).

<table>
<thead>
<tr>
<th>Utilization category</th>
<th>Limited</th>
<th>Average</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occasional use</td>
<td>0.5</td>
<td>0.65</td>
<td>0.8</td>
</tr>
<tr>
<td>Frequent</td>
<td>0.65</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>Intense</td>
<td>0.8</td>
<td>1</td>
<td>1.2</td>
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4 KNOWLEDGE OF THE BUILDING

For the evaluation of the seismic safety of existing buildings, or for the implementation of strengthening interventions, the importance of the knowledge phase is asserted, actively contributing to the assessment of the structure.
The knowledge of the structure intervenes in fact in a substantial way in the seismic verification, since the seismic code foresees partial safety factors (Confidence Factors, ranging from 1.00 – exhaustive – to 1.35 - limited knowledge), i.e. properly decreasing the adopted materials strength and stiffness values, or decreasing the acceleration related to the different limit states, depending on the acquired information on the building.

In particular, it is asked to demonstrate a sound understanding of the fabric, from a historical, constructive-geometric and mechanical point of view (Figure 1). In the case of cultural heritage buildings such exigency is still stronger, since it is particularly difficult to find data concerning the original conception of the structure and the modifications intervened during the time (due to anthropic interventions, to materials ageing, to external actions); moreover, the execution of a complete investigation campaign can be excessively invasive. The definition of the characteristics of the fabric is intended to identify an interpretative model necessary for both a qualitative understanding of the structural functioning and a quantitative definition for the structural analysis. The essential steps for the attainment of a comprehensive understanding of the fabric are the following:

i) identification and localization of the building, of its relation with the surrounding structures, definition of the site seismic demand;

ii) complete geometric and damage pattern survey;

iii) definition of the historical and structural evolution of the fabric, intended as the sequence of phases meaningful from a structural point of view;

iv) individuation of the resisting structure, paying attention to the constructive techniques and details, to the structural elements’ connection;

v) identification of materials constituting the structural elements, of their deterioration, of their mechanical characteristics;

vi) knowledge of the soil and of the foundation structures.

An important feature of the guidelines is the mention of the monitoring as the main tool for a conscious control of the historical buildings, since it allows to evaluate during the time the behaviour of the structure, enabling the scheduling of the maintenance works, and indicating the possible necessity of strengthening or repair interventions. Monitoring activities start with the basic visual inspection, to evaluate macroscopic changes in the structure (damage pattern onset, widening of existing cracks…), until arriving to more sophisticated electronic controls on significant mechanical or physical parameters.

5 STRUCTURAL MODELS

For what concerns the evaluation of the structural response of the historical buildings, rather innovative contents are considered in the codes and technical documents. In particular, it is stressed the necessity to evaluate the response of individual portions of the structure that can
manifest an independent behaviour in occasion of a seismic event. In fact, from the structural
damage observation after several seismic events recorded in Italy in recent decades, it was no-
ticed that the effective response of an existing masonry building to horizontal actions can be
hardly defined, in the majority of cases, by just considering the global behaviour of the struc-
ture.

![Figure 2](image1.png)

Figure 2: (a) Local collapse, out-of-plane of the façade wall’s last level, historical centre, Salò, Brescia
(Salò earthquake, 2004); (b) damage interpretative model (Giuffrè 1993).

Due to lack of connection between walls, walls and floors, to the reduced in plane stiffness of
floors, to the masonry composition and to the actual crack pattern denounced by the structure,
the majority of damage suffered by existing masonry buildings presents in many cases local
characteristics, related to individual structural elements that are not able to manage an effective
load redistribution to the rest of the building (Magenes et al. 2000, Modena et al. 2004). This
especially applies to out-of-plane actions, as denounced by the wide observation of local dam-
age, with partial collapse of masonry panel and the rest of the building still standing (Figure 2).
Figure 3 to Figure 5 are representative of seismic damage occurred to churches during the Salò-
Garda lake earthquake (November the 24th, 2004).

![Figure 3](image2.png)

Figure 3: (a) Damage in correspondence of the bell-tower, Annunciation church, Salò, Brescia;
(b) damage interpretative model (Salò earthquake, 2004).
Figure 4: Onset of the façade out-of-plane overturning, limit state of damage, S. Maria Immacolata church, Nave, Brescia (Salò earthquake, 2004).

Figure 5: Façade out-of-plane overturning, beyond the limit state of damage, S. Benedetto da Norcia church, Vobarno, Brescia (Salò earthquake, 2004).

Figure 6: Typical failures: (a), (b) masonry buildings (Giuffrè, 1993); (c), (d) churches (Lagomarsino, 1997); (e), (f) palaces (scheda rilievo danni ai palazzi, DPC, min. BBCC, 2006).
The historical masonry structures represent an extremely heterogeneous sample concerning structural typologies and constructive techniques, and the adoption of suitable interpretative models can not disregard such peculiar features. Several matrices graphically depicting the more common failure modes, based on a vast damage classification work after the recent seismic events and referred to specific building typologies, were defined (Figure 6). Moreover, evidences such as the construction of the building following “correct” empirical rules (regola d’arte) or the historical response of the building to past seismic events, considered as real scale tests on the building, are input data that have to be taken into consideration for the definition of appropriate behavioural models.

Concerning the overall seismic evaluation of the historical buildings, non linear analyses are generally preferable, even if not applicable without a thorough comprehension of the specific characteristics of the analyzed building, according to the possibility to describe the inelastic behaviour of masonry. It is in any case allowed the use of kinematic mechanism models extended to the totality of the structure, provided that the seismic action is correctly shared between the resisting elements of the building.

Specific codes for the evaluation of the overall seismic vulnerability of individual masonry buildings or aggregate of masonry buildings (VULNUS, Bernardini et al. 1990), and for the safety evaluation of the different rigid body kinematic mechanisms, related to the individuated macroelements, according to the seismic standards (C-SISMA, Valluzzi et al. 2004), were implemented at the University of Padova.

A wide research was performed to appreciate the reliability of the proposed models, also in comparison with “traditional” global assessment methods widely used in the last decades for masonry buildings, such as the storey non linear static analysis (Circ. Min. LLPP 21745 30/07/1981). Comparative analyses applied to buildings severely damaged during the 1997 Umbria Marche earthquake defined that in general, global analytical procedures, when applied to historical masonry building, can be misleading in the interpretation of the actual behaviour of the analyzed buildings, since the effects of the earthquake were fully appreciable at the moment of the execution of the analyses, finding a better match with analytical procedures (macroelements approach) considering local rigid body kinematic mechanisms (Valluzzi et al. 2001).

Figure 7: (a) application of the C-SISMA software to selected kinematic mechanisms, buildings in aggregate in the historical centre of Castelluccio di Norcia (PG), damaged after the 1997 earthquake; (b) results of the analysis, different mechanisms plotted vs. the “percentage” of seismic verification according to the seismic standards (OPCM 3431/2005) (Munari 2005).
The use of limit analysis for the global seismic evaluation of buildings was then applied to several different typology structures, as palaces (Figure 8), where a global model could have proposed results of reduced reliability and difficult interpretation, and churches (Figure 9), also with comparative analyses after the execution of light strengthening interventions, essentially aimed at the seismic improvement of defined portions of the complex.

Evaluations between the application of limit analysis and non linear finite elements models were applied in the S. Maria Assunta Cathedral in Reggio Emilia, for defined portions of the structural complex, obtaining interesting comparative results provided that suitable material constitutive laws are considered in the numerical model (Figure 10).
6 INTERVENTIONS

General requirements, based on vast research work and on the observation at a real scale of the performance of already executed interventions, are indicated in the seismic code to define the methodology of strengthening interventions, intended to reduce the seismic vulnerability according to the exigencies of preservation of the building.

The main objective is the respect of the functioning of the structure, generally intervening in well defined areas and avoiding to vary in a significant manner the global stiffness distribution. If necessary, all of the strengthening operations should be applied in a regular and homogeneous way, and to be estimated and justified by calculating their effect in terms of variations in the global behaviour of the structure. Interventions should be performed only after the evaluation of their effectiveness and the impact on the historical construction. Particular attention must be moreover paid in the executive phase, in order to guarantee a good and effective quality. A list (non exhaustive) of advised intervention techniques is then given, providing the professional with a series of alternative choices, validated through on field and laboratory research. The possibilities and limitations of each technique are briefly explained, and in any case it is not forbidden the use of innovative techniques or particular solutions, whose efficacy must however be demonstrated.

It was noticed that a “to do list” in case of strengthening intervention is not viable, since specific and effective intervention in one case can be ineffective or, even worst, detrimental to the seismic capacity of the structure in other cases. It was abandoned the idea that it is possible to...
confer to each structure a “box” behaviour, by means of indiscriminate “a priori” interventions, considering that, for example, a stiff R.C. floor is not crucial for the safety of a masonry ordinary building (Figure 11).

The general indications that stand below the suggested techniques are the improvement of the seismic performance of the building mainly by using traditional methodologies, also adopting innovative techniques and materials. In the first place it is necessary to allow the structure to manifest a satisfactory global behaviour, by improving the connections between the masonry walls and between these and the floors. This goal may be achieved via the insertion of ties (Figure 12), confining rings (Figure 13), and tie-beams (preferably in reinforced masonry or steel, also in R.C. but with restrictions, Figure 14). A traditional technique as the “scuci-cuci” (substitution of damaged/cracked elements with new ones for the reestablishment of the structural continuity) can be employed with particular attention since it comports original material substitution. An effective connection between floors and walls is useful since it allows a better load redistribution between the different walls and exerts a restraining action towards the walls’ overturning. Considering wooden floors, a satisfactory connection is provided by fasteners anchored on the external face of the wall (Figure 15).
Interventions aimed at the in-plane stiffening of existing floors must be carefully evaluated since the horizontal seismic action is transferred to the different masonry walls in function of the floor plane action, depending on its stiffness. A limited wooden floors stiffening is obtained by providing, at the extrados of the existing floor, a further layer composed by wooden planks, with orthogonal direction respect the existing (Figure 16). The use of metallic belts or FRP strips, disposed in a crossed pattern and fixed at the extrados of the wooden floor (Figure 17), or the use of metallic tie-beams bracings, may improve the stiffening effect.
Interventions aimed at increasing the masonry strength may be used to re-establish the original mechanical properties lost because of material decay or, alternatively, to upgrade the masonry performance. Techniques used must employ materials with mechanical and chemical-physical properties similar to the original materials. Interventions should be provided in a way to be uniformly distributed (both strength and stiffness). With opportune cautiousness, suggested techniques are the "scuci-cuci", non cement-based mortar grouting (Figure 18), mortar repointing (Figure 19), insertion of "diatoni" (masonry units disposed in a orthogonal direction respect the wall’s plane) or small size tie beams across the wall, with connective function between the wall’s leaves (Figure 20).
7 CONCLUSIONS

A significant step ahead was moved in the direction of the preservation of cultural heritage buildings in seismic prone areas. The recent Italian seismic code (OPCM 3274/2003 and successive supplements and modifications), and the successive guidelines (latest version, 2006) for the application of the seismic standards to cultural heritage buildings, are substantially in line with the requirements of cultural preservation expressed by different methodological documents (Athens charter, 1931; Venice charter, 1964; ISCARSAH Recommendations, 2005).

The observation of the damage caused by the earthquakes in the recent period was essential for the definition of new interpretative models, adjusted on the effective damage patterns experienced by the structures, and also for the validation (or repudiation) of intervention techniques that demonstrated different performances during the seismic event.

The knowledge of the building’s history, the detailed evaluation of the current state of structure and materials, the evaluation of the behaviour of the structure at regular time intervals (monitoring), the comprehension of the peculiar characteristics of each building in order to define suitable interpretative models, can be considered integral parts of the seismic assessment of any historical buildings. For this reason, structural models fitted for new constructions are considered generally not effective in the case of cultural heritage buildings, and a qualitative evaluation is believed to be significant in the overall judgement of their seismic performance.

REFERENCES


Casarin F. 2006. Structural assessment and seismic vulnerability analysis of a complex historical build-
ing. Doctoral Thesis, University of Trento/University of Padova
the Venice Charter, international charter for the conservation and restoration of monuments and sites, Venice 1964
Circ. Min. LLPP (decreto of the Ministry of Public Works) n. 21745 30/07/1981
Ministerial Decree (D.M 16/01/1996): technical regulation for constructions in seismic areas (in Italian).
Ordinance of the Prime Minister (O.P.C.M. 3274, 20/03/2003): first elements about the general criteria for the seismic classification of the national territory and the technical regulations for constructions in seismic areas
Ordinance of the Prime Minister (O.P.C.M. 3431, 03/05/2005): further changes and upgrade to the O.P.C.M. 3274, 2003
Scheda per il rilievo del danno ai beni culturali – palazzi. Dipartimento della Protezione Civile, Ministero dei Beni Culturali, approved with Prime Minister Decree, 23/02/2006.
Guidelines for the application of the seismic standards (OPCM 3274/2003) to cultural heritage buildings 2006 (draft version).