Guidelines for seismic retrofitting of ancient masonry buildings

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Summary

This article contains a concise report of criteria and methodologies for repairing and consolidating masonry buildings in historical centres damaged by the 1997 Umbro-Marchigiano earthquake.

The described procedures are contained in the "Handbook for the post-earthquake rehabilitation and reconstruction of buildings", promoted by the Regione dell’Umbria and directed at designers involved in the reconstruction process.

The aim of this work is to provide operative guidelines of an interdisciplinary nature, involving professionals from numerous disciplinary areas.

1. Introduction

Whilst defining regulations and criteria for the reconstruction process, the Regione dell’Umbria was keen to draw our attention to the protection and improvement of historical centres and traditional building typologies, by promoting and editing a handbook directed mainly at professionals operating on historical buildings in Umbria.

With the aim of making the Regione dell’Umbria’s initiative known throughout the technical and scientific community, which has the greatest interest in such an issue, this article concisely relates some principles and typologies of intervention contained in the chapter on methods of intervention. This chapter deals in particular with interventions on traditional buildings, which, even when lacking the requisites of monumental ones, are nevertheless worthy of attention both as individual units and for the unitary whole that they help to define. The text, therefore, illustrates a reconstruction process which bears in mind aseismic safety and at the same time the protection of that architectural, historical and environmental heritage that the earthquake-prone area is so rich in.

2. Aims and methodological aspects

The typology and methods of intervening on masonry buildings, illustrated in the above text, comply with the general principles listed in the specific recommendations of the Regione dell’Umbria and of the Minister for Arts and Culture.

Such provisions are generally of a conservative nature. The aim in particular is to direct designers towards interventions which combine greater safety with historical and environmental aspects, which encourage the re-use of traditional materials and techniques, the need for an in-depth analysis of the building, and the quest for a satisfactory level of quality in terms of intervention.

The operative strategy therefore adopted involves maintenance, at the same time, responding to the needs of aseismic behaviour.

In the ambit of "compatible reconstruction", there is less certainty as to the real effectiveness of partial consolidation which makes the masonry building hybrid, with a mixed behaviour (and at times inconsistent) between that of historical masonry and that of r.c. elements inserted therein.

To be able to provide a correct diagnosis, it is particularly important to analyse the building types and gain an in-depth understanding of the structure (often concealed by a series of interventions over time), preliminary operations which help to pinpoint the key to the operation.

If we follow this course of action (in the traditional logical sequence: diagnostic-diagnosis-therapy), often, at least concerning structures with adequate masonry, light, local interventions are sufficient to give (or give back) the building the pre-established level of aseismic safety.

In the handbook particular importance is given to the methods of achieving quality masonry, indispensable for counting on adequate mechanical performance, and to the links between different elements and different organisms, given the importance of this aspect on the analysis of possible kinematic collapse mechanisms.

An error that we observe only too often in buildings undergoing "adjustment" is when the floors are stiffened without considering whether or not the
masonry structure is able to bear horizontal actions attributed to it.

Priority is hence given to rectifying structural weaknesses. A preliminary survey suggests a strictly necessary intervention involving the reconstitution of resistant mechanisms, if deteriorated, or their strengthening if deemed inadequate, alongside the introduction of new supports where substantial structural weaknesses have been pinpointed.

Regarding the text in question, particular attention has been lent to the behaviour and possible interventions on serial buildings, characteristic of historical centres, given the lack of bibliographic references and complexity of the issue, very different from that of the isolated building.

3. Quality of masonry and seismic behaviour

Whoever has performed surveys on damaged buildings has no doubt noted the importance of the masonry's quality. Whether in large towns or small mountain villages, the worst damage has been observed in buildings constructed with shapeless masses of stones or non structural perforated bricks. The rubble visible at ground level and the scanty portions of building still standing are evidence of bad-quality assemblage and precarious mortar.

In these cases we cannot speak of kinematic collapse mechanisms, since the masonry wall does not behave in the same way as a monolithic solid. During an earthquake the wall crumbles, not possessing an adequate level of internal connection.

Cracks are extremely indicative of the quality of masonry. A panel with irregular fractures throughout indicates disconnected masonry with small stones arranged in a chaotic fashion, without considering the horizontality of lines. Isolated cracks, on the other hand, reveal monolithic behaviour: the masonry is subdivided into two or more elements which maintain their form and shift reciprocally between themselves. In the latter case, the problem should be sought out in the overall functioning of assemblage and connections rather than in the quality of the masonry.

In the case of plastered walls, when judging the overall crack situation we must bear in mind the difference in behaviour of masonry and the layer of plaster, a particularly marked difference in the case of thick cement (unreinforced) plaster, often visible and, at times, entrusted with improbable structural tasks. Owing to the concrete face's greater rigidity, it absorbs a large part of the initial stress.

In buildings recently consolidated with the technique of reinforced plaster, most of the damage verified is ascribable to poor functioning of the system formed by the original wall and two r.c. plastered faces. Damage due to in-plane seismic action is less common and if anything visible on the lower part of the building where the plaster connects with the foundations, which are not as rigid as the overlying wall. In these areas, the condition of mortar is evidently bad owing to the masonry's constant saturation caused by the upward infiltration of water and impermeability of the concrete. Immediately above the foundations, the earthquake therefore encountered a hollow wall, where the external walls were constituted by several centimetres of reinforced concrete, while the heavy filling no longer possessed structural capacity.

4. Observed kinematic collapse mechanisms

In buildings where the quality of masonry proved to be adequate, the damage verified was often ascribable to collapse mechanisms characterised by the typology and quality of connections between components of the building itself; connections which, in ordinary static conditions and with the action of just loads, marginally contribute to the overall stability of the organism, but in case of earthquakes assume a decisive role.

In fact, seismic action implicates the onset of horizontal forces which the unilateral constraints, generally ideal for resisting vertical loads, are not always able to withstand. Other types of constraint are therefore needed here and their absence would produce detachments that could eventually lead to collapse.

Out of plane collapse mechanisms have been observed in a variety of forms, linked to the wall's particular constraint conditions. As to historical building, unmodified by recent interventions, we have observed horizontal cylindrical hinges around which revolve entire unheld walls and flexural collapses with paraboloid profile in the case of panels constrained on three sides. Fig. 1 shows flexural failure in a panel tied to the orthogonal walling, in the presence of masonry panels effectively tied to the orthogonal walls and with the top side not held by any device.

Fig. 2 shows how the out of plane behaviour of the individual units is not largely influenced by the presence of other buildings. Under the same conditions linked to the particular site and building typology, we have often observed how terraced housing, in the presence of premodern support mechanisms, behaves decidedly better in the face of seismic phenomena.

Note how the "historical" solutions tend to make the neighbouring buildings collaborate (for example, through retain arches): an antiethical formulation compared with current regulations, which instead stipulate the creation of joints for the structural separation of buildings.
Fig. 1 – Wall constrained on three sides in the presence of in-plane orthogonal stress. The photo and drawing below reveal the complete absence of connections between the two faces of masonry.

Fig. 1 – Parete vincolata su tre lati in presenza di sollecitazioni ortogonali al piano. Nella foto e nel disegno in basso si può notare la mancanza totale di collegamenti tra le due cortine della muratura.

Fig. 2 – Crumbling façades and historical solutions to the problem.

Fig. 2 – Crolli dei prospetti e soluzioni storiche al problema.
More complex is the case of buildings recently retrofitted with the introduction of new concrete floors. The extent of damage has highlighted the collapse of entire panels or substantial parts of them, while often the floor has remained intact. This new collapse type has been tackled according to two levels of interpretation: kinematic and dynamic. The aim of the analyses is to highlight the behaviour of the floor slab–wall system, which does not appear to be adequately represented by the usual methods of structural analysis.

Fig. 3 presents a kinematic interpretation with the singling out of macroelements in the wall which remain integral on their inside and which shift reciprocally around hinges. Above is represented the case of a rigid floor: not being able to adapt to the profile of the top part of the wall, it decompresses or even discharges the perpendicular wall subjected to overturning. The case demonstrates a flexural behaviour of the slender load-bearing wall, owing to action from the left, while with action from the right, a shear behaviour prevails. In the same Fig., as a comparison, is an example of a deformable floor (with a two-way framework). Here, we can see the positive effects of a greater deformability.

Fig. 4 displays a qualitative dynamic interpretation of overturning in the presence of rigid floors. Here, we observe how the dynamics of seismic stress and, in particular, the propagation of accelerations from the foundations to the top of the building, cause "whiplash" to the upper part of masonry, positioned perpendicularly to the direction of the earthquake. In such an instance, the presence of a relative acceleration between the top of the walls and roof block (and hence a horizontal force applied in the baricentre of the roof itself) produces a rigid rotation of the ceiling, which tends to rise up from the wall. Therefore lost is the restraining action exercised by the stringcourse on the underlying masonry, which collapses under acceleration action.

It is interesting to observe the collapse types due to coplanar actions, more frequently verified in earthquakes of Umbria and the Marches. Case A represented in Fig. 5 is characterised by the rotation of a wedge-shaped masonry element. The closer its diagonal profile is to the vertical, the poorer the quality of masonry. Case B reveals seismic stress undoubtedly greater than the former. We can observe the actual sliding of an even larger portion of masonry: the nature of the kinematic mechanism is clearly evident from the reciprocal position of cracks.

Mechanism C can be observed alternately with mechanism B and shows masonry of adequate mechanical characteristics in that even moderate tensile strength can avoid Mechanism A occurring.

Of considerable interest was the analysis of damage mechanisms in the presence of apertures. As an example, Fig. 6 shows the interpretation of damage to a building in Busche (Gualdo Tadino) through an analysis of Kinematic mechanisms of the wall plane.

The sequence shows the façade wall’s subdivision into macroelements. Diagram 1 illustrates the rotation of the left-hand end part, singled out by the line of apertures (sector A of rotations). The same applies for the right-hand end portion, the moment the seismic stress changes direction. Diagram 3 displays a sliding kinematic mechanism (sector B of translations) of the triangular portion, which no
longer benefits from the restraint of the left-hand load-bearing end, now detached.

Note how the pinpointing of sectors is largely conditioned by the layout of apertures and presence of arches on the ground floor.

This behaviour type of walls subject to in-plane actions is verified in both isolated buildings and terraced housing.

In the case of wall plane mechanisms, we can affirm that considerations evolved through the singling out of monolithic elements, are significant only if the quality of masonry is adequate enough to avoid disintegration.

5. Kinematic collapse mechanisms in terraced housing

In the case of terraced housing that has not undergone substantial modification, we have predominantly verified partial damage and collapses with crumbling corners, cymatia and roofs, while the rest of the structure has remained intact. The limited effectiveness of links between the masonry elements is such that the terraced housing as a whole does not present a uniform behaviour: each portion supports itself and what rests directly above it.
Fig. 5 – Modes of damage for in-plane stress of masonry.
*Fig. 5 – Modi di danno per murature sollecitate nel piano.*

Fig. 6 – Effect of apertures on the formation of crisis sectors A and B.
*Fig. 6 – Effetto delle aperture sulla formazione dei settori di crisi A e B.*
a) Actions perpendicular to the wall plane: overturning of the single cells.
   In terraced housing, the extent of damage due to actions perpendicular to the walls is largely the same as that of isolated buildings.

b) In-plane actions: effects of seism on the façade wall and main inside wall.
   Parallel to what we may observe for a single masonry wall, we can examine the in-plane response of the terrace block in relation to possible kinematic mechanisms of rotation and translation. The former are triggered off by moderate horizontal stress, sufficient to isolate from the rest of the masonry structure a wedge-shaped macroelement diverging upwards. The wedge, determined by the quality of the masonry and presence of apertures, tends to rotate around the hinge produced by the particular constraint conditions (chains, retaining and restraining elements). For the sake of brevity, this wedge is indicated as "sector of rotations" or sector A. In this way, the main effect of the kinematic mechanism is emphasised, essentially consisting of a rigid rotation of the wedge. Walls sensitive to this collapse type are generally those of the end cells not bounded by other cells. Due to actions originating from the centre of the terraced housing, the end cell behaves as an isolated structure. It therefore offers no guarantee of stability in the face of horizontal seismic actions. Such an occurrence is sometimes prevented by premodem aseismic support mechanisms which prove to be very effective. In fact, to quash the tendency to overturn it is often sufficient to employ devices which restrain (tie-rods) or retain (propping arches, buttresses).

The units that benefit from the restraint of the bordering cells are more stable, being able to exploit the retaining action on the two sides. However, this occurs only when the façade of the cell is aligned with those of adjacent ones. The opposite case involves one or two sides unrestrained as indicated on the right in Fig. 8.

The kinematic mechanisms of in-plane horizontal sliding are instead triggered off by seismic action greater than that which triggers the above rotations and interests a wedge, indicated here as "sector of translations" (sector B), forming a wider angle with the vertical in comparison with sector A. Models effected on typical dimensions and typologies have provided numerical results from which it is possible to establish that for current masonry typologies, earthquakes measuring VII-VIII degrees on the MCS scale (for which a value of C has been adopted (multiplier of inertial mass) equivalent to 0.20 -- 0.24) produce the crisis owing to the rotation of sector A, while in order to trigger the kinematic mechanism of translation sector B, earthquakes require an intensity higher than VIII (and therefore values of C generally higher than 0.28).

This is confirmed by surveys carried out on various residential blocks of historical building, where the non-bounded cells reveal fractures that systematically reappear, though in each case with varying degrees of instability, according to the distribution of apertures on the various floors and where sector B’s collapse is a result of activation of sector A’s kinematic mechanism. Only in cases where the quality of masonry is decidedly better (adherence is sufficient to avoid subdivision of the wedge near the free side) can we verify the presence of sliding. Generally, however, the level of damage is fairly contained, proving how kinematic mechanisms which interest sector B are less violent.
With regard to both kinematic mechanisms of sector A and sector B, we can thus affirm that each cell absorbs the actions transmitted by its preceding structure and discharges stress onto the successive cell (buttress function). The most serious problems are hence located in walls which have a free end: in this zone the presence of apertures is therefore critical.

Owing to the considerable influence exercised by the apertures on the formation of wedges, precarious situations are verified, for instance, in blocks used for business purposes where the ground floor rooms are transformed and given large openings which make the wall inadequate to resist horizontal seismic stress.

It is interesting to note that transferring the observations made for the façade wall to the central wall of the block (generally possessing fewer openings), the extent of damage is much less significant. On the whole, the central wall performs a decisive static function and acts as a backbone, stabilised by the perpendicular walls. If many terraced blocks have managed to resist seismic action, it is probably due to this greater "integrity" of the backbone wall.

As to the factors determining the formation of hinges in one point rather than another, we can affirm that it is generally the geometric particularities which dictate the conditions of the extremities. The hinge around which sector A rotates is identified by the difference in rigidity introduced by the staircase wall. Such a point also delimits the line below which the flow of tension may reach foundation level without provoking sliding.

6. Examples of plates

Below is a summary of some indications and plates regarding: a) chaining interventions; b) roof stringcourses.

6.1. Chaining interventions

In the absence of toothing between the façade wall and perpendicular walls, when even the anchorage of the floor slabs appears ineffective, the wall’s resistance to perpendicular actions is essentially linked to slenderness; in these conditions the wall offers little resistance to overturning (1st damage mode) and may be pushed beyond the limit of equilibrium even by relatively moderate forces. In these cases, the wall’s low resistance to overturning can be effectively compensated through a better arrangement of restraining elements. In fact, the constraint produced by the wooden floor in the face of seismic action is a unilateral type: the wall cannot shift inward and is prevented from shifting outward only by the friction produced from the effect of the floor’s weight on the wall. It is obviously not possible to rely solely on the effectiveness of friction, nor on the toothing between perpendicular walls.

The vulnerability of the building is therefore strongly conditioned by damage mechanisms of the 1st mode, and their control is the prime aim of any preventive intervention. In this report, for the sake of brevity, we will only be examining the chaining intervention, in an endeavour to pinpoint and define the criteria of placing and dimensioning. To this end, it is necessary to follow a parallel course, flanking kinematic analysis with the design solution: to introduce a chain means to modify the resistant scheme, therefore, it is important to re-examine the structure in order to identify the new damage mechanisms.

The chains are generally positioned at floor level. The tie-rod must transfer to the transversal walls the force which would otherwise cause overturning of the outer wall. The mechanical problem thus involves pinpointing a channel for this transmission, which neither presents weak rings nor triggers dangerous concentrations of stress.
Tie-rods positioned near the transversal walls are the most effective, but it is often necessary to place anchors in intermediate positions also. The latter solution should also be considered when the length of the tie-rod is not sufficient to guarantee the formation of a discharging arch (created by seismic thrust) inside the wall. Generally, the distance should not be more than 10 times the width of the wall (and in any case not more than 5 m) and such distances between two centres should also be evaluated in relation to the existence and frequency of passing elements.

The damage mechanisms which interest masonry walls stressed by coplanar seismic actions (2nd damage mode) are triggered easily, but generally implicate rather high multiplier values of collapse and hence rarely reach the point of collapse. The wall, fractured by in-plane horizontal action, slides over itself or revolves around a hinge due to the effects of seismic action but, if well constructed, does not lose its load-bearing capacity.

If the wall has been built according to regulations, this form of damage can be defined as ductile, in the same way as constructions in r.c. and steel: in fact, the cracks in the masonry walls can be several centimetres wide without there being a dangerous loss of equilibrium.

Another very important aspect regards the distribution of shearing actions on the brace walls. In the case of rigid floors, the general procedure of calculation currently used permits the apportioning of horizontal forces according to the rigidity of the various load-bearing walls. In the presence of wooden, steel and brick floors, it is necessary to attribute each portion of wall only with horizontal forces produced by vertical loads, which in static conditions rest on such a portion (areas of influence).

The chaining intervention also has positive effects in the face of second-mode kinematic mechanisms. However, in-plane resistance only increases if the tie-rod reaches portions of masonry where the action transmitted by the tie-rod head can be discharged to the ground.

6.2. Roof stringcourses

The effectiveness of roof stringcourses strongly conditions the safety of the building. It is not possible to interpret the stringcourse's action in relation to 1st and 2nd mode mechanisms: in fact, the action of these devices is much more complex and their effectiveness depends on how they reduce the thrust of the roof beams, distribute vertical loads in static conditions, apportion horizontal forces produced by seismic action, link the perpendicular walls, and achieve a box-like behaviour. In actual fact, it is impossible to obtain all these characteristics at the same time, save through interventions that could deform the masonry structures, with serious damage, if badly performed, to the safety of the building. It would therefore be appropriate to focus on just some of the “fundamental” functions, like the link between walls, control of thrust and attainment of box-like behaviour.

Two already experimented solutions are proposed in place of the classic r.c. stringcourses: the reinforced masonry stringcourse and chain-stringcourse in steel (plates C and D).

While the first contributes to the apportioning of loads, the purpose of the steel stringcourse is to reduce the thrust of the roof and link the vertical walling.

Summarised below is a list of the positive and negative characteristics of the two systems:

- Stringcourse in reinforced masonry:
  - requires dismantling of roof;
  - easy execution on horizontal surfaces; it is more difficult to follow the slope of the gables;
  - has a good vertical deformability which permits it to discharge weight onto the underlying masonry, avoiding the so-called "beam effect" of the r.c. stringcourses [7];
  - the reinforcement may be used to restrain the eaves or brick or stone cornices;
  - can be made of brick or stone in respect of the aesthetics of the building;
  - does not create problem of cold bridges.

- Stringcourse in steel:
  - can be effected with or without dismantling the roof;
  - can be applied to a single wall or the entire top perimeter so as to form a reinforcement ring;
  - in masonry with horizontal or very irregular curvatures, it is necessary to mould the section bar and level the area of support;
  - does not re-distribute roof thrust onto portions of wall, which continue to receive the same vertical and horizontal load, and hence does not negatively alter the building's resistant mechanisms;
  - in unplastered buildings it has strong aesthetic impact;
  - requires little maintenance (anti-rust treatment) if not covered with plaster;
  - intervention is reversible.

The solutions listed in plates C and D undoubtedly provide devices for the reduction in thrust of the roof structure's orientation, for linking the walling and, in the case of the reinforced masonry stringcourse, for distributing vertical loads without significantly altering the overall functioning of the historical masonry building.
Conclusions

For the sake of brevity, this article relates only some of the criteria and methodologies contained in the text arranged for the Regione dell’Umbria. It is necessary to refer to the handbook for a more in-depth examination of the work carried out.

Notes

1 The Volume was coordinated by Prof. Francesco Gurrieri, Dean of Florence’s Faculty of Architecture, and the chapter “Repair and consolidation of masonry buildings” was entrusted to Prof. Antonio Borri of Perugia’s Faculty of Engineering, with the collaboration of Ing. Antonio Averio of the same Faculty and Ing. Giovanni Cangi, freelancer in Città di Castello (PG).

2 Regione dell’Umbria, Recommendations for designing and effecting reconstruction and restoration processes, with repair and seismic improvement, compatible with the protection of architectural, historical and environmental aspects.

3 General Instructions for drawing up restoration projects for architecture of historic-artistic value in a seismic zone, approved on 29/10/96 by the national Board for the protection of Cultural Heritage from seismic risk, of the Minister for Arts, Culture and Environment, and subsequently adopted, with some integrations, by the Higher Council of Public Works.

Manuale pratico per la riparazione di antichi edifici in muratura

Sommario

Nel presente articolo vengono riportati, in forma sintetica, alcuni dei criteri e delle metodologie per gli interventi di riparazione e consolidamento degli edifici in muratura appartenenti ai centri storici danneggiati dal sisma umbro-marchigiano del 1997.

Le procedure descritte sono contenute nella pubblicazione “Manuale per la riabilitazione e la ricostruzione posttsismica degli edifici” promosso dalla regione dell’Umbria e diretto ai progettisti impegnati nella ricostruzione.

Lo scopo è quello di fornire indicazioni operative di carattere interdisciplinare coinvolgendo professionalità provenienti da molteplici aree disciplinari.