Assessment of the seismic resistant capacities of traditional masonry buildings and retrofitting interventions to reduce their vulnerability

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Abstract

On the basis of the experience gained on the occasion of the Umbria-Marche, Italy, 1997 earthquake, the research investigates the seismic vulnerability of the masonry buildings realized with traditional non-aseismic techniques. Specific reference is done to the building typologies that are typical of the villages and the towns located in the central Italy area along the Apennines chain. Using the damage analyses already performed by the Authors with reference to the above mentioned earthquake the most frequent crisis mechanisms and the corresponding activation causes are identified. Effectiveness of alternative retrofitting techniques is discussed.

1 Introduction

The present work deals with the seismic vulnerability of traditional masonry buildings with typologies that are typical of the villages and towns located in the central Italy area, along the Apennines chain. We mainly refer to two or - at maximum - three storey buildings made of irregular dressed stones cemented with poor mortar and having roofs mainly with a double pitch and longitudinal (purlins, lombard roofs) or transversal (struts, piedmontese roofs) frame main elements.

Once identified the damage processes and the most relevant crisis mechanisms that are more likely to occur under a seismic event, as they are correlated with the typological and structural specificities of constructions, the
study intends to provide valid criterions for identifying the most appropriate intervention strategies for the vulnerability reduction.

The present work develops from the results of the research performed by the Authors on the occasion of the 1997 Umbria-Marche, Italy, earthquake (with epicentre in Colfiorito and 5.8 magnitude Richter, VIII degree MCS intensity), a research based on the processing of damage data collected by the Authors themselves in the earthquake area.

This research [1] [2] [3] [4] [5], performed through a methodology already proposed by the Authors [6] [7], has allowed to identify on a statistical base the most significant damage scenarios related to specific crisis mechanisms. Moreover it has been possible to identify the vulnerability factors related to specific typological and structural characteristics of the constructions (characteristics of the structural components, of their connections and those of the whole structural system) in turn relatable to the above mentioned mechanisms.

2 Damage scenarios and relative crisis mechanisms

The damage scenarios and the corresponding crisis mechanisms that are most significant with respect to the frequency of occurrence and to the global involvement of the structure are reported in the following.

- *Scenario/mechanism A*: damage characterized by a roof frame disarrangement (possibly with chimney-top involvement) and/or failure of the relative connections to the bearing walls (fig. 1, pictures (a) and (b)).

  This type of damage, with failure mechanisms not involving the masonry walls, has mainly regarded buildings with roofs having the frame main elements arranged horizontally and resting on the transversal walls. In this cases the damages of the connections were concentrated in correspondence of the transversal walls. They mainly consisted in the slipping off of the roof beams consequent to the restrain capacities deterioration of the relative wall support. This phenomenon has been often made worse by the effect of the vertical seismic action that can cause a friction reduction when directed upwards. These failures have been often accompanied, or substituted, by detachment damages between the roof frame and the longitudinal walls.

- *Scenario/mechanism B*: damage characterized by partial or total failure of the walls bearing the roof and, consequently, of the roof (fig. 2, pictures (a) and (b)).

  This type of damage has regarded principally buildings with the roof having the frame main elements arranged according to the roof pitch. The damages concerned the longitudinal walls bearing the roof and they have been the consequence of local shearing or overturning phenomena. These phenomena have been generated by the thrust of the roof itself, possibly accentuated by the vertical seismic action. In corner zones, damages sometimes occurred in both the converging walls, causing the collapse of the whole masonry corner.
Figure 1: Damage scenarios type A, characterized by damage at the roof and at its connections to supporting walls.

Figure 2: Damage scenarios type B, characterized by failure of masonry walls supporting the roof and, consequently, of the roof.
Scenario/mechanism C: damage characterized by local buckling or overturning of the masonry walls in the direction orthogonal to their plane, without involvement of the roof (fig. 3, pictures (a) and (b)).

This type of damage has principally regarded the walls not bearing the roof and the floors, and the roof tympanums as well, especially in presence of stiff roofs. The overturning action has been generally accentuated by the roof thrust.
Also in this case, when the damage occurred simultaneously in a couple of walls converging in a corner, the collapse of the whole masonry corner has followed.

- **Scenario/mechanism D:** damage characterized by cracking of masonry walls, with a simple or double diagonal “shear-type” cracking pattern (fig. 4, pictures (a) and (b)).

  This type of damage has principally regarded the walls bearing the roof and the floors, mainly in case of enough stiff roofs. The vertical seismic action, with its crushing effect on the masonry walls, often contributed to accentuate the cracking pattern.

### 3 Vulnerability factors

The factors and the association of factors depending on the typological and structural characteristics of the construction that have been revealed fundamental in the activation of the different crisis mechanisms are reported below:

- **mechanisms A:** not enough stiff roofs realized with structural elements scarcely connected among them and to the masonry walls;
- **mechanisms B:** roofs with frame main elements thrusting bearing walls quite weak (with respect to the masonry texture and the panels thickness) and not sufficiently connected to the roof itself;
- **mechanisms C:** concomitance of stiff and heavy roofs scarcely connected to the supports, with weak walls due to the mechanical characteristics of the masonry walls themselves (possibly formed by two different panels without adequate interconnections) and/or due to large free surface of the walls themselves (possibly for lack of transversal walls or horizontal tie-beams effectively linked);
- **mechanisms D:** concomitance of stiff and heavy roofs generally well connected to the bearing walls, with walls scarcely resistant in their plane due to the mechanical characteristics of the masonry and/or due to the large number of openings (possibly badly arranged within the walls with respect to the absorption of the seismic action).

Beyond the vulnerability factors specifically cited with reference to the different crisis mechanisms, further factors have revealed themselves important for their influence on the damage scenarios. This factors depend on the general characteristics of the building, as its height, its degree of symmetry in plane, the efficiency of the connections among the different walls, the soil characteristics and in particular its slope, the presence of adjacent buildings.

### 4 Intervention types

The most efficient intervention types (see technical literature [8] [9] [10] [11]) in contrasting the different crisis mechanisms are summarily reported in the following Prospect 1, in relation to the different architectonical and structural vulnerability factors. The interventions regarding the roof are also proposable for the floors.
These interventions can be directed both to the recovery of the damaged buildings and to the retrofitting of the existing ones having analogous typological and structural characteristics.

A cost-benefits analysis, that pays attention to the specific intervention context, is generally necessary for identifying the best solution.

Prospect 1. Main intervention types for contrasting the different crisis mechanisms.

- **Mechanisms A:**
  - improvement of the connection degree among the elements of the roof frame (intervention: linking of the roof elements);
  - improvement of the connection degree of the roof frame to the bearing walls (interventions: tie-beams, anchorages).

- **Mechanisms B:**
  - improvement of the connection degree among the elements of the roof frame (interventions: see above);
  - improvement of the connection degree of the roof frame to the bearing walls (interventions: see above);
  - reduction of the roof thrusting characteristics (interventions: linking of the roof elements and stiffening of the floor, tie-rods);
  - strengthening of the wall areas bearing the principal and the secondary roof beams (interventions: tie-beams, strengthening of the masonry texture through the sewing-unsewing technique and/or injection of binding mixtures, tie-rods, closure or strengthening by framing of openings in the roof proximity).

- **Mechanisms C:**
  - improvement of the connection degree among the elements of the roof frame (interventions: see above);
  - improvement of the connection degree of the roof frame to the bearing walls (interventions: see above);
  - strengthening of the walls with respect to the actions orthogonal to their plane (out of plane bending) (interventions: interconnection among the masonry walls, filling of possible niches, strengthening of the masonry texture through the sewing-unsewing technique and/or injection of binding mixtures, application of wire nets incorporated in concrete casts, toothing among masonry walls, reinforced perforation in correspondence of the connections among the walls, tie-beams, tie-rods).

- **Mechanisms D:**
  - strengthening of the walls with respect to the actions in their plane (in plane shear) (interventions: strengthening of the masonry texture through the sewing-unsewing technique and/or injection of binding mixtures, application of wire nets incorporated in concrete casts, closure or strengthening by framing of openings in case of excessive number or bad distribution of them).
The interventions illustrated in the above reported prospect can be accompanied or substituted by interventions regarding the global characteristics of the construction and in particular the global organization of the structural system. These interventions aim at the reduction of the stress level in the structural elements [8] by reducing the acting seismic forces and/or by better distributing them among the bracing walls.

The above mentioned interventions mainly aim at the reduction of structural masses, as well as at the reduction of torsional effects that can be reduced by creating or adjusting seismic joints or by modifying the stiffness distribution.

With respect to the structural mass reduction by lightening the floors, and in particular the roofs, it has to be noticed that the intervention, with the consequent reduction of the horizontal seismic forces, is particularly effective in case of crisis mechanisms related to overturning phenomena (B and C crisis mechanisms). With regard to the A and D crisis mechanisms the intervention is less effective as far as the reduction of seismic loads is accompanied by a reduction of masonry lateral resistance due to the decrease in friction and shearing capacities related in turn to the gravity loads.

5 Intervention strategies

In order to adequately define the intervention strategies, intended as choice of organic intervention programs, it is first necessary to consider the foreseeable damage processes that can occur during an earthquake. This has to be done in a clear and synthetic vision of the construction global behaviour.

Recent earthquakes have demonstrated that roofs, and in a less measure the other floors, play a fundamental role in the construction seismic response. In fact, they play a double role: a negative one as transmission elements of the vertical and horizontal seismic loads, a positive one as constraining elements of the walls. It has, moreover, to be considered the stabilizing and strengthening effect of the compression actions, gravity loads, transmitted by the roofs to the bearing walls.

The comprehension of the role played by the roofs is therefore crucial for explaining response of constructions and their damage processes.

On the basis of this consideration it can be noticed that the above described A, B, C and D damage processes or mechanisms can be regarded as connected among them in a global damage process that is illustrated below.

The roof disarrangement, or also its simple detachment from the walls (A mechanism), eliminates the constraining action that the roof plays on the walls: therefore, the roof only plays its negative role of seismic action transmitter. The consequent partial or total damage of the bearing or not bearing (B and C mechanism) walls due to actions orthogonal to their plane (transmitted to a large extent by the roof) determines the failure of these walls. Therefore, they are no longer able to contribute to the absorption of the seismic actions working in their plane, as requested by a correct and suitable space behaviour of the construction.

In order to avoid failures that are premature and inconsistent with the logic of a solid space behaviour, it is therefore necessary that the strengthening
interventions prevent first of all the activation of $A$, $B$, and $C$ local crisis mechanisms. In this way the construction can be leaded to a space behaviour with an ultimate crisis mechanism (global crisis mechanism) related to the attainment of the ultimate resistance capacities of the walls in their plane, through the development of $D$ local crisis mechanisms.

6 Intervention for the reduction of the vulnerability of structural systems with a space behaviour

The seismic resistant capacities, and therefore the vulnerability, of constructions to which it has been ensured a space behaviour can be evaluated by push-over analyses of the relative structural systems considered in their actual three-dimensional configuration.

These analyses generally refer to modelling contemplated by codes [12] [13], assuming the presence of rigid floor diaphragms and assigning the system seismic-resistant capacities to the reacting capacities - and in particular to the shear resistances - of the walls in their plane. In the modelling the walls are supposed as decomposed in different vertically continuous masonry piers (POR method).

This type of modelling does not consider the alterations induced on the behaviour of the single masonry elements by their belonging to walls that, with their particular morphological characteristics, can influence this behaviour.

It is therefore suitable to perform push-over analyses on sample walls, opportunely modelled, so as to allow to define the damage processes consequent to the crack development and also to evaluate the wall mechanical capacities, and in particular the resistant ones, as reduced by the presence of the specific vulnerability - or weakness - factors pointed out by the previous damage analyses.

It is so possible on the one hand to introduce some correctives in the evaluation of the wall (assemblage of different masonry elements) mechanical characteristics (stiffness, resistance, ductility) when performing the global push-over analyses, on the other to define the most suitable strengthening interventions of the walls themselves for increasing the resistant capacities in their plane. This has to be done with particular reference to the walls that are weakest for the presence of significant vulnerability factors, since the crisis of these walls can induce a global failure. The strengthening interventions can act at level of the causes or at level of the effects by preventing the cracking process development.

Push-over analyses on the strengthened walls allow quantifying and comparing the performance improvements obtained with the different solutions.

7 Conclusions

The definition of the possible damage scenarios and of the related vulnerability sources depending on the typological and structural characteristics of the
traditional masonry constructions is essential for defining possible intervention strategies to reduce their seismic vulnerability. This result can be mainly achieved through the results of detailed analyses of the damage produced by seismic actions.

It is therefore possible to establish both the intervention priorities and the modalities to realize them. This is in particular related, besides to the identification of the specific vulnerability sources, also to the definition of the damage evolution process from its beginning to the reaching of the collapse mechanism.

The work points out the needs of primarily proceeding to the interventions ensuring the connections among the different structural elements so as to obtain a solid space behaviour of the construction. The construction vulnerability will, at this point, mainly depend on the resistance limits of the walls in their plane. These limits are conditioned by the presence of specific weakness factors, such as masonry texture and openings.

Push-over analyses of the walls allow identifying the cracking processes in the walls themselves and the most suitable interventions for preventing these processes and for increasing the seismic resistance capacity of the considered elements. Moreover, they allow evaluating the vulnerability levels of the original systems and of those obtained with strengthening interventions.

References


