UMBRIA-MARCHES EARTHQUAKE OF 26 SEPTEMBER 1997: DAMAGE SCENARIOS AND VULNERABILITY SOURCES IN THE NOT-ASEISMIC MASONRY BUILDINGS

G SARÀ[1], G BARBETTI[2], A BONI[3], F MARILLI[4], R NUDO[5] And S VITI[6]

SUMMARY

The present investigation concerns the response to the seismic action of the traditional masonry buildings, therefore not provided with aseismic measures, located in the Umbria and Marches places hurt by the double seismic event of 26 September 1997. The investigation, performed on a statistical basis, points out the most frequent types and scenarios of damage. These scenarios are associated, by the individuation of the crisis mechanism, to the vulnerability sources related to the architectonic-structural characteristics of the buildings. That allows to come to useful conclusions about the most appropriate intervention strategies to be adopted referring to the different building situations.

INTRODUCTION

On 26 September 1997 the Umbria and Marches regions, and in particular the Perugia and Macerata provinces, have experienced a couple of seismic events of medium-high intensity. The two shocks, occurred at 2:33 and 11:40 a.m. with epicentre around Colfiorito (Perugia), had a magnitudo M_L of 5.5 and 5.8 respectively, and an average intensity, in the epicentre area, equal to the VII and VIII degree of the MCS scale. While the concrete buildings have been on the whole lightly damaged, the masonry buildings, generally realized by traditional, not aseismic techniques, have been seriously damaged, particularly in the zones near the epicentre. This occurred both to constructions of the historical centres, with or without monumental character, and to the buildings of the most modern city suburbs and of the towns and villages spread in the territory.

The aim of the following investigation is the determination of the main sources of seismic vulnerability, as pointed out by the damages resulting from the above mentioned seismic event, with reference both to the old buildings and to the most recent ones but made without aseismic measures. Buildings with monumental character have been excluded from the investigation.

The determination of the sources of seismic vulnerability, with reference to the different building situations and typologies, is fundamental to determine the most appropriate strategies and techniques both for repairing of the damaged buildings and for retrofitting and strengthening of the existing building heritage for the aseismic prevention.

The investigation has been performed according to the procedure followed by the Authors in some previous works about the determination of vulnerability sources by sampling of RC buildings on the basis of the response to seismic excitations [Sarà & Nudo 1992, 1993, 1994, 1997]. Such procedure analyzes the response of different buildings going back from the effects (damages) to the causes (vulnerability sources); the results are then generalised on a statistical basis.

[1] *Dipartimento di Costruzioni, Università di Firenze, I-50121 Firenze, Italy Email: sara@dicos.unifi.it*
[2] *Dipartimento di Costruzioni, Università di Firenze, I-50121 Firenze, Italy*
[3] *Dipartimento di Costruzioni, Università di Firenze, I-50121 Firenze, Italy*
[4] *Dipartimento di Costruzioni, Università di Firenze, I-50121 Firenze, Italy*
[5] *Dipartimento di Costruzioni, Università di Firenze, I-50121 Firenze, Italy*
[6] *Dipartimento di Costruzioni, Università di Firenze, I-50121 Firenze, Italy*

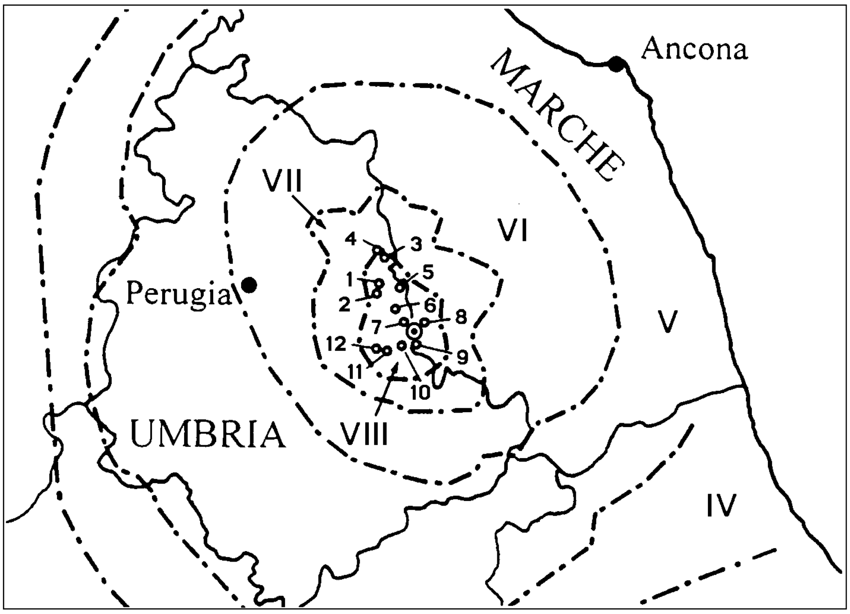

Figure 1. Epicentre and isoseismals relating to the earthquake of 26 September 1997. Distribution of the localities object of the survey: (1) Nocera Umbra, (2) Nocera Umbra Scalo, (3) Costa, (4) Colle, (5) Bagnara, (6) Annifo, (7) Colfiorito, (8) Taverne, (9) Cesi, (10) Volperino, (11) Serrone, (12) Casenove.

The following phases of procedure are identified:

– description, for each building, of the damage in terms of location, kind, amount and consequent definition of the relative “damage scenario”;
– individuation, for each building, of the estimated crisis mechanism, even in its evolutionary features and of the relative behavioural phenomenon of activation;
– individuation of the architectonic-structural characteristics and of their associations as estimated causes of activation of the phenomenon resulting in the damaged state and therefore identified as vulnerability sources;
– statistical evaluation of the frequency of the different damage scenarios related to the different crisis mechanisms and of the corresponding vulnerability sources, defined in terms of associations of architectonic-structural characteristics.

The procedure has been integrated and supported by tests, performed with the aid of appropriate physical and numeric modellings, which aim to confirm the validity of assumptions about the crisis mechanisms and the corresponding sources.

THE INVESTIGATION

Surveying and sampling of the buildings

The investigation has been opened carrying out an inspection, together with the appropriate surveys and cataloguings, of a set of more or less seriously damaged masonry buildings located within the zone of the so called “crater” around the earthquake epicentre, for a total of about 130 buildings (Fig.1). In particular, for each of these buildings, the damage and the architectonic-structural characteristics have been surveyed, even with reference to the soil [Sarà et al. 1998, 1999a, b].

Before going on to the subsequent elaborations, a selection of the sampled buildings has been made, in order to remove those with not enough surveying data and also those with a not important and difficult to read damage. The elaborations have therefore concerned the remaining sampling of 78 buildings located in several places in the territory of the towns of Nocera Umbra (Perugia) (11 buildings in the historical centre, 3 in the northern suburb near the Hospital, 9 in Nocera Umbra Scalo, 5 in the outlying wards of Costa and Colle, 4 in Bagnara), Foligno (Perugia) (4 buildings in Casenove, 1 in Serrone, 6 in Volperino, 9 in Colfiorito, 10 in Annifo), of Serravalle di Chienti (Macerata) (4 buildings in Taverne, 12 in Cesi).

Damage analysis

The most frequent types of damage are listed in Prospect 1. In the same the relative percentages of frequency are shown with reference to the set of the examined buildings (only the "primary" damages have been included in the calculation, excluding the damages directly induced by them). The Figures 2-8 show some of the most significant damages. In Prospect 2 the most frequent and significant damage scenarios are reported, defined by a "main" damage, associated to other complementary damages. In the same prospect the frequency percentages of such damage scenarios are shown. As observed in the prospect the main damages defining the different damage scenarios can be divided into two large sets: the damages of the roofs and the relative supporting structure (33%) and the damages of the masonry walls (67%). The last ones can be divided into damages due to the actions out of the wall plane (32.5%) (buckling, overturning) or to the actions in the wall plane (21%) (shear diagonal cracks) or at last can get the character of local damage near to singularities of different origin (13.5%).

A comparative check of the type of damage relative to the different examined places shows that in the old buildings of the historical centres the damage of the masonry walls is mainly characterised by localised failures (buckling, breaking) typical of masonry subjected to degradation or consecutive remakings. Instead the adjacency of buildings in general prevented from global settlements. The buildings in the more recent centres have shown, again with reference to the masonry walls, a priority of failures due to overturnig; in other cases, when the masonry quality resulted to be better in terms of panel stability, a priority of failures for shear actions, with the typical diagonal cracks, has been observed. The damage of the roofs resulted to be prevalent, with respect to that of the masonry walls, in the smaller centres, where the buildings are on the average more modest, generally without remaking of the roof, and of less height.

Prospect 1. Damage types.

(1) Damage of chimneys and/or of the texture of the roof
- (1.1) Damage of chimneys (2%)
- (1.2) Damage of the texture of the roof (15%)

(2) Breaking of the roof border and of connection to supporting walls
- (2.1) Detachment crack between roof, or tie beams of the roof, and supporting wall (2%)
- (2.2) Pull out of roof beams from supporting walls (12%)

(3) Detachment between corner walls (10%)

(4) Local breaking or buckling of masonry walls
- (4.1) Cutting of the top portion of the roof support (17%)
- (4.2) Local breaking of the wall (4%)
- (4.3) Local buckling of the wall (6%)

(5) Partial or total overturning of walls
- (5.1) Overturning of the top portion of the wall at connection to the roof (12%)
- (5.2) Overturning of the gable wall of the loft (5%)
- (5.3) Overturning of the wall (17%)

(6) Diagonal cracks in the walls
- (6.1) Simple diagonal cracks in the walls (18%)
- (6.2) Double diagonal cracks in the walls (21%)

(7) Vertical cracks in the walls located at the chimney-flues or at the masonry local remakings
- (7.1) Vertical cracks in the walls located at chimney-flues (4%)
- (7.2) Vertical cracks in the walls located at masonry local remakings (6%)

(8) Local cracks in the walls near openings
- (8.1) Cracks above and below openings (splitting of lintels, overturning of wall elements) (6%)
- (8.2) Cracks at corners or flanks near openings (4%)
- (8.3) Damage of frames of openings (7%)

(9) Damage in the walls at generical singularities
- (9.1) Crushing of walls below balconies with great overhang (1%)
- (9.2) Damage due to lateral contrast between floor slabs and walls (4%)

Figure 2. Civil building in Annifo (Perugia): damage of the structure of the roof and of the border elements connected to walls.

Figure 3. Civil building in Nocera Umbra (Perugia): collapse for overturning of the upper part of masonry panel supporting the roof.

Figure 4. Civil building in Serrone (Perugia): collapse for overturning of the masonry walls supporting the roof.

Figure 5. Civil building in Cesi (Macerata): overturning of the corner walls.

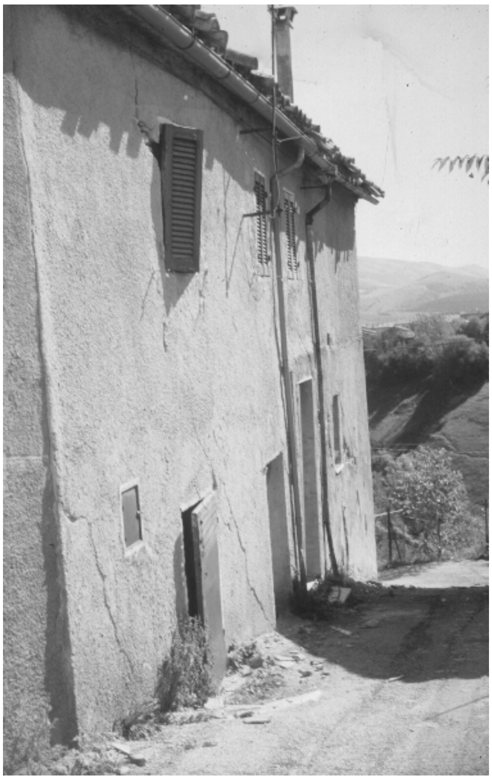

Figure 6. Civil building in Annifo (Perugia): simple diagonal cracks at the facade wall.

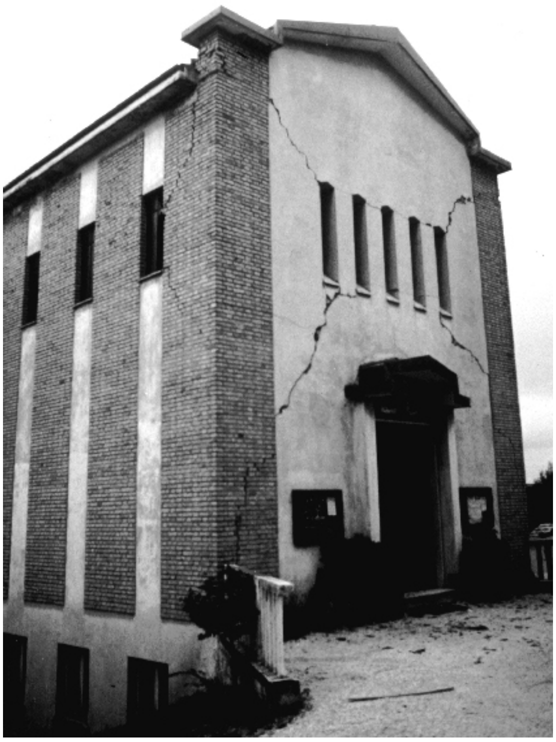

Figure 7. Church in Nocera Umbra Scalo (Perugia): double diagonal cracks at the facade wall.

Figure 8. Civil building in Nocera Umbra (Perugia): vertical cracks in the wall due to the chimney-flue.

Prospect 2. Damage scenarios.

Scenarios (T) Damage concerning the roof and its connections to supporting walls (14%)
- (T1) Main damage: damage of chimney and of the roof texture (7.5%)
- (T2) Main damage: local breaking of the roof border due to the cracks at connection between roof, or roof tie beams, and walls, or due to pull out of roof beams from supporting walls (6.5%)

Scenarios (MS) Damage concerning masonry walls supporting the roof and, consequently, the roof (19%)
- (MS1) Main damage: local breaking of the top portion of walls located at roof support (6.5%)
- (MS2) Main damage: partial or total overturning of walls supporting the roof (12.5%)

Scenarios (MR) Damage due to local buckling or overturning of masonry walls without the roof involvement (32.5%)
- (MR1) Main damage: local buckling of walls (10%)
- (MR2) Main damage: partial or total damage of walls (16.3%)
- (MR3) Main damage: partial or total overturning of walls, in conjunction with damage of walls with simple or double diagonal cracks (6.2%)

Scenarios (MT) Damage of masonry walls with simple or double diagonal cracks due to shear, without local buckling or overturning of walls (21%)
- (MT1) Main damage: damage of walls with simple diagonal cracks (5%)
- (MT2) Main damage: damage of walls with simple diagonal cracks, in conjunction with double diagonal cracks (2.5%)
- (MT3) Main damage: damage of walls with double diagonal cracks (13.5)

Scenarios (ML) Local damage of walls at discontinuities of the masonry texture, at openings, at generical singularities (13.5%)
- (ML1) Main damage: vertical cracks in the walls due to discontinuities of the masonry texture (chimney-flues, masonry local remarking, etc.) (2.5%)
- (ML2) Main damage: local damage in the walls at generical singularities (adjacency of slabs, etc.) (2.5%)

Prospect 3. Architectonic-structural characteristics and vulnerability sources.

(1) Characteristics of the roof
- (1.1) Texture of the roof (18%)
- (1.2) Weight and stiffness of the roof (26%)
- (1.3) Connection between main structure of the roof and supporting walls (27%)
- (1.4) Connection between secondary structure of the roof and supporting walls (28%)
- (1.5) Connection of chimneys (6%)

(2) Characteristics of floors and balconies
- (2.1) Overhang of balconies (12%)
- (2.2) Weight and design loads of floors (1%)

(3) Characteristics of masonry walls
- (3.1) Masonry walls and panels
  - (3.1.1) Masonry texture and thickness of the panel (55%)
  - (3.1.2) Masonry texture and tie beams of the overall walls (28%)
  - (3.1.3) Dimensions of masonry panels in their plane (17%)
- (3.2) Openings
  - (3.2.1) Distributions and number of openings in the longitudinal masonry walls (17%)
  - (3.2.2) Distributions and number of openings in the transversal masonry walls (3%)
  - (3.2.3) Openings near the roof (9%)
  - (3.2.4) Openings near the corner (9%)
- (3.3) Local remakings, connections, opening frames
  - (3.3.1) Discontinuities in the masonry texture: local masonry remakings, chimney-flues (18%)
  - (3.3.2) Connections between masonry walls (19%)
  - (3.3.3) Frames and openings (10%)

(4) Foundations and soil
- (4.1) Soil settlement due to land-slide (5%)

(4.2) Soil in slope (18%)
(4.3) Soil pressing against constructions (3%)

(5) Morphology of the building in plan and corresponding structural non-uniformities
(5.1) Shape of the building in plan (8%)
(5.2) Quantity of longitudinal walls (6%)
(5.3) Quantity of transversal walls (6%)
(5.4) Non-uniformity of the structural system in plan (5%)

(6) Morphology of the building in elevation and corresponding structural non-uniformities
(6.1) Height of the building (14%)
(6.2) Building with variable foundation plan (6%)
(6.3) Non-uniformity of the structural system in elevation (1%)

(7) Adjacencies
(7.1) Adjacencies of the building to the road plane (5%)
(7.2) Adjacencies to the other buildings (15%)

Prospect 4. Associations between damage scenarios and vulnerability sources.

Damage scenarios	Vulnerability sources more frequently associated to the specific damage scenario
(T1)	Texture of the roof (83%) Connection of chimneys (33%)
(T2)	Connection between main structure of the roof and supporting walls (60%) Connection between secondary structure of the roof and supporting walls (20%)
(MS1)	Connection between main structure of the roof and supporting walls (60%) Connection between secondary structure of the roof and supporting walls (40%)
(MS2)	Connection between main structure of the roof and supporting walls (90%) Masonry texture and thickness of the panel (90%)
(MR1)	Masonry texture and thickness of the panel (75%) Continuity lack in the masonry texture (50%)
(MR2)	Masonry texture and thickness of the panel (77%) Texture of the roof (54%) Dimensions of masonry panels in their plane (54%)
(MR3)	Masonry texture and thickness of the panel (100%) Masonry texture and tie beams of the overall wall (80%)
(MT1)	Distribution and quantity of openings in the longitudinal masonry walls (50%) Connections between masonry walls (50%)
(MT2)	Masonry texture and thickness of the panel (100%) Masonry texture and thickness of the wall (100%)
(MT3)	Masonry texture and thickness of the panel (64%) Weight of the roof (55%)
(ML1)	Connections between masonry walls (100%) Continuity lack in the masonry texture (100%)
(ML2)	Masonry texture and thickness of the panel (43%) Masonry texture and tie beams of the wall (43%)
(ML3)	Overhang of balconies (100%) Shape of the building in plan (100%)

Vulnerability sources

Referring to the different types and scenarios of damage we have determined the architectonic-structural characteristics which are thought to be responsible for the activation of the phenomenon and subsequently of the crisis mechanisms which are at the origin of the damages themselves. Prospect 3 shows a classification of the different architectonic-structural characteristics which are thought to affect the seismic vulnerability of the examined buildings, and therefore are identified as vulnerability sources. In the same prospect we reported the percentage of cases, with reference to the global sampling of the buildings, where each characteristic has been considered as origin of damage activation. By the examination of the prospect it is immediately clear the different importance assumed from the several architectonic-structural characteristics in order to determine the seismic vulnerability of the buildings. The investigation has been then developed towards the determination of the frequency of association of the different vulnerability sources with the main damage scenarios as previously defined. In Prospect 4 we reported, with reference to the different damage scenarios, only the mainly recurring vulnerability sources. In the same prospect this frequency is reported as a percentage respect to the whole of the buildings associated to the specific damage scenario considered each time.

CONCLUSIONS

The investigation pointed out the most frequent damage scenarios which developed in the traditional, therefore lacking in aseismic measures, masonry buildings by the earthquake of Umbria and Marches of 26 September 1997. It also pointed out, with reference to the different building situations, the architectonic-structural characteristics recognisable, separately or in association, as vulnerability sources because of their action as activation factors of the phenomenon underlying the crisis mechanisms related to the different damage scenarios. It was also possible, by means of statistical evaluations, to set a scale of the importance of the different vulnerability sources, and that on the basis of the severity and the diffusion of damages.

At the end of the work it is worth noting the fundamental importance of "connections" in order to determine the response of the buildings. In fact almost the whole of the damages can be related to deficiencies in connections, viewed in a broad sense. About that, on the basis of results, the following conclusions can be drawn:

- the buildings in adjacency, leaning together but with a continuity on the floors, often gave a better response than the isolated ones;
- the efficiency of the connections between floor and walls resulted particularly important for the general tightness of the buildings;
- the openings, as origin of discontinuities in the masonry walls, resulted to be important vulnerability sources, in particular if not bordered into the frame in an efficient way;
- the masonry with natural or artificial, poorly bonded elements resulted particularly weak; the double face masonry walls, lacking in an effective connection between the panels, also resulted weak;
- squared stone or brick cants and courses made an efficient confining action on the masonry walls; the steel rods also resulted particularly efficient in containing and connecting;
- the tie beams, when they were present, made a good action of linking, but sometimes this took place together with perturbations on the behaviour of the masonry wall because of the discontinuity introduced in the masonry texture.

The above observations show the importance of connections over all the levels of the structural organisation. Therefore it is advisable that the interventions on existing buildings, both with a restoring and a consolidating character, are mainly addressed to a general improvement of the systems of connection, with evidently differentiated measures from one case to the other on the basis of the vulnerability sources specific of each building.

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