

Study of the seismic vulnerability of complex masonry buildings

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Abstract

The study of the seismic vulnerability of complex buildings belonging to an historical centre located in the Umbria region in Italy is presented here. An earthquake struck the area in 1997, which emphasized the high vulnerability of the masonry buildings, even in consolidated conditions. Since then a systematic study was carried out in collaboration among universities and public bodies, in order to set up proper methodologies for survey and damage classifications, structural analysis modelling and improvement intervention proposals. The necessity of organizing the study on building typologies (isolated, rows and complex aggregates) was evidenced. This allowed us to select suitable procedures for the seismic vulnerability assessments and to prove the reliability of simplified macro-element kinematics models to describe the behaviour of existing masonry buildings in limit conditions. Those models are particularly indicated for complex aggregates, where the high level of irregularities and structural deficiencies can make inapplicable standard procedures (e.g. based on the “box” behaviour), and are used both for vulnerability prediction analyses and for simulation of possible retrofitting interventions.

Keywords: seismic vulnerability, masonry typologies, complex buildings, macro-modelling, limit analysis, kinematics mechanisms.

1 Introduction

Complex buildings in seismic area have specific vulnerability aspects which can make very difficult the adoption of common structural assessment procedures usually applied for regular buildings [1] [2].

The presence of geometrical irregularities both in plan than in section (lack of correspondence among walls and floors along vertical or horizontal lines) and constructive specificities (efficiency of connections, quality of constitutive



materials and their typology) requires the application of devoted methods based on the structural macro-modelling [3] [4]. This concerns the limit analysis performed by application of single or combined kinematics models involving the equilibrium of structural macro-elements both for in-plane and out-of-plane mechanisms. Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual bond and restraints (e.g. the presence of ties or ring beams), the constructive deficiencies and the characteristics of the constitutive materials. They can be more reliable in describing the real structural behaviour than common equivalent static procedures, based on the “box” behaviour of the structure and on the elastoplastic behaviour of the masonry. Kinematics models provide a collapse coefficient $c=a/g$ (where a is the ground acceleration and g the acceleration of gravity), which represents the masses multiplier able to lead the element to failure [5]. In the simplified assessment procedures, the mechanism connected to the lowest value of c is the weakest one and, consequently, the most probable to occur.

In such a context, a multilevel approach, including proper systematized survey and diagnosis investigations is essential [6], to reach a suitable knowledge for the correct choice of possible repair intervention techniques. This methodology has been tested and validated preliminarily on a large range of different typologies (isolated buildings and aggregates as row buildings) which allowed to set up computerized procedures for the study on large scale of historic centres ([7], [8]), and to define a series of guidelines for restoration and structural improvement of historic buildings in seismic area [9].

In the paper, the first analysis of some complex aggregates belonging to a historic centres located in the Umbria region in Italy, namely Castelluccio di Norcia (PG), is described.

2 The centre of Castelluccio di Norcia

Castelluccio di Norcia is a little village situated on top of a hill in the Umbria region (Italy), which buildings follow a very typical helicoidal morphology (see fig. 1). Historical and more detailed notes about the centre are given in Binda *et al.* [10], which the reader is referred to.

Different typologies of buildings are present: very few isolated new constructions, the old stables (arranged in rows), and a number of complex aggregates, developed during time due to subsequent transformations of the site.

The centre was only few damaged during the 1997 earthquake, thus provisions assessments are currently in need. The main observed damage was due to lack of maintenance, low quality of the materials and connections, and structural behaviour often worsened by incompatible retrofitting [3] [1].

3 The vulnerability analysis of complex buildings

3.1 Description of the complex building

Due to the high morphological and structural irregularities of complex aggregates, it is fundamental to organize the study on homogeneous portions of



the building blocks (named in the following as UI: Intervention Unit), where also interventions should be designed and executed consistently, despite different units can refer to different owners (see Binda *et al.* [10]).



Figure 1: View of the plain of Castelluccio and plan of the center with indication of the aggregate considered in the study.

In the following, the study of a complex building including four adjacent blocks is described (fig. 2). The building is on a slope which develops downwards in N-S direction. Timber floors and roofs are still present in most of the units, even some substitution with r.c. slabs were performed (UI 140 and 141); at the first level, depressed and barrel vaults are present (fig. 3). Ties are introduced in correspondence of the first floor, limitedly to the W and S sides. Masonry is made of stone in sub-horizontal courses with presence, in some zones, of clay brick shims; conversely, the UI 141 is completely made on regular clay brick layers. Partial re-buildings were performed in the past, thus discontinuities and lack of homogeneities are also present (fig. 4). The walls have a double-layer section, with lack of transverse connection among them. A scarce connection is also detected between roof and the top of the walls and among walls at the corners and intersections. Moreover, the presence of several openings, often not aligned along the vertical direction, limits the effective portion of masonry able to counteract the seismic action.

As for the crack pattern, the main damage is concentrated on the upper levels of the South side (UI 143-144, see fig. 2) and of the West side (UI 145), involving basically the corner (fig. 2). Vertical and sloped cracks were detected, indicating incipient mechanisms both out-of-plane and in-plane.

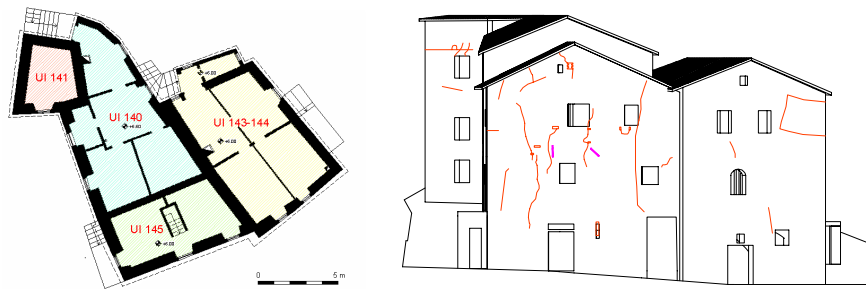


Figure 2: Plan of the building with indication of the four blocks (UI: Intervention Unit) and view of the South side with evidence of the crack pattern.

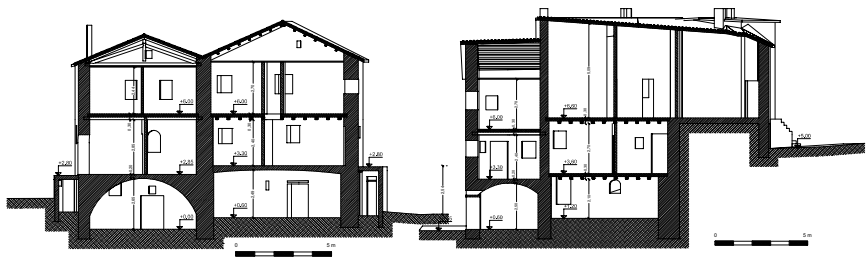


Figure 3: Sections (W-E, left) (N-S, right) showing the three storeys and the vaults at the first level.

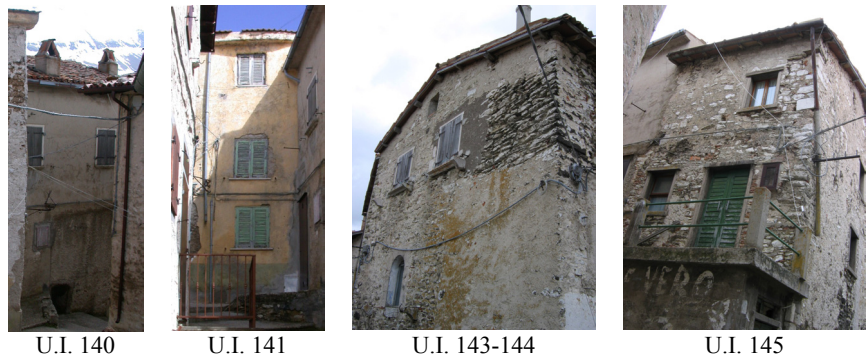


Figure 4: View of the blocks considered in the study.



3.2 Vulnerability analysis of the building

The seismic assessment is performed both at global and local level, by using two automatized procedures implemented in Visual Basic at the University of Padova: VULNUS, and C-SISMA, respectively (Bernardini *et al.* [7], Valluzzi *et al.* [1]). VULNUS defines two indexes, I1 and I2, related to the in-plane and the out-of-plane resistance (fig. 5), respectively; it combines the most probable mechanisms and it is able to give a global estimation of the vulnerability of the complex. Also damage distributions related to the EMS98 classification are possible (Gruntal [11]). By C-SISMA is possible to select the most significant macro-elements in the building and to apply a number of different out of plane and in-plane single kinematic mechanisms of collapse; the procedure is able to indicate the lowest seismic coefficient correspondent to the most brittle mechanisms to occur. The contextual contribution of the two procedures in the assessment phase allows to complete the vulnerability analysis by using reliable methodologies for existing masonry buildings.

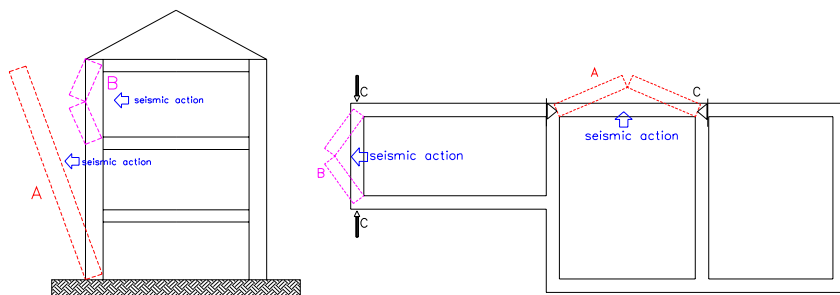


Figure 5: Example of out-of-plane mechanisms combined in VULNUS.

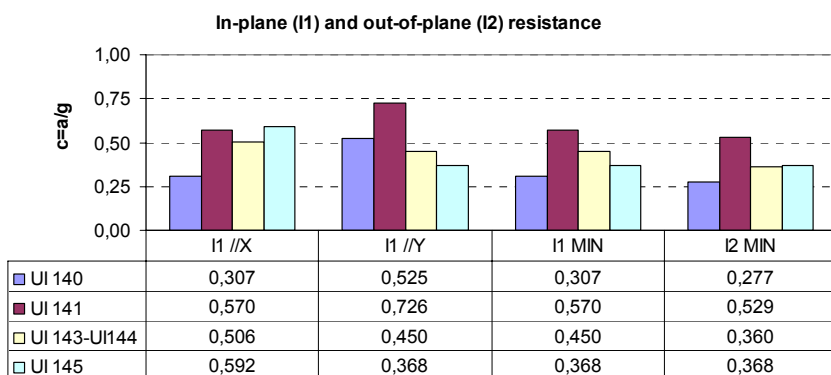


Figure 6: Results of VULNUS: comparison among the minimum I1 (in-plane) and I2 (out-of-plane) indexes; for I1 results obtained for X (i.e. W-E) and Y (i.e. N-S) directions are also shown.

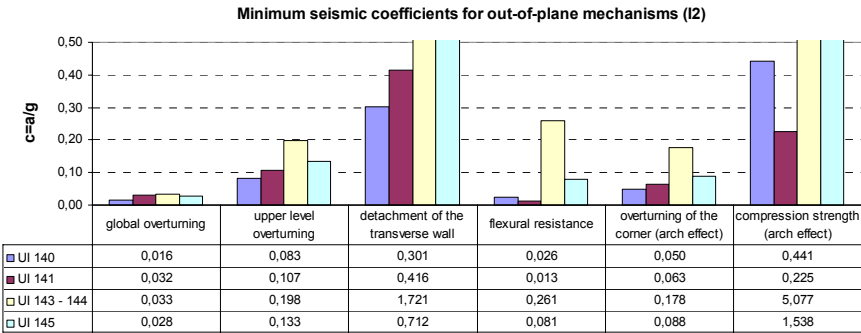


Figure 7: Results of Vulnus: comparison among the coefficients related to out-of-plane mechanisms (I2 index). The arch effect is intended developed in the thickness of the masonry.

The c-Sisma procedure considers in-plane mechanisms related to the activation of kinematics chains and out-of-plane mechanisms related to horizontal and vertical strips of masonry (fig. 8). Results obtained at local level confirmed the Vulnus outcomes and allowed to evidence some particular deficiencies in the connections among the structural elements of the buildings.

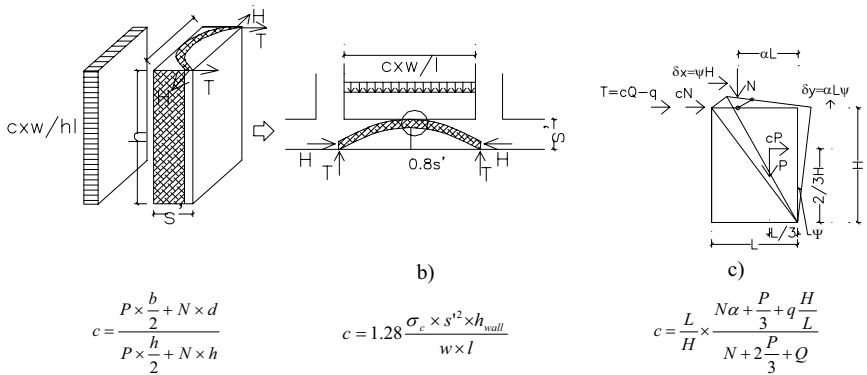


Figure 8: Examples of simple kinematics models for out-of-plane (a: overturning of a solid wall) (b: crushing of the masonry in the arch effect) and in-plane mechanisms (c: effect of in-plane overturning actions).

The obtained results in terms of seismic coefficient can be directly compared, for vulnerability assessment, with the limit value given by the current standards: as the site belongs to a seismic zone having high risk, the mean limit value, considering a medium level of knowledge of the building, is around 0.36. All the indexes and the single coefficients lower than that limit indicate unsafe conditions, corresponding to the activation of a possible mechanism.



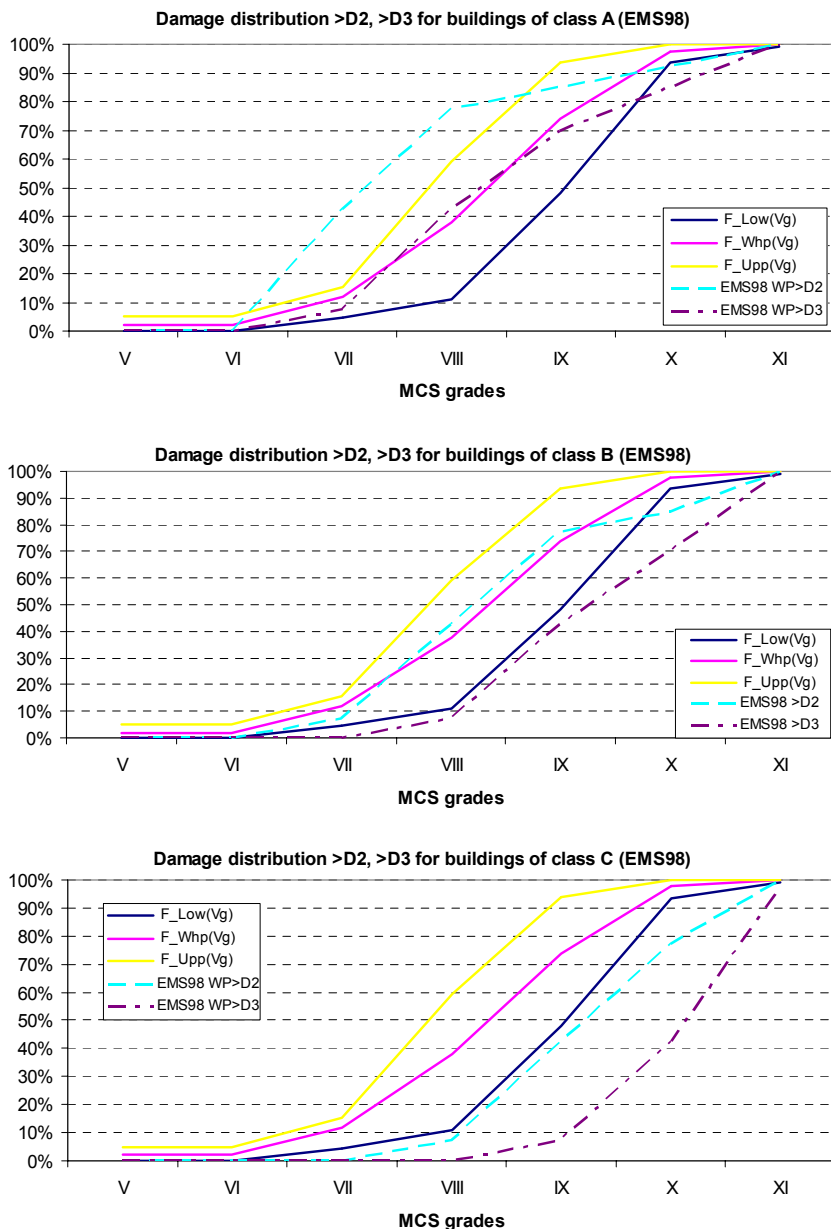


Figure 9: Damage distribution defined by cumulative percentage of buildings suffering damage >D2-D3, for each vulnerability class A, B, C, and for different earthquake intensities (MCS grades).

The results confirm the evaluations obtained by the on-site observation (structural regularity, construction details, materials, crack pattern, etc.): the three UI made of stone masonry are particularly irregular and vulnerable both to in-plane and out-of plane effects (global overturning, flexural resistance and overturning of the corner are the most brittle mechanisms to occur) (fig. 6 and 7); their global vulnerability is estimated “very high”, whereas UI 141 becomes to the “medium” vulnerability class.

Results can be also evaluated in terms of damage scenarios obtained through fragility curves or damage probability matrices (DPM) [12] [13]. Fig. 9 shows the damage distribution related to the EMS98 classification for specific vulnerability classes of buildings (A, B, C, related to higher, medium and lower vulnerability) and for different seismic intensity grades; the intermediate damage D2-D3 categories (moderate-heavy) has been considered as significant for the provisional analysis.

It is possible to observe as the range of variability related to the vulnerability class of buildings (marked by the upper and lower bounds, and by the central distribution as white probability curve) is progressively close to the heavy damage (>D3) for class A and to the moderate one (>D2) for class B, whereas for class C the EMS98 distribution is not included between the two *Vulnus* boundaries.

4 Conclusions

The vulnerability assessment of complex buildings requires the application of simplified procedures able to describe the mechanical behaviour both at global and local level. They are based on the overcoming of equilibrium conditions rather than on the achievement of materials' maximum strengths, as the high irregularities and lack of homogeneities characterizing the aggregates can produce very high vulnerability involving very brittle out-of-plane mechanisms. The preliminary phase of diagnosis, based on proper survey and investigation methods, is fundamental to point out the elements characterizing specific vulnerabilities; they have to be taken into account during the subsequent phases of structural analysis, in order to propose suitable and compatible intervention solutions. The study will be extended to the entire centre of Castelluccio di Norcia, in order to complete the provisional analyses on large scale and to provide proper possible recommendations for the assessment of complex buildings in high seismic hazard areas.

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