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On Overturning of the Façade in Churches with Single Nave: Some Case Studies from L'Aquila, Italy, 2009 Earthquake

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Abstract The recent earthquakes have shown the high vulnerability of the façades of churches, which detached from the longitudinal walls and failed by overturning. While being well known, this collapse mechanism is still under study as regards the contribution provided by the connections with longitudinal walls as well as the influence of masonry morphology. Three churches with single nave, which have suffered the abovementioned damage during the April 2009 earthquake in L'Aquila, Italy, are considered in the present paper. The seismic behavior of the churches is analyzed taking into account the effective morphology of masonry, by means of 2D Distinct Element analyses under both increasing static forces and dynamic acceleration pulses. The resulting capacity curve is then evaluated and compared to the case of a rigid body overturning showing to what extent the latter model provides a reliable estimate of the seismic behavior of the façade.

Keywords: Masonry, church, overturning, distinct element method

Introduction

The analyses of the structural damage caused by Friuli (Doglioni et al. 1994) Umbria-Marche (Lagomarsino et al. 2004) earthquakes and by the most recent event in L'Aquila, highlight that the behaviour of churches under seismic actions may be described referring to a limited number of collapse mechanisms. In most cases, owing to the lack of connections between structural elements, the abovementioned mechanisms involve portions of the structure, called macro-elements, which behave almost independently with respect to the remaining part of the church. Some of these mechanisms were described by Rondelet (1802) and reproposed by Giuffrè (1991) in the context of the seismic analysis of masonry buildings. The churches with single nave, owing to their structural conformation, are particularly vulnerable to the overturning of the façade. In fact, as reported by Lagomarsion and Podestà (2004) referring to a statistical analysis of the damage surveyed near the epicentre during the Umbria-Marche earthquakes, more then the 90% of the churches showed a damage pattern related to the abovementioned mechanism. Different levels of damage were encountered depending on the quality of the connections between the façade and the longitudinal wall, on masonry morphology and on the presence of tie bars. Thus, a reliable evaluation of the contribution of such factors on the capacity of the façade to resist seismic actions constitutes a crucial point for the vulnerability prediction of churches.

In the present paper three churches with single nave are considered, which, during L'Aquila earthquake, suffered the detachment of the façade from the longitudinal walls. In the first part a brief description of the churches is given.

In the second part the macro-element constituted by the façade and the longitudinal wall is modelled using the Distinct Element Method. In order to reproduce masonry morphology and the quality of the connection between walls, masonry is regarded as an assembly of rigid irregular blocks connected by frictional non-cohesive interfaces. The meshes of the models are automatically reproduced starting from a CAD reproduction of the surveys of the external leaves of churches. The models obtained are able to capture the essential features of ancient masonry behavior which rely meanly on the arrangement of the stones within the wall more than on the mechanical properties of the components. The out-of-plane capacity of the macro-element is then evaluated by means of push-over

analyses, with a loading profile proportional to the distribution of the mass, and by means of dynamic analyses under acceleration pulses.

In the third part, the resulting capacity curves are compared with those obtained by modeling the façades of churches as rigid blocks, providing a preliminary overview on the effects of the morphology of masonry and the quality of connections.

Description of the Churches

Originally six churches with single nave were located in Abruzzo, Fig. 1. Within this set of churches only three have been considered, which are approximately coeval, and show analogous geometrical characteristics: *San Paolo ad Peltuinum* located in Prata d'Ansidonia, *Santa Maria degli Angeli fuori porta Napoli* located in L'Aquila and *Santa Maria ad Cryptas* located in Fossa.

Figure 1: Location of the single-nave churches analyzed

The church of San Paolo ad Peltuinum, originally dated between VII and VIII centuries, was rebuilt in the XII century after a total collapse. The façade and the longitudinal walls of the nave consist of two distinct types of masonry: the first, which is encountered up to two-thirds of the total height of the walls, present the outer leaf of regular square stone disposed on horizontal courses with thin mortar joints. The upper part of the wall is composed of rubble masonry having thick mortar joints, Fig. 2a and Fig. 3a.

The church of Santa Maria degli Angeli fuori porta Napoli was built approximately between XII and XIII centuries. The façade was built later than the remaining part of the building and is characterized by an outer leaf in regular squared stones, Fig. 2b. On the contrary, the longitudinal wall shows a rubble masonry of small and irregular stones separated by thick joints, Fig 3b.

The façade of Santa Maria ad Cryptas church (XII-XIII century) consists of a regular assembly of squared stone disposed on regular courses, Fig. 2c. The longitudinal walls are made by irregular units poorly shaped, which have dimensions similar to those of the façade and are disposed on irregular courses, Fig. 3c.

The damage observed in the three churches after the April 2009 earthquake consists of the formation of a sub-vertical crack between the façade and the rest of the structure as shown in Fig. 3.

(a) (b) (c)

Figure 2:The façades of the churches: San Paolo ad Peltuinum (a), Santa Maria degli Angeli (b), Santa Maria ad Cryptas (c)

Distinct Element Analysis

The mechanical behavior of the macro-element constituted by the façade and the longitudinal wall is modeled by means of the distinct element code UDEC (Itasca, Minneapolis, MN, USA) in which the blocks are modeled as 2D rigid bodies and the joints as 1D interfaces with Coulomb friction.

Starting from the survey made in the field, first, the effective morphology of the outer leaf of the walls in correspondence to the corner of the façade is reproduced in CAD and then, through a pre-processor set up for this purpose, the corresponding mesh is automatically generated, consisting of polygonal blocks and joints reproducing the shape and arrangement of the stones within masonry walls, Fig. 3.

According to the features of the model some simplifications in the geometry proved necessary in order to proceed directly to the construction of the mesh. Since mortar joints are considered simply as contacts betweens the stone, each contact is placed in the middle of the joint thickness. The surround of the stone blocks is represented as a polygon, with a high value of rounding at the corners so as to avoid interlocking, which might derive from an unrealistic representation of the block.

Since during the centuries a progressive deterioration of ancient mortar occurs, the latter has weak mechanical properties so that it is reasonable to model the joints as frictional interfaces without cohesion and tensile strength.

Since the model is plane, two different densities have been assigned to the façade and to the longitudinal wall, so as to account for the different depth of these two elements. In order to evaluate the effects of the connections between the parts constituting the macro-element, two different configurations are defined: 1) isolated façade 2) façade connected to the longitudinal wall, being the connection provided by the stones located, in accordance with the arrangement surveyed in the field, across the interface that separates the two structural elements. The first configuration prefigures the lack of cohesion on the interface between the macro-element parts, so as to isolate the façade from the remaining portion of the structure. In the second configuration high stiffness and cohesion is given along the above-mentioned interface so as to ensure the continuity of the displacement field between the two parts of the stones that are located astride the façade and the longitudinal wall. The latter configuration reproduces the actual response of the churches, whereas the comparison with the response of the first configuration gives information on the effect of the connection between the façade and the longitudinal wall.

(a) (b) (c)

Figure 3: Damage pattern and distinct element meshes of the corner of the façade: church of San Paolo ad Peltuinum(a), church of Santa Maria degli Angeli (b), church of Santa Maria ad Cryptas (c)

The static analyses are carried out as follows. First gravity is applied and then an increasing horizontal acceleration is applied in successive steps; for each step the analysis is performed until an equilibrium configuration is attained. The equations of motion are integrated explicitly in the time domain and the contacts, which are made or get lost, are automatically recognized during the analysis. The load steps are progressively decreased when approaching the collapse horizontal load, that is the first value of acceleration for which the response diverges. The last value of acceleration for which convergence is reached is considered as the out-of-plane strength capacity λ (g).

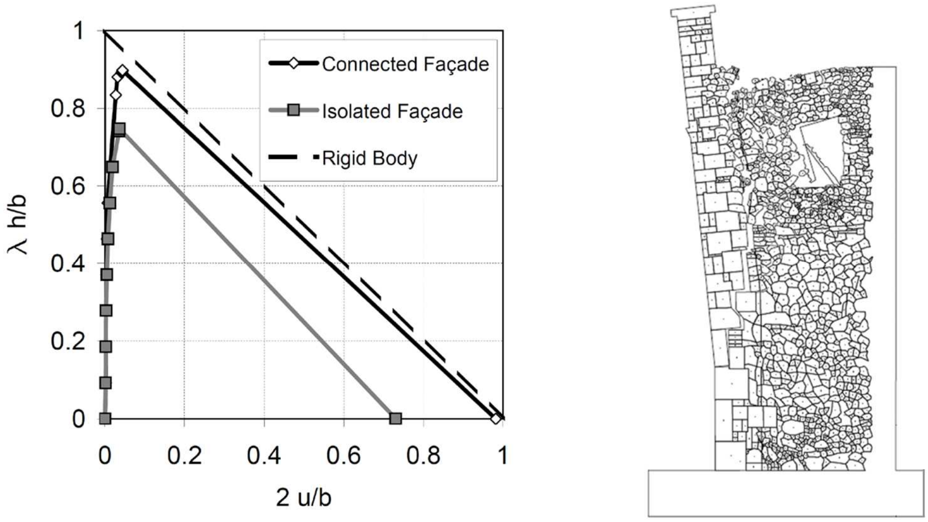
The dynamic analyses are conducted applying first the gravity load and then a squared acceleration pulse sustained for a fixed time interval. Once the acceleration has ended, the system is allowed to evolve under gravity and the motion is recorded. The capacity in term of displacement is then defined as the displacement of the gravity center u beyond which the macro-element collapses under the effect of its self weight only.

Discussion of the Results

The pushover curves obtained by means of the distinct element analyses are reported in Fig. 4, Fig. 5 and Fig. 6 where the horizontal acceleration λ and the displacement of the gravity center of the façade u are plotted respectively as relative values of the collapse acceleration (b/h) and the ultimate displacement ($b/2$)of a rigid monolithic block having the same dimensions b (base) and h (height) as the façade.

The results show that, referring to the isolated façade, the masonry morphology causes a reduction in strength capacity between 63-80% of that of the monolithic body, in agreement with the results presented in literature, (de Felice 2010).

The presence of longitudinal connection with the wall of the nave produces an increase of strength that depends on the quality of the connection itself. Referring to the church of Santa Maria degli Angeli, a slight increase is observed (20%) since the small dimensions of the stones and the absence of efficient connections are insufficient to prevent detachment of the façade from the longitudinal wall, Fig. 4.

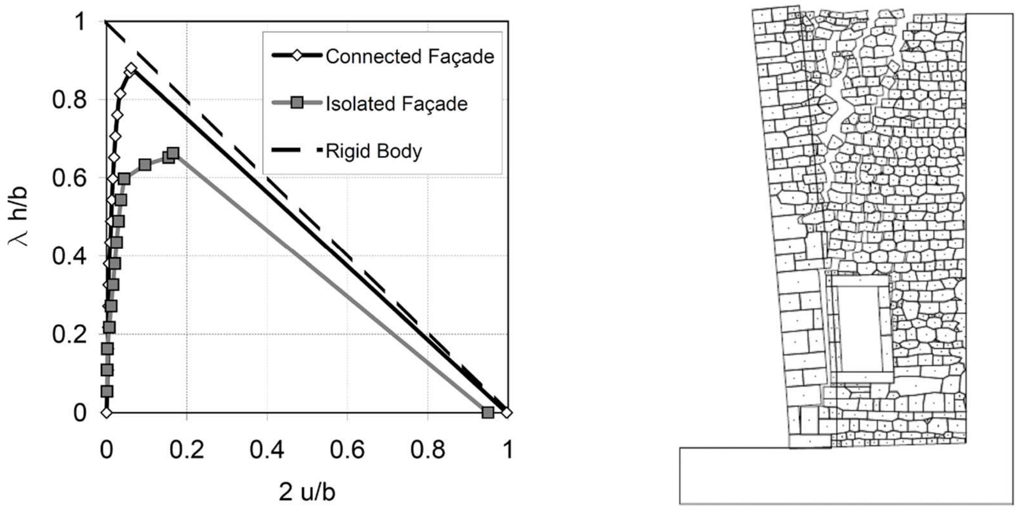


(a) (b)

Figure 4: Pushover curves (a) and collapse mechanism (b) of the façade of the church Santa Maria degli Angeli

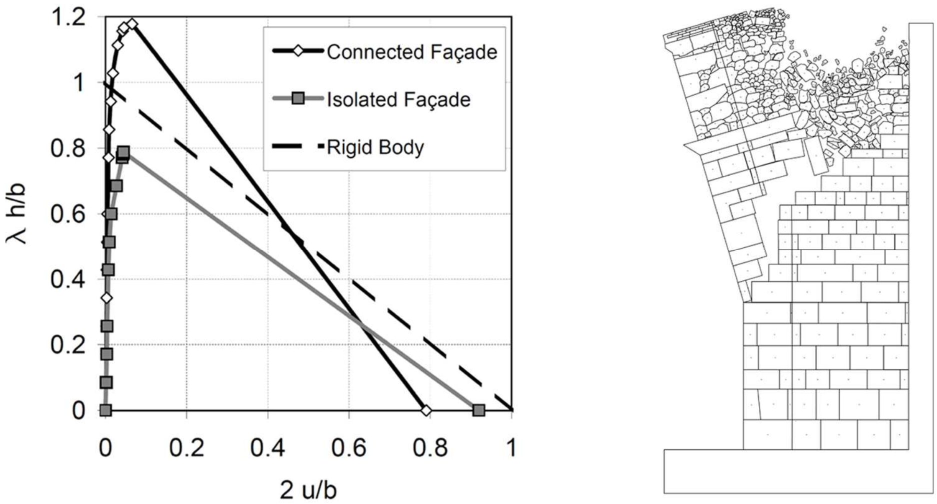
In the case of Santa Maria ad Cryptas church the increase in strength reaches 40% compared to the isolated façade. In any case, the strength of the whole system remains lower than the strength of the monolithic block, Fig. 5.

Finally an increase in strength of 50% is encountered in the case of San Paolo ad Peltuinum where, due to the good quality of the outer leaf of the masonry located in the corner of the façade, a different collapse mechanism is observed, which consists of a rotational motion around a hinge located at approximately mid-height of the wall of a macro-element composed by the upper part of the façade and a triangular portion of the longitudinal wall, Fig. 6.



(a) (b)

Figure 5: Pushover curves (a) and collapse mechanism (b) of the façade of the church Santa Maria ad Cryptas



(a) (b)

Figure 6: Pushover curves (a) and collapse mechanism (b) of the façade of the church San Paolo ad Peltuinum

Conclusions

The paper presents a first attempt to include the feature of masonry fabric in the seismic assessment of historic buildings. The analyses of three churches with single nave that have suffered a serious damage during the recent 2009 earthquake of L'Aquila, have been presented and the out-of-plane failure by overturning of the façade investigated. The effect of both morphology of masonry section and quality of the connections with longitudinal walls has been investigated by means of distinct element analyses. In the definition of the meshes, attention was paid to reproducing the effective arrangement of the stones starting from the survey of the external leaves of the walls belonging to the churches. The preliminary results, which have been collected on a limited number of cases, highlight the effectiveness of the classical approach adopted for evaluating the out-of-plane seismic behavior of masonry walls, based on rigid block assumption, since the decrease in strength related to the morphology of the wall section is balanced by the increase in strength provided by connections with longitudinal walls. Clearly, those cases in which the façade has a good connection with longitudinal walls, may display a significant increase in out-of-plane strength capacity, as in the case of the church of San Paolo ad Peltuinum.

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