Int. Journal for Housing Science, Vol.37, No.1 pp. 1-10, 2013
Published in the United States

SEISMIC BEHAVIOR OF BUILDING FAÇADES

Angelo Lucchini and Alberto Stefanazzi
BEST (Building Environment Science and Technology) Department,
Politecnico Di Milano, Milan, Italy
angelo.lucchini@polimi.it

Maria Adelaide Parisi
DIS (Structural Engineering) Department,
Politecnico Di Milano, Milan, Italy
parisi@stru.polimi.it

ABSTRACT

Up to now the behaviour of the non-structural elements has scarcely been considered in the building seismic design; all the efforts and the design decisions have been in fact mainly focused on the structural components. The observation of the very significant technical and economical damages as well as of the loss of safety consequent to a lack of seismic features and resistance in the building fabric and particularly in the façades (intended as the complex of the external walls and their veneers), envisages the concrete need to extend the seismic design also to these non-structural building parts. The paper will therefore deal with the analysis of the seismic behaviour and damage suffered in Italy by typical external walls and façades veneers with specific reference to the area of L'Aquila, heavily damaged by earthquake in 2009. The damage occurred in L'Aquila to a wide number of selected buildings is discussed and associated to the various types of masonry and veneers. As to the items of the building repair and new constructions in seismic areas, the paper refers to the practical case of the façade's micro ventilated veneers and suggests some basic design and construction criteria for their safe application in areas classified with high probability of earthquake.

0146-6518/01/1-10, 2013

Key words: Seismic Behaviour and Design of Façades, Seismic Design of Micro Ventilated Veneers.

The Earthquake in L'Aquila: A Real Case-Study

On April 6th 2009 at 03.32 there was an earthquake measuring 5,9 of the Richter scale and 6,3 moment magnitude (Mw), with epicenter in the nearby of Roio Colle, Genzano and Collefracido in the province of L'Aquila. The event interested a huge part of central Italy. The official final assessment report states 308 deaths, more than 1600 injured people and an economical damage estimated up to more than 10 billion Euros. This earthquake destroyed many buildings and disrupted the life of the whole province for months. On the other hand it allowed researchers to analyze the most frequent and relevant registered damages on buildings, so creating a catalogue according to the technologies, materials and age of the damaged constructions.

The modern Italian building tradition, which was started and developed after the 20th century with the advent of reinforced concrete, is based on the realization of load-bearing frame structures (in reinforced concrete), non load-bearing brick walls and concrete-brick slabs. The two main typologies of walls, used since post World War II till now, are the following:

- multiple layer walls (also known as hollow or cavity walls): they are a double wall envelope, with a cavity and thermal insulation standing in the middle, characterized by low weight and weak mechanical resistance, whose external finish can be in bricks, brick tiles or plaster (this technology was the most used from 1950 to 1990);

- monolayer walls: they are made of a monolithic brick panel, plastered on the internal side and often paired with an external coating shell. Monolayer walls have higher weight and mechanical performance compared to the multi layered ones (the former became diffused already in 1980 and are still most used).

Seismic events notoriously stress the whole building with a combination of horizontal, vertical and rotational movements and with an intensity increasing with the height, weight and stiffness of the various building structural and non structural components. Building reaction to seismic stress depends on primary structures (beams, columns, shear walls, etc.) as well as on secondary ones (walls, etc.): typology, geometry, mechanical characteristics and mutual connections. Seismic stresses are in fact transferred from the ground to each system and sub-system of the building body, filtering through the primary and secondary structures.

Wall damages and failures can happen depending on wall typology.

Multi layer walls are characterized by cracks which are often paired with breaks and fall of their fragile outer layers, usually mainly located at upper and lower floors (the former because of the higher seismic deformations and the latter for the higher values of the combined dynamic stresses), especially if the façade walls are only partially supported by the slabs. Brittle failure modes are typical of this wall typology.

On the contrary, external monolayer walls are able to offer higher mechanical strength to crushing and shear stresses caused by frame deformation and interstory drift; therefore they tend to be more stiff and to absorb higher energy amounts. As a consequence, if the ultimate material's strength is exceeded, they can be affected by very severe damages.

Through the direct observation of L'Aquila's buildings external walls damages, it was possible to identify and catalogue the following break and crack types:

- Oblique cracks with break and collapse of wall pieces or whole quoins. In this case ruptures are generally corresponding to St. Andrew's cross or double cross patterns. Masonry is subjected to horizontal forces resulting from the frame of the building and reacts according to a strut and tie beam mechanism. This behaviour generates high stresses and cracks inside the masonry in case of exceeding of its mechanical strength (see Figure 1.1). In the worst cases, collapse of the entire wall can occur.
-

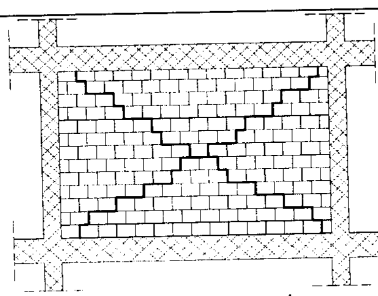

Figure 1.1: oblique cracks

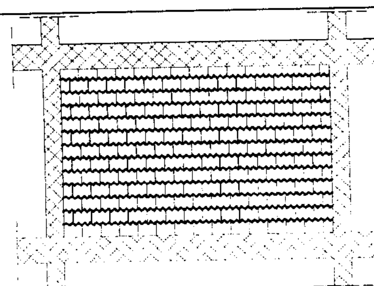

Figure 1.4: break-up of mortar joints

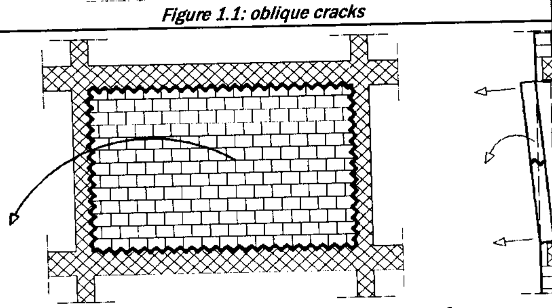

Figure 1.2: linear cracks at frame-masonry interface

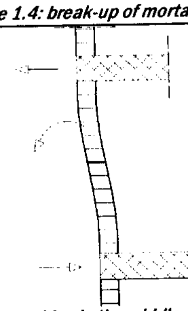

Figure 1.5: cracking in the middle of the masonry

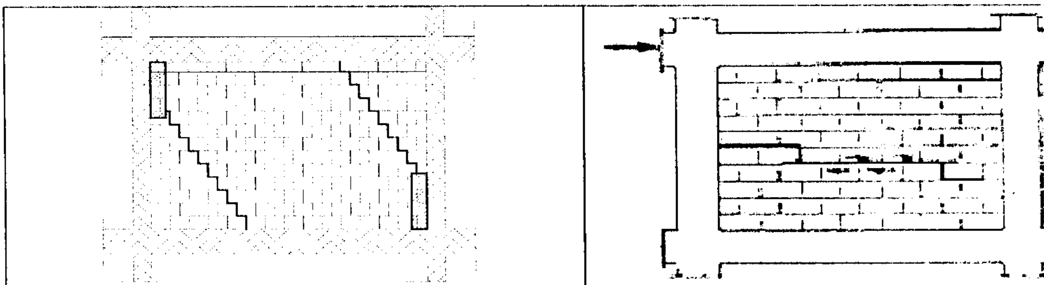

Figure 1.3: crushing at wall corners *Figure 1.6: cracking of masonry due to sliding*

Figure 1 Failure modes of façade masonry walls within reinforced concrete structural frames.

- Linear cracks at frame - masonry interface with breaks and collapse of wall material. This kind of lesion, regarding first of all the mortar located in the joints, between masonry and frame structure, happens when the masonry is well assembled and while its collaboration with the structure is weak. Cracks and wall breaks and collapse are favoured by wall slenderness and yieldingness, as well as by lack of mechanical ties and/or mortar infill at the interface wall-structure (see Figure 1.2).
- Crushing at wall corners with break and collapse of wall pieces or whole quoins. This kind of lesion can happen on well assembled walls, characterized by high mechanical strength, when the strut and tie beam mechanism occurs. The masonry high strength opposed to the frame dynamic deformation provokes yielding and cracks in the walls, particularly in areas like corners subjected to the highest pressure. In that case a partial wall break and collapse its possible (see Figure 1.3).
- Break-up of mortar joints with break and collapse of wall quoins. The break-up of mortar joints makes the entire wall unstable as the various elements of the masonry lack any mutual bond, thus allowing differential movements among them. When this happens, bricks lose compactness and crumbles. The main causes can be searched among mortar choice, preparation and use (see Figure 1.4).
- Cracking in the middle of masonry and collapse due to destabilization outside the wall plane. Plane drift highly stresses walls, deforming them to a S shape with an inflection point in the center line. The fracture destabilizes the wall causing its collapse (see Figure 1.5).
- Cracking of masonry due to sliding with break and collapse of wall quoins. Horizontal forces led on walls by the frame structure can provoke an unusual sliding of the upper on the lower part of the masonry, so generating serious horizontal crackings. These fractures can cause the fall of the wall, partially or in the whole. The main causes of this kind of damage are mainly the geometric variation of the wall section, such as the presence of niches, system pipes, etc., or mistakes in the wall construction (see Figure 1.6).
-

Other kinds of wall cracking, breaking up and yielding might also happen and be due to a combination of the above mentioned breaking modalities.

Therefore, in case of earthquake damages it is fundamental to identify very quickly which are the unstable walls in order to prevent safety risks during rescue operations and to define safety measures for damaged buildings. The study, the classification and the dissemination on typical seismic breaking and yielding modalities for walls inserted into reinforced concrete frames of building is at the basis of life safeguard.

Repairing operations for masonry walls

When the rescue phase after the earthquake is over, the attention turns on the building damage survey and reconstruction planning at urban and building scale. After the identification of unsafe buildings to be demolished and those to be fixed, acting on both structural and non structural parts in order to reduce seismic vulnerability it is necessary, to identify the correct actions for damaged wall consolidation.

Reconditioning of masonry should be done through appropriate strengthening and reconstruction techniques, respectful of the building global seismic response, avoiding incompatibilities between primary and secondary structures. The choice can be done between cooperating walls and walls independent from the reinforced concrete building frame.
Cooperating walls contributes towards building frame structure stiffening, as they have enough stiffness and strength to oppose frame displacements and deformations. Such walls are generally reinforced by metallic bars, lattice or nets structures to reach adequate mechanical strength. This ensures higher strength, efficient connections between wall and frame, better element deformability and lower fall risk of collapse in case of damaged wall quoins.

A first kind of reinforced masonry can be realized inserting single steel bars or plane lattice structures within the mortar joints, connecting them also to beams and columns (this typology can be easily used through the construction phase or reconstruction of consistent wall parts - see Figure 2.a).

A second typology of reinforced masonry can be based on the application of a metallic or carbon mesh within the plaster layer on the wall external face, to be connected both to masonry and building frame by the mean of chemical or mechanical plugs. This kind of reinforcement carries out three different functions: makes the masonry walls working as a unique stiff panel; connects each panel to the frame structure, wraps up the entire building transforming it into a rigid body. This stiffening modality is suitable for application on existing walls which have been damaged by an earthquake or need integration to reduce their seismic vulnerability (see Figure 2.b). The reinforcement amount to be used should be decided according to the area seismic classification. Excessive reinforcement elements can be selfdefeating. The use of reinforced walls should be therefore carefully evaluated and calculated by structural designers.

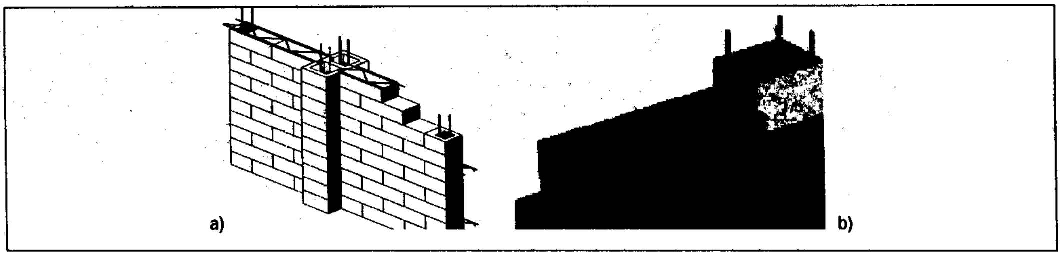

Figure 2 position of reinforcements in cooperating reinforced walls: a) reinforced masonry by insertion of single steel bars or plane lattice structures within the mortar joints, b) reinforced masonry by assembling a metallic or carbon mesh within the plaster layer on the external face

Independent walls (see Figure 3), are so called because they are not rigidly connected to the reinforced concrete structural building frame. They do not collaborate in case of earthquake with the building primary structure. Such masonry walls are strongly linked to the slabs below which bear their weight and provide appropriate stability. Their other three sides are untied to columns and upper beams. They can be however provided with mechanical connectors functioning as sleeves (i.e. absorbing only forces which are perpendicular to the façade - see Figure 4). The upper joints between walls and beams do not have mechanical constraints, to ensure appropriate independence between masonry and building frame.

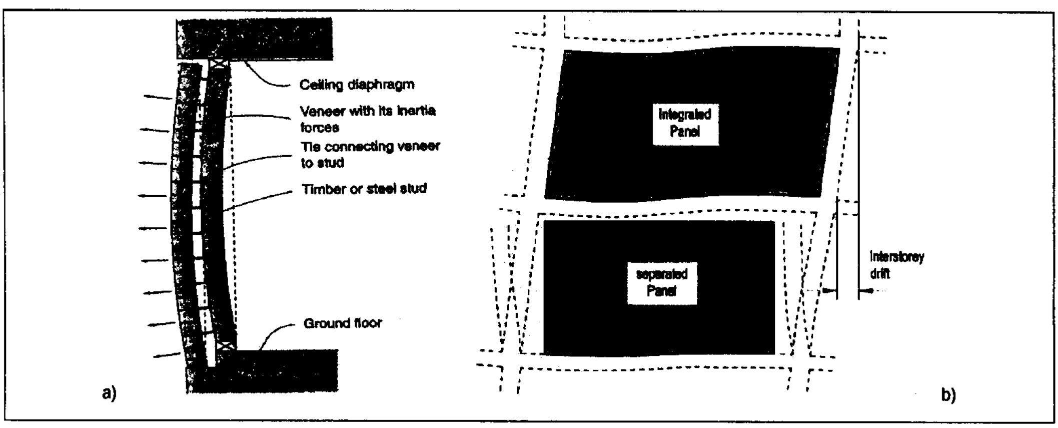

Figure 3 a) typical behaviour of an independent wall (cross section), b) different behaviour of an integrated and a separated wall panel during an earthquake (image taken from "Seismic Design for Architects")

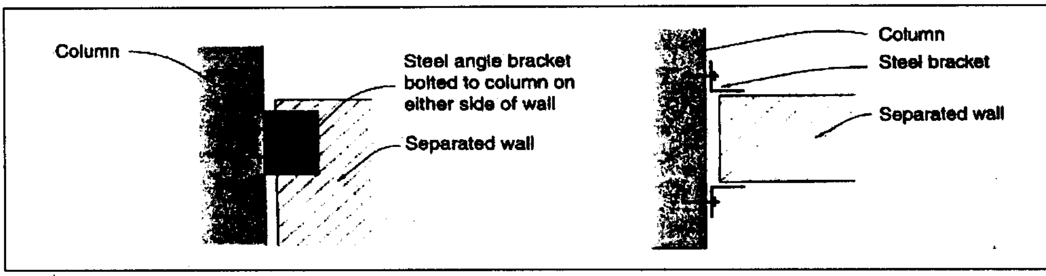

Figure 4 sleeve connectors to link facades walls to columns in reinforced concrete building frame structure (image taken from "Seismic Design for Architects")

This avoids cracks because of the interference among walls and structural frame. Such functional joint has to be properly sealed to guarantee right air and water tightness. This kind of wall can be realized by multilayered dry technology with a low frontal mass or by multilayered light and reinforced masonry.

In both cases the aim is to use light weight walls with high thermal and hygrometric performances and low seismic vulnerability.

The use of Micro-ventilated cladding systems

Claddings systems made of back ventilated slabs or tiles veneers can be appropriate to realize seismic resistant façade in both existing and new buildings, instead of employing traditional finishing such as plasters, bricks, brick tiles or other coverings. The ventilated cladding systems are to be installed on the masonry external plane, and can give the building high architectural quality while implementing its hygrothermal performances. Façade veneers of this kind can be supported by spot fixing devices (metal squares or anchors) or continuous substructure (stiles, rails or stiles and rails).

Spot fixing devices (usually four for each slab or tile) entrust their anchorage and safety exclusively to the building frame structure as well as to the masonry walls at their back. They are fixed at these bearing elements by the mean of chemical or mechanical plugs. Such kind of fixings, if not correctly chosen and installed, can suffer yielding thus causing dangerous constraints among the slabs. This infringes the following rule of thumb: when used in ventilated façade veneers, slabs and tiles have always to remain one another mechanically independent, this to allow their hygrothermal dilatation, acoustic and seismic vibrations and to avoid dangerous interactions and consequent mechanical stresses.

Systems having a substructure usually rely on stiles or stiles and rails. Their anchorage to the building structures is made directly by the mean of a fixed point corresponding to one of the beam or slab of the r. c. structural frame and indirectly through two or three bracing anchorages on the façade masonry wall, this according to the height from floor to floor. Such static scheme allows transferring the vertical and horizontal loads from the façade to the building structural frame, using the masonry wall only as a stiffening element, just to oppose those actions perpendicular to the façade plane (wind and seismic forces), thus reducing the needed cross inertia of the stiles. Each single slab is hung and fixed to stiles or to rails through devices suitable to ensure one another mechanical resistance and independence, and also correct functionality to the cladding systems as a whole.

The masonry, subjected to vibrations and movements, is the façade most stressed element during a seismic event.

If the external veneer is installed just using spot fixing devices, it can be then severely affected by lesions and damages depending on: masonry typology (traditional types can suffer serious damages as described before), direct fixings to masonry, difficulty in the introduction of stress reducing elements between fixing and slabs and lack of independence between the slabs. Moreover, damages of the masonry are in this case directly transferred to the external finishing with high risks of collapse of the latter. In other words, to cracks, breaks and local collapses in the masonry correspond lacks of stability and/or collapses in the façade ventilated veneer. Therefore, it has to be assumed that spot fixing systems are suitable only to be used in geographic areas at low seismic risk and in buildings characterized by simple shape and limited height.

The façade ventilated veneers supported by a substructure have instead a different and less critical seismic behaviour. If the slabs are really independent one another, they can move and vibrate without constraints to dissipate seismic energy. Furthermore, the substructure helps the veneer to better follow and absorb the building seismic movements and deformations.

Specific studies performed by the Authors on the seismic resistance of façade ventilated veneers demonstrate that:

- the façade masonry walls, working as direct support of spot fixing devices or as stiffening basis for cladding systems equipped with a substructure, should have appropriate seismic resistance and connections to the building structural frame;
- a masonry wall integrated in the building structural frame is more indicated to support a ventilated slabs or tiles veneer than a separated wall (like sketched in Figure 3)
- because of the high probability of serious damages and collapse of the slabs in case of earthquake, the use of spot fixing devices should be cautiously evaluated and discouraged when ventilated slabs or tiles veneers are to be installed in seismic areas, particularly in case of high rise or complex shape buildings;
- ventilated cladding systems equipped stiles or stiles and rails substructure can be appropriate for using in seismic areas, even on high rise and complex shape buildings;

- a stiles and rails substructure can let the ventilated veneer (in tiles or slabs) better absorb the seismic building movements deformations and vibrations, than one made only of stiles or rails;
- in cladding systems with appropriate substructure, the seismic resistance can be furtherly improved by integrating the slabs or tiles fixings by accessories suitable to absorb and dissipate vibrations and dynamic stresses;
- the use of cladding systems with certified seismic resistance it is not sufficient to guarantee the real seismic resistance of every single element and of the whole cladding system when the construction of the building structural frame and of the masonry wall, as well as the installation of the veneer and of its substructure are not well appropriate.

The only building built in the city of L'Aquila according to these criteria (a quite large public office building with solid integrated masonry walls, marble slabs and clay tiles ventilated façade veneers) didn't suffered appreciable damages, a part light sliding of some marble slabs and consequent disalignment of their vertical joints and little chippings at the edges of a few terracotta tiles (see Figure 5). Not even one of the slabs and tiles of its façades ventilated veneer went broken or collapsed.

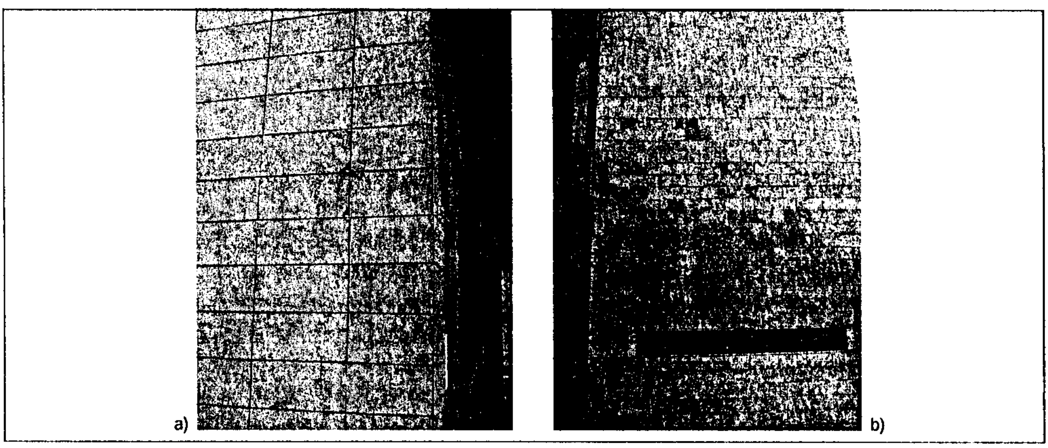

Figure 5 view of the façade ventilated veneers of a public office building in L'Aquila (Italy) after the earthquake happen on April 6th 2009. a) chippings at the edges of a few terracotta tiles, b) disalignment of some vertical joints among the marble slabs.

Conclusions

The 2009 earthquake, which heavily damaged the entire territory of L'Aquila, stimulated studies on the seismic behaviour and performances of the traditional Italian building technology. From surveys performed on the field resulted that most of the

building having a concrete frame structures survived the earthquake although some other completely collapsed because of design and/or construction faults.
The Authors have studied the case and investigated in particular the behaviour of façades and non structural walls. Results referred to the practical case of the façade ventilated veneers have been herein presented.

References

[1] Italian Civil Protection Department, Reluis Laboratory - Linee guida per il rilievo, l'analisi e il progetto di interventi di riparazione e consolidamento sismico di edifici in muratura in aggregato, Rome, 2009
[2] Charleson A. -Seismic Design for Architects, Outwitting the Quake, Architectural Press is an imprint Elsevier, USA 2008
[3] New Zealand Society for Earthquake Engineering - Architectural Design for Earthquake. A guide to the design of non-structural elements, School of Architecture, Victoria University of Wellington, 2007
[4] M. R. Lindeburg, K. M. McMullin - Seismic Design of Building Structures: A Professionals Introduction to Earthquake Forces and Design Details, Professional Publication, USA, 2006
[5] U.S. Government - Risk Management Series - Designing for Earthquakes - A Manual for Architects, FEMA 454, USA, 2006