

SEISMIC BEHAVIOR OF AN INFILLED RC FRAME BUILT IN EARLY TWENTIETH CENTURY

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Abstract. *Seismic vulnerability of existing RC buildings, designed without considering seismic forces, is becoming a problem of growing concern especially for structures of relevant and/or strategic use for which OPCM 3274/2003 orders a seismic assessment.*

In this context, among the buildings of the University of Padova, which can be considered of 'relevant' use, there are an high percentage of RC structures. They were built at the beginning of the 20th century and designed only for gravity loads.

This study focuses on the seismic behavior of one of these buildings which houses the Department of Pharmacy. It was built in 1937 and it is a three-storey infilled RC frame structure.

Its seismic vulnerability was analysed starting from a knowledge phase which included the collection of available historical documentation, field investigations and in-situ and laboratory tests. Mechanical properties of concrete and structural details were obtained from the original report of calculation, corings (laboratory tests on cores), sclerometer, pacometer and local scarifications to verify the conformity of the original structural drawings with the real execution. These data were, then, used for performing structural analyses on a FE Model of the building, in which infill walls were modeled as equivalent struts.

Three different models of the structure were created: model 1 with struts located to simulate the 'short column' effect due to the presence of the spandrels between perimetral openings, model 2 without spandrels and model 3 with structures in isolated configurations. In this way a comparison between shear values on columns and displacement values between different structural bodies was possible and it will allow to identify the more realistic modelling strategy from a safety level point of view.

1. INTRODUCTION

The assessment of seismic vulnerability of existing buildings has become a fundamental issue as result of the evolution of the National and European codes. In particular, Italian OPCM 3274/2003 [1] classified the whole Italian territory as seismic. This code was followed by the current building code (NTC2008) [2] which upgraded the seismic hazard level.

Those standards imposed different procedures of structural design and verification, especially with regards to reinforced concrete (RC) buildings.

In the past, during 20th century, usually RC buildings were designed only considering the contribution of gravity loads (vertical forces), without considering horizontal seismic forces. So, in the design phase simplified modelling schematization were used.

Therefore, the need to verify security and vulnerability of traditional RC buildings designed only for vertical loads is pressing. The overall capacity of existing buildings to seismic loads according to current codes can be evaluated performing seismic analyses.



Figure 1: General view of the building.

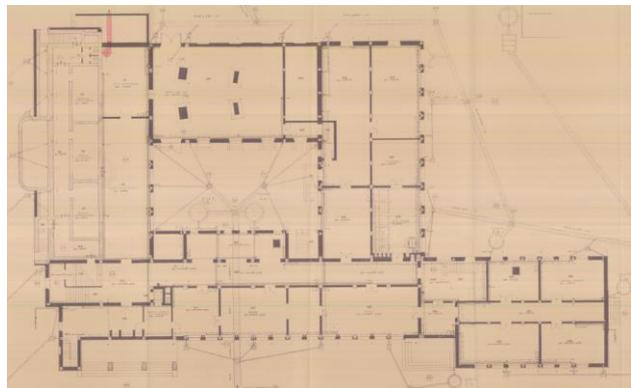


Figure 2: General Basement of the complex: historical plan.

Analyses must also evaluate the presence of infill masonry which can affect the global structural behavior. More recent seismic codes highlight the influence of infill walls, but without indicating how to consider them in the structural modelling. Experimental results suggest to consider infills acting as equivalent diagonal struts (Polyakov 1960, Stafford Smith Mainstone 1966 1971 1974, Klingner and Bertero 1978).

In this framework, the seismic structural behavior of the RC infilled frame of the Department of Pharmacy of the University in Padova was studied, focusing on the influence of the modelling scheme used for infill walls in the global structural behavior.

With this purpose linear dynamic analyses were carried out, comparing two different configurations: one scheme considered the presence of infill masonry and the effectiveness of spandrel walls, whereas the other one does not consider those elements. In the first configuration spandrel walls were modeled only for masonry walls along the perimeter. Here the 'short column' effect is most relevant due to the presence of large openings and spandrel walls in the RC frame (Figure 1).

Analyses were performed according to the Italian Building Code (NTC2008), after an extended knowledge phase of collection of historical documentation, field investigations, in-situ and laboratory tests on materials.

Analyses results are related to the Limit State of Significant Damage (SD).

2. CASE STUDY ANALYSIS

The complex was built in 1937 and is characterized by a RC frame on 4 levels, one of which is partially underground. It was designed and built as a single unit, without additional parts or expansions, so the actual aspect reflects the original one.

Three different structural blocks (Figure 3) are created by three expansion joints only few centimeters thick: a block A has a C-shape, the other two (block B and C) have a regular shape and one of these has only two storeys (block C). Part of the basement of the C-shape block is a bunker with RC walls of thickness between 75 and 40 cm (Figure 4).

Inter-story height ranges from 4.50 m to 5.30 m, beams span ranges from 3 to 7 m, and structural mesh consists of 27x17 axes (Figure 7); finally, the roof is flat.

Pillars have a variable cross-section ($40 \times 30 \text{ cm}^2$ and $30 \times 50 \text{ cm}^2$ on the lower floors, $26 \times 26 \text{ cm}^2$ on the upper floors) and smooth reinforcement bars with diameters from 15 to 20 mm. Stirrups step is 20 cm.

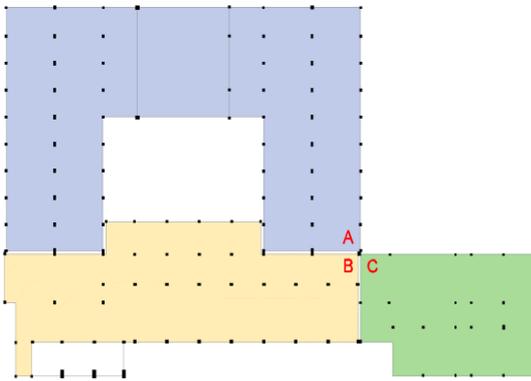


Figure 3: Identification of 3 separated blocks (A-B-C) and pillars distribution.



Figure 4: Basement floor: portion corresponding to the RC bunker is highlighted in black.

The knowledge phase was aimed to the identification of properties and details parameters to use in the FE model of the structure. Correspondence between the original historical documentation and the current structure was verified by means of in-situ surveys (April-July 2013), non-destructive tests (sclerometer, pacometer, pull-out) and medium-destructive tests (local scarification, pull-out, corings) on each floor of the building.

Investigation results did not reveal any significant crack patterns or decay status; however, some deficiencies were found such as low properties of concrete and the absence of seismic structural details. Moreover, especially at upper levels, columns have a very small cross-section, stirrups step is very large and structural joints between the three different structural bodies are only few centimeters thick, so without aseismic characteristics.

For evaluating the influence of the expansion joints in the displacement demand a third model was created, modeling the three blocks (C, B and C-Figure 3) divided by joints.

2.1. Material properties

In historical RC buildings inadequate construction details and obsolete construction techniques are frequently combined with the presence of not high quality materials. For these reasons, the study and analysis of an historical building need a deep understanding of the structure and of its characteristics: a greater level of knowledge will allow to make a more realistic assessment of its vulnerability.

In-situ visual surveys, non-destructive and medium destructive tests were performed to obtain mechanical properties (Figure 5 and Figure 6). Results showed a significant variations

of concrete mechanical properties between the two lower levels (basement and ground floors) and the two upper levels (first and second floors): in the lower ones concrete cores has an average cubic compressive strength of 17,45 MPa, whereas the average value in the first and second floors was 8,70 MPa.

Investigations results and visual surveys generally showed a low quality of concrete due, mainly, to aggregate segregation and inadequate granulometry that produce poor mechanical adhesion between cement and aggregates and between concrete and reinforcement bars.



Figure 5: Details of beam scarification: identification of reinforcement bars and stirrups.



Figure 6: Details of pillar scarification: identification of reinforcement bars and stirrups.

In the assessments of ductile mechanisms, elements capacity was calculated with reference to average values of strength obtained from investigations divided by the confidence factor (CF) which was fixed equal to 1,2. Thus, the mechanical properties of concrete used are the following: concrete cylindrical compressive strength $f_{cd} = f_{cm} / CF = 17,45 / 1,2 = 14,54$ MPa for the first two levels, $f_{cd} = f_{cm} / CF = 8,70 / 1,2 = 7,25$ MPa for the last two floors (Table 1).

Table 1: Concrete mechanical properties.

	localization	f_{cm} [MPa]	f_{cd} [MPa]	E [MPa]
Concrete	Lower floors	17,45	14,54	28052
	Upper floors	8,70	7,25	24950

The yielding strength of steel is $f_{yd} = f_{ym} / CF = 215 / 1,2 = 179,2$ MPa (Table 2).

Table 2: Steel mechanical properties.

	localization	f_{yk} [MPa]	f_{yd} [MPa]	E [MPa]
Steel	All floors	215	179	200000

Mean value of concrete elastic modulus was calculated according to NTC2008, avoiding to perform some other concrete cores.

No destructive investigations were performed on infill masonry walls, so their mechanical properties were assumed as suggested by NTC2008 [3] and according to results from visual local surveys and plaster removals (Table 3).

Table 3: Mechanical masonry properties [Table C8A.2.1, NTC2008].

Masonry	f_m [MPa]	T_0 [MPa]	E [MPa]	G [MPa]	w [kN/m ³]
perforated bricks	5,00	0,35	4500	1350	12

3. MODELLING

The definition of the model was possible through the comparison between historical documentation and data from in-situ investigations performed in the building.

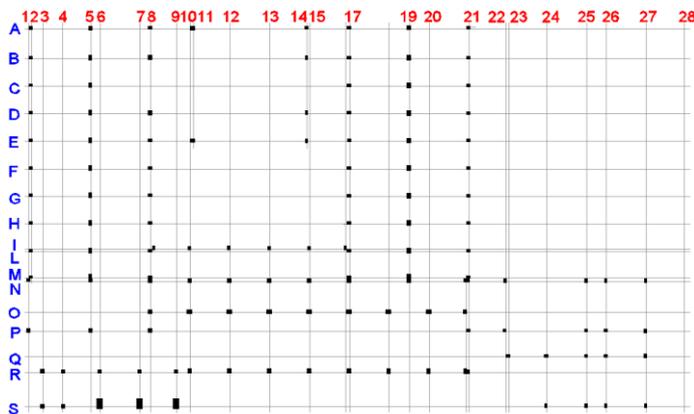


Figure 7: Distribution of RC frame: plan axes.

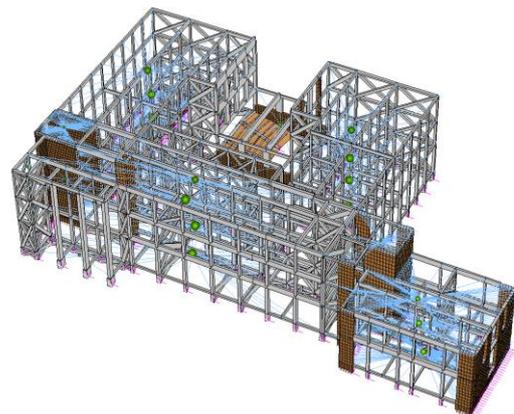


Figure 8: Modelling of RC frame: FE Model.

Three FE models were created in three dimensions where beams and columns were modeled using beams elements. Models characteristics are illustrated in Table 4.

For modelling masonry stairwells and load bearing masonry walls (where there is not RC frame) plate elements were used (Figure 8). Plate properties are the same of infill masonry walls (Table 3).

Rigid floors were modeled using rigid links which connected the top of all vertical elements.

Table 4: Identification of three different models created.

Model	Modelling
1	The RC frame does not consider the presence of perimetral spandrel walls
2	The RC frame consider presence of infill masonry and of the effective spandrel walls
3	The three different isolated configurations (A-B-C) divided by expansion joints

3.1. Infill modelling

The presence and the influence of infills masonry walls represented a complex aspect to analyze [4]. The critical factors are: masonry is a non-homogeneous and anisotropic material, its softening behavior is difficult to identify and boundary conditions of panels could be not investigated.

The decision was to model infills inserting a couple of truss elements able to carry only axial forces. In this type of models resistant mechanism of the panel (i.e. its stiffness) is activated, mainly, in presence of lateral actions, such as seismic forces.

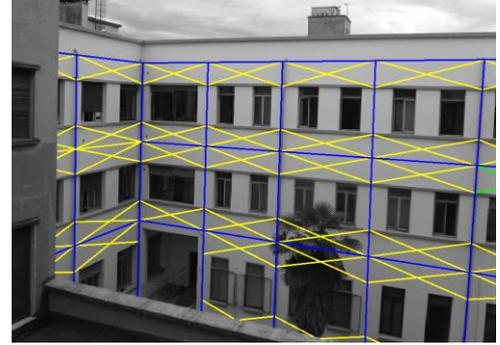
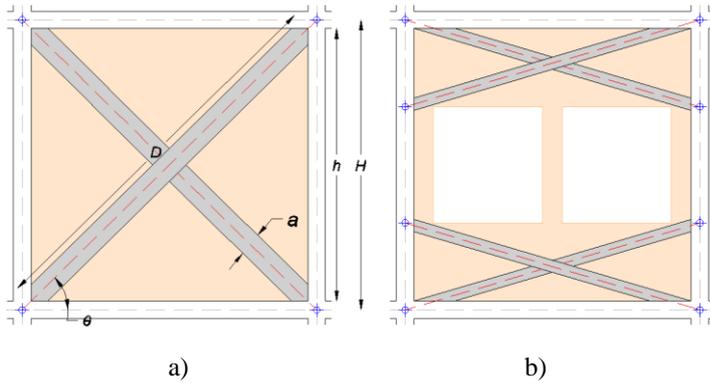


Figure 9: Modelling of infill walls: a) without openings and b) in case of openings

Figure 10: Modelling of infill walls assumed scheme

Masonry properties were defined in agreement with the results of the investigation campaign: mechanical parameters were calculated considering a level of knowledge LC2 applied to values for "masonry with perforated bricks" [NTC2008] (Table 3).

Infill masonry walls were modeled as equivalent struts resistant only to compression with width a , length d and thickness t (equal to the real thickness of the infill wall). The width a was evaluated with the Klingner and Bertero formula (1978) [5]:

$$a = 0.175D(\lambda H)^{-0.4} \quad (1)$$

The parameter λ depends on the relative flexural stiffness frame-panel and was defined using the Stafford Smith et Carter formulation (1969) [6]:

$$\lambda = \sqrt[4]{\frac{E_m t \sin(2\theta)}{4E_c I_{col} h}} \quad (2)$$

The other parameters are: D diagonal panel; H pillar height; h panel height; E_c and E_m , respectively, elastic modulus of concrete and masonry; I_{col} inertia moment of columns; θ angle created by the equivalent strut with the horizontal plan.

3.2. Global models: opening and infill walls

Generally, infill walls can completely develop their lateral load bearing capacity when they have no openings. It can be reasonable do not consider infill walls when openings are big in relation to the area of infill wall. This study is aimed to verify this usual assumption, comparing stress results from linear dynamic analyses on models 1 and 2 (Table 4). In the model 1 infill masonry walls were considered only if able to significantly contribute to carry seismic loads, otherwise, there were considered as non-structural dead loads. In the model 2, spandrel walls located at the top and at the bottom of perimetral openings were added. This

second model was used to assess the effect of infill masonry walls as seismic resistant system and the effect of 'short column' that they create.

4. METHODS OF ANALYSIS

In the models used for linear dynamic analyses, elastic modulus of concrete was considered equal to $0,5 E_c$, in order to take into account cracking phenomena. Also, infill walls elastic modulus was halved ($E_m = 1800$ MPa) for each diagonal element, in order to consider that only the compressed strut works.

Dead loads (structural and non-structural) were applied to the structure as masses on floors, assumed infinitely rigid.

No soil-structure dynamic interaction was taken into account, therefore fixed constraints at foundations were modeled.

Spectral analysis was performed considering the design spectrum and applying it along both main directions X and Y.

Seismic input was obtained from the horizontal acceleration spectrum, considering negligible vertical component. Parameters used for the determination of the design acceleration spectrum of the horizontal component for a ground of category C and the location of Padova were the following:

- independent parameters: $a_g=0.099g$ - $F_0=2.597$ - $T^*_C=0.342$ - $S_S=1.50$ - $C_C=2.109$ - $S_T=1.00$ - $q=1.5$;

- dependent parameters: $S=1.50$ - $\eta=0.667$ - $T_B=0.171s$ - $T_C=0.512s$ - $T_D=1.995s$.

According to §C8.7.2.4-NTC2008 the behavior factor q can be assumed from a value of 1.5 to 3. On the safe side the minimum value was used (1.5).

4.1. Results

The presence of infill walls can decrease the values of lateral displacements and contribute in lateral capacity of the RC frame. However, they can produce the increasing of shear stress in localized portion of columns (beam-pillar nodes).

Shear failure is a critical aspect of RC 'short column' configuration: the evaluation of this mechanism is important in relation to the low ductility and brittle behavior.

Indeed, §4.4 of OPCM 3431/2005 (the upgrading of OPCM 3274) indicates that in structural infills able to provide stiffness and significant resistance must be considered [7].

In addition, current Italian Building Code (§5.13 of NTC2008) illustrates the issue of "local effects" associated to the presence of infill masonry walls which do not extend for the full height of pillars and it specifies the method of shear evaluation in the unconfined portion of the column. Infill walls, even if conceived as non-structural, must necessarily be studied during the knowledge phase: identification of properties and details of infill walls will allow to identify a more realistic configuration and stresses on the RC frame.

In the performed linear dynamic analyses, a first important comparison of results concerns average displacements values at the top of the building developed by model 1 and 3. It is interesting to notice that the building composed by 3 separated blocks (model 3). In both directions, X and Y showed higher displacements than values model 1 (Figure 11).

In the model 2 with spandrel walls and infill masonry there is a minimal further decreasing of displacements values than model 1.

These results suggest that a future intervention on the building for improving its seismic behaviour would be the closure of the three expansion joints.

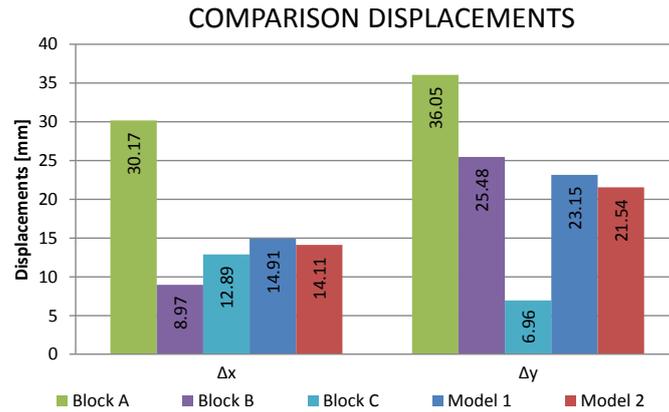


Figure 11: Comparison average displacement of configurations for spectral analyses: model 3 (blocks A, B and C), model 1 and model 2.

As regard stresses, comparing model 1 and model 2; in the model 2 the arising of local effects were evident all along the perimeter. In spectral analyses, the increasing of shear values on the perimetral (axes 2,8,17,21, I and R) pillars were significant: obtained values showed that the increasing of stress is higher in Y direction, where there are an higher number of modeled spandrel walls (Figure 12 and Figure 13).

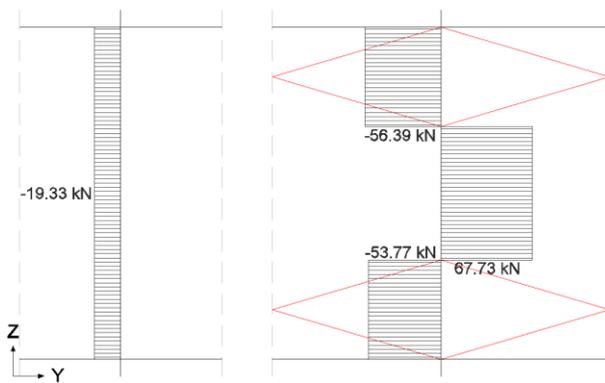


Figure 12: A comparison of shear forces and local effect of perimetral walls along Y direction, axis 2, for spectral analyses: 0.3X + Y seismic combination

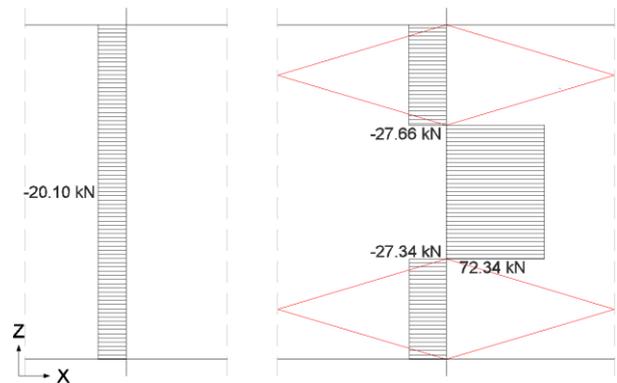


Figure 13: A comparison of shear forces and local effect of perimetral walls along X direction, axis R, for spectral analyses: 0.3Y + X seismic combination

Regarding axial forces on infill and spandrel walls, infills had a significant increasing and greater stress values than spandrel walls. However axial force values do not exceed compression strength of the equivalent struts (Table 3).

5. CONCLUSION

This work deals with the seismic behavior of an historical RC frame designed for only gravity loads and without aseismic structural details. The aim was to highlight the influence of infill masonry walls in the RC frame behavior and what are their effects.

In situ and laboratory tests were planned and carried out and, then, linear dynamic analyses in agreement to the Italian Building Code (NTC2008) were performed on a FE model of the structure. Three models were created as described in Table 4.

Main results are the following:

- in model 1 displacements values decreased compared to model 3 (three blocks, A-B-C, separated by expansion joints). Additional reduction of displacements were observed in the model 2 with infills and spandrel walls. In this case the contribution of masonry elements was positive;
- the modeling of spandrel walls and infill masonry involved different local effects in the RC frame elements. The effect of 'short column' developed on pillars and determined a significant increasing of shear stress values;
- infill masonry and spandrel walls increased structural strength and stiffness compared to a bare RC frame; however, these elements may introduce unfavorable local effects of interaction with the RC columns,

Such results confirm the key role of infill masonry walls in the assessment of seismic vulnerability of RC frames. However, the performed linear analyses do not take into account the non-linear behavior of elements: therefore, results are on the safe side. A possible further research would include an evaluation of local mechanism through non-linear analyses, supported also by mechanical properties of infills from in situ tests.

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