Seismic Performance Assessment of a Masonry Infilled Ductile RC Structure

Marco Valente

***Abstract*—The seismic performance of a masonry infilled four-storey RC structure designed according to earthquake-resistant provisions was investigated through numerical analyses and the influence of masonry infills and openings on the structural response was discussed. On the basis of experimental tests carried out at the JRC Elsa Laboratory, numerical models were developed in order to properly simulate the seismic response of the masonry infilled RC structure and a simplified assessment approach based on nonlinear static pushover analyses was applied. The presence of masonry infills and openings considerably changed the distribution of damage throughout the structure. Due to the increase of stiffness provided by the infills, the attainment of the different Limit States was anticipated in terms of drift in case of infilled structure with respect to the bare counterpart. According to the simplified assessment procedure, the influence of infills on the seismic response of the ductile RC structure was beneficial, though a strength decrease was observed after the failure of infills. A concentration of damage was registered at the first storey for high levels of seismic action, but the deformation capacity of the structure was large enough to accommodate the demand and a significant reduction of damage was registered compared to the bare structure.**

***Index Terms*—Masonry infills, nonlinear static analysis, RC structure, seismic performance.**

I. Introduction

Experience and observations from past earthquakes and experimental tests show that infill panels, usually considered as non-structural elements, can strongly affect the seismic response of reinforced concrete (RC) frame structures. The main purpose of this study is to evaluate the effects of masonry infills and openings on the seismic performance of a ductile RC structure. The study was based on results of laboratory tests carried out at the JRC ELSA Laboratory and the accuracy of the developed numerical models of bare and infilled RC structures was evaluated through comparison with the experimental tests. A simplified procedure based on nonlinear static pushover analyses was used for the seismic assessment of the structure. The numerical results obtained from nonlinear static and time-history analyses are presented for different structure configurations: a) bare structure (no infills); b) fully infilled structure (without openings); c) partially infilled structure (with openings).

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II. Numerical Models and Validation

The accuracy of the numerical models developed for the bare and infilled RC structures was evaluated through comparison with the experimental tests carried out at the JRC ELSA Laboratory at Ispra (Italy). The test building was designed as a high ductility RC framed structure, according to the then current drafts of Eurocode 2 and Eurocode 8, for a peak ground acceleration a_g=0.3g and medium soil conditions. Fig. 1 shows the plan and elevation view of the test structure. Pseudo-dynamic tests were carried out on the RC structure in the bare and masonry infilled configurations. A high-level test with nominal acceleration 50% larger than the value adopted in design was preceded by a low-level test with an intensity scaling factor of 0.4. Further details concerning the test structure, the mechanical characteristics of the materials, the amount of reinforcement and the experimental campaign were reported in [1].

Numerical models of the RC structure were developed using all the available theoretical and experimental data by means of the computer codes Seismostruct and Ruaumoko. The infill panels were modelled using the equivalent diagonal strut model. Simple modelling with equivalent diagonal struts is able to simulate the global seismic response of infilled structures and is suitable for practical applications. The cyclic behaviour of the infill panel was modelled adopting the hysteresis rule proposed by Crisafulli [2] to simulate the axial response of masonry. The effect of the openings was taken into account by reducing the strut area and thus the infill panel stiffness. Several researchers suggest different reduction factors to describe the decrease of stiffness, depending on the dimensions and the position of the openings. In this study different stiffness reduction factors were considered for different opening percentages, as proposed by Asteris [3]. In order to validate the numerical models, nonlinear dynamic analyses were performed on the four-storey RC structure in the different configurations assuming the same accelerogram used for the low-level and high-level pseudo-dynamic tests. Fig. 2 shows the comparison between experimental and numerical results of the top displacement time history for the bare and fully infilled structures under high-level earthquake. The numerical models were able to satisfactorily reproduce the experimental results for both the structural configurations in terms of time history trend, phase and maximum values.

Fig. 3 compares the damage distribution on the external frame of the building in the two different configurations in case of high-level earthquake record. The Park & Ang

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damage index was used to estimate damage in reinforced concrete ductile members, [4]. The uniform distribution of damage observed on the bare structure in the experimental tests was confirmed by the numerical analyses. The maximum values of the damage index were registered at the beam ends and a weak beam-strong column mechanism with regular distribution of damage was observed. The effects of the non-structural masonry infills placed at all storeys of the external frames on the global seismic response of the structure were investigated. As expected, an increase in stiffness, strength and dissipation capacity was highlighted by numerical analyses. The regular distribution of infills resulted in a concentration of ductility demand at the lower storeys. The column-to-beam damage index ratio was larger than in the case of the bare structure and the beginning of the progressive formation of a storey-level mechanism was observed. The progressive failure of the masonry infills at each storey may activate a series of weak-column strong-beam storey mechanisms, which may lead to high ductility demands in the columns. Smaller values of the damage index were registered at the upper storeys with respect to the bare structure. The values of the damage index computed in the numerical analyses were in satisfactory agreement with the damage observed in the experimental tests.

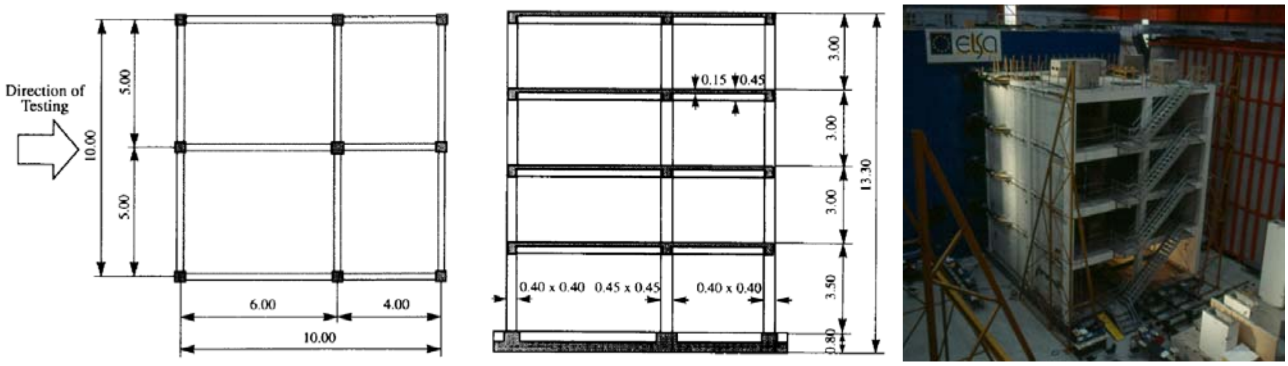

Fig. 1. Plan and elevation view of the bare and infilled RC structure.

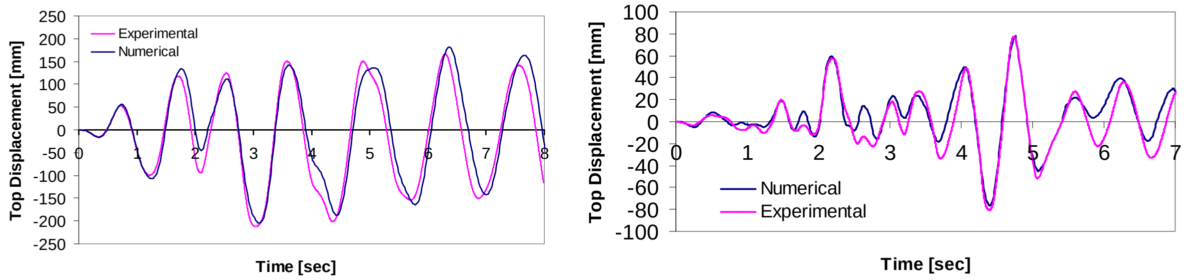

Fig. 2. Top displacement time history response of the bare structure (left) and of the fully infilled structure (right) under high-level earthquake: experimental and numerical results.

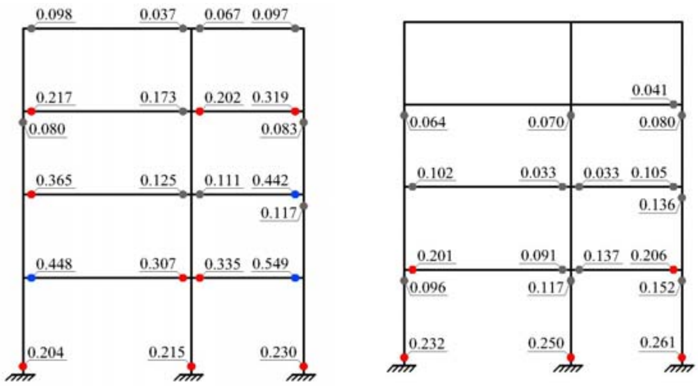

Fig. 3. Damage distribution on the external frame of the RC structure: Bare (left) and infilled (right) configurations.

III. Seismic Performance Assessment

According to Eurocode 8, a simplified assessment procedure based on nonlinear static analyses was used and the damage level in the structures was evaluated with reference to three Limit States (LS): Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC). Each limit state was achieved in the structural model once a specific chord rotation was attained in one of the members of the structure. The ultimate chord rotation and the chord rotation at yielding were evaluated according to Eurocode 8 Part 3, [5]. Nonlinear static analyses were performed on the bare and masonry infilled structures and the base shear - top displacement curves are presented in Fig. 4.

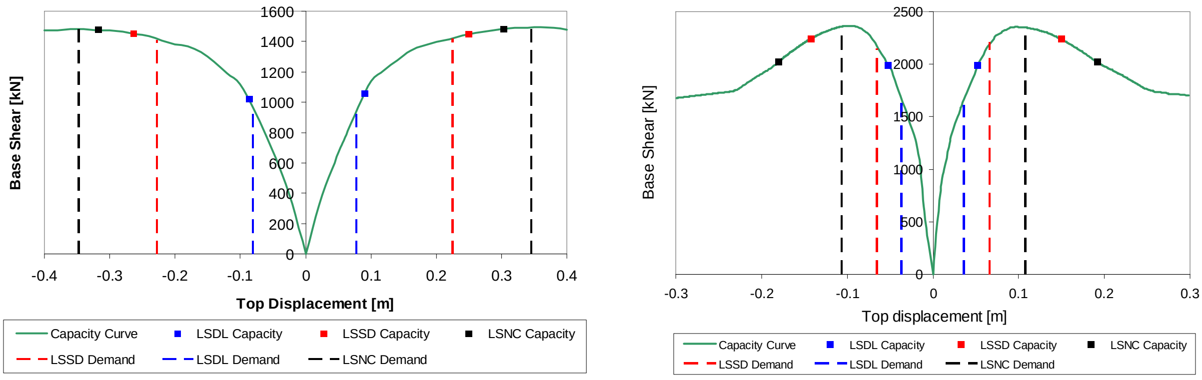

Fig. 4. Displacement capacity and demand for the bare (left) and infilled (right) structures at the different limit states.

The seismic demand was evaluated with reference to the Eurocode 8 response spectrum (Type 1, soil class B) considering a seismic intensity level equal to Sa_g=0.4g (*S* = soil factor). The bare structure was able to satisfy the seismic demand at the LSDL and LSSD, but lacked the appropriate capacity at the LSNC. A gap in terms of maximum top displacement was observed at the LSNC and the difference between the seismic demand and the displacement capacity was 4.3 cm (34.6 cm vs 30.3 cm). The results of the simplified procedure showed that the first attainment of the member capacity occurred at the beam of the first floor, where the most significant damage was observed in the laboratory tests and the highest value of the Park & Ang damage index was registered during nonlinear dynamic analyses. Numerical predictions showed that the structural capacity was greatly influenced by the presence of masonry infills. The expected contribution of the masonry infills in terms of both strength and stiffness was evident when comparing the response of the different structural configurations under monotonic loads, Fig. 4. The maximum base shear of the infilled structure was much larger (1.7 times) compared to the bare structure. However, after a certain point the strength of the infilled structure substantially decreased with increasing deformations as a consequence of the progressive failure of infills, until it reached the strength of the bare structure. The high stiffness provided by the masonry infills led to anticipate, in terms of drift, the development of global inelastic mechanisms in the infilled frames compared to the bare frame. A concentration of damage was observed at the first storey of the infilled structure. The application of the assessment procedure showed that the infilled structure was able to withstand the displacement demand due to seismic action equal to Sa_g=0.4g for all the different limit states. At the LSNC the seismic demand in terms of top displacement was reduced to 10.8 cm, whereas the capacity of the structure was equal to 19.2 cm. Due to the large contribution of the infill to the strength and stiffness of the structure, the seismic demand was drastically reduced with respect to the bare structure. In the infilled structure an extensive damage in the masonry panel was registered at the first storey and the first attainment of the capacity of a member occurred at the column of the first floor.

The influence of the masonry openings on the response of the structure was investigated too. The presence of openings of different sizes was considered at each storey of the large bay of the external frame of the building. Fig. 5 reports the results obtained from the numerical analyses on the structure with infill walls presenting 25% and 20% opening percentage, respectively, for the first and upper storeys. The equivalent diagonal strut model was used to represent the infill panel and openings were considered by varying the strut width. The introduction of openings affected the dynamic characteristics of the structure. As expected, the fundamental period increased with increasing the opening size due to reduction in stiffness of the model. The effects of the openings on the behaviour of the structure were clearly evidenced by the pushover analyses. The presence of openings within the infill walls decreased the stiffness and the strength of the fully infilled structure, and the drop of strength was less evident than the case of fully infilled structure, as shown comparing Fig. 4 and Fig. 5. In case of infilled structure with openings the damage concentrated in the second storey. The application of the simplified assessment procedure showed that the infilled structure was able to withstand the displacement demand due to seismic action equal to Sa_g=0.4g for all the different limit states.

Nonlinear dynamic analyses were performed on the different structures under study by using seven scaled real accelerograms with satisfactory compatibility between the mean elastic response spectrum and the Eurocode 8 response spectrum (Type 1, soil class B). Different earthquake intensity levels were considered in the numerical analyses. Fig. 6 shows the inter-storey drift profiles along the height of the structures analyzed under seismic intensity level equal to 0.6g and the influence of the masonry infills on the structural behaviour was apparent. The inter-storey drift profiles indicated that the distribution of damage was different between the bare and infilled structures. The maximum drift demand on the bare structure was registered at the second storey. On the contrary, the drift demand on the fully infilled structure concentrated at the first storey without excessive demand at the upper storeys. As expected, numerical analyses showed an increase of both strength and stiffness for the infilled structures with respect to the bare counterpart. The masonry infills caused a significant increase of the maximum base shear, as shown in Fig. 6. The increment of the base shear was influenced by the masonry openings, which reduced the maximum values for the infilled structures. Satisfactory agreement in terms of base shear values was observed comparing numerical results of the pushover and time-history analyses.

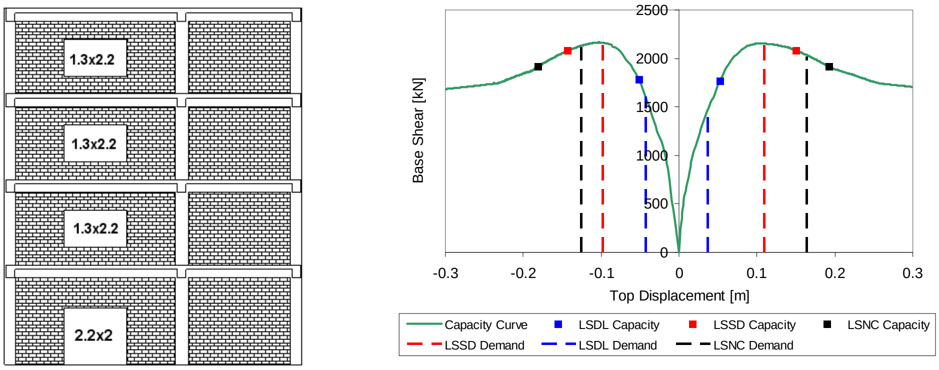

Fig. 5. Elevation view of the infilled structure with openings (left) and displacement capacity and demand for the infilled structure with openings at the different limit states (right).

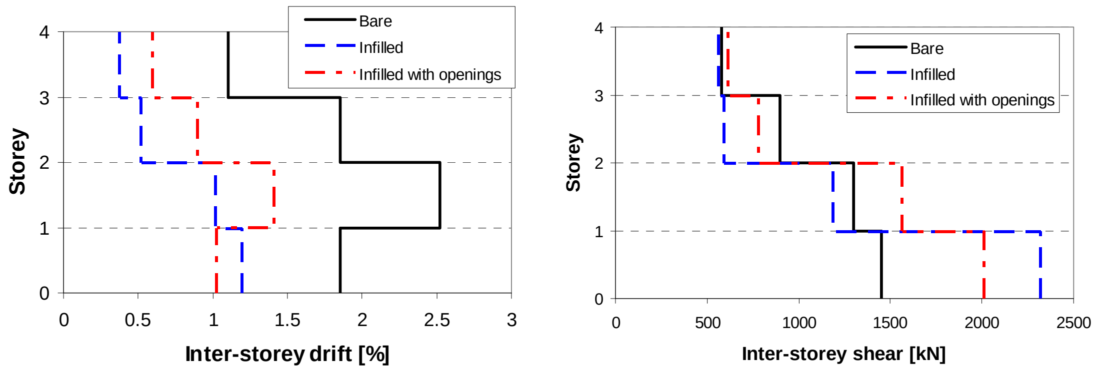

Fig. 6. Storey drift (left) and storey shear (right) profiles for the investigated structures at 0.6g seismic intensity level.

The column contribution to storey shear resulted lower in the infilled structure than in the bare counterpart. In presence of masonry openings, the column contribution to storey shear increased with respect to the infilled structure without openings.

IV. Conclusion

The displacement-based assessment procedure adopted in this study allowed to investigate the influence of masonry infills on the seismic performance of a ductile RC structure and provided results consistent with the experimental evidence and with nonlinear dynamic analyses. Due to the increase of stiffness provided by the infills, the attainment of the different Limit States was anticipated in terms of drift in case of infilled structure with respect to the bare counterpart. The presence of masonry infills and opening considerably changed the distribution of damage throughout the structure. The maximum drift demand on the bare structure was registered at the second storey. On the contrary, the drift demand on the fully infilled structure concentrated at the first storey. Masonry infills significantly contributed to the lateral stiffness and load resistance of the structure, but a decrease of strength was observed after the failure of infills. Severe damage for high seismic intensity levels may be expected for non-ductile structures because of the strength reduction due to the damage of the infills. According to the simplified assessment procedure, the influence of infills on the seismic response of the ductile RC structure investigated in this study was beneficial, though the drop of strength after the peak. The deformation capacity was large enough to accommodate the demand and a significant reduction of damage was registered compared to the bare structure. The presence of masonry openings affected the structural response and the damage distribution throughout the structure.

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