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Out-of-plane behaviour of masonry infilled RC frames with openings under cyclic loading

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Abstract

The majority of multi-storey buildings worldwide are constructed as reinforced concrete frame structures with masonry infill walls. Whereas frames, unlike infill walls are considered load-bearing. Yet, infill walls contribute to the structure's overall behaviour during seismic activity. Also, infill walls can impose hazard and safety issues due to Out-of-Plane instability. Consequently, this paper presents the results of experimental studies on reinforced concrete frames with unreinforced masonry infill walls, with and without openings. The study included six specimens: bare and fully infilled frame, while the others contained centric and eccentric door and window opening. The specimens were loaded in one direction by cyclic, quasi-static out-of-plane drift forces. Both drift driven tests and openings were rarely studied in the field of out-of-plane infilled walls behaviour. The experiments were monitored by two independent measuring systems, i.e. 3D optical (ARAMIS) and physical (linear variable differential and force transducers) systems. It was found that the infill wall did not contribute to the frame's overall behaviour. Albeit, the infill walls accumulated a significant amount of damage, especially the ones with openings.

Key words: Out-of-Plane Behaviour, Masonry Infilled RC Frames, Openings, Cyclic Loading

1 Introduction

Majority of multi-storey buildings are built from load-bearing frames made either from reinforced concrete (RC) or structural steel, commonly infilled by some kind of an infill wall or a panel. Such buildings are viewed as seismically vulnerable and special anti-seismic regulations are used for their design.

In Europe, most multi-storey buildings have structural systems made from RC frames with unreinforced masonry infill walls. Most of the infill walls consisting of hollowed clay blocks. For the design of such buildings, Eurocode 8 [1] provisions are used for seismic design and detailing. Whereas during the seismic action, structures are loaded and frames interact with the infill. The infill wall renders the behaviour of the frame by affecting its stiffness, stress distribution, failure modes, etc. Yet, Eurocode 8 does not require or provide the means of accounting for the infill walls contribution in seismic action. Moreover, it classifies the infill wall as a non-structural member. Consequently, the research of frame and infill wall interaction sprung to give designers adequate tools to assess the matter.

The field that examines the frames with masonry infill walls can be divided into 3 groups based on the action on its plane: 1) In-Plane (IP); 2) Out-of-Plane (OoP); 3) Combined. Whereas, combined action can be IP+OoP, OoP+IP and simultaneous IP&OoP action. Naturally, the seismic wave impacts a building in combined and simultaneous action with both inertial and drift forces. However, to better comprehend the effects it has on the structure, it is needed to be dissected to its original planes.

Furthermore, the OoP field of research has 3 main test methods, sorted by prevalence: 1) Inertial; 2) Dynamical, and; 3) Drift force method. Certainly, the dynamical method is the best as one can gain insight into the effect of both inertial and drift forces, vibrational modes, member accelerations, structural dampings, etc. However, such methods require expensive equipment and specimens, while also lacking a high degree of experimental control. Therefore, researchers tend to use more simplified methods that focus on a single aspect of the whole phenomena. When compared to dynamical (e.g. [2,3]), inertial (e.g. [4–6]) and drift force method both have certain level similarities. Yet, when the latter two are compared among themselves, there are nearly no similarities. Moreover, the effects are opposite to each other as the inertial force causes heavy damage to the infill wall, leaving the frame intact. Vice-versa is true for the drift force method. For more about the comparison between different experimental approaches, refer to [7,8] papers. Also, note that there is a lack of research done with drift methods. Namely, there were only 2 researches [9,10] done with drift methods in the ’90s on steel, fully infilled frames.

This paper presents an experimental campaign that examined a nearly or non-existing research topic of drift loading on RC frames with and without infill walls and openings positioned centrically and eccentrically.

2 Materials and methods

2.1 Specimens description

The following experimental campaign was the second part of a test series that was performed at the Faculty of Civil Engineering and Architecture Osijek. The first part of the series included IP cyclic, quasi-static load on the RC frames with and without masonry infill walls and openings positioned centrically and eccentrically. For more information about the first part of the series, please refer to [11]. The second part consisted of the same specimens, loaded by cyclic, quasi-static OoP drift load. However, unlike the first part of the series, the second did not include the gravity load.

The specimens were designed as medium ductility class (DCM) per EN 1998-1 [1] provisions and were scaled to the 1:2.5 ratio. The masonry units were cut at the mid-height and were classified as Group II by the EN 1996-1 [12] provisions, which also classified the general-purpose mortar as M5. Prior to OoP test series, the damages to the cover concrete were repaired. The repairs consisted of discarding loose parts and priming the cavity surfaces that were finally filled with fibre-reinforced, sulphate-resistant thixotropic mortar *Mapegrout*. The mortar was classified by EN 1504-3 provisions [13] as class R4 structural mortar. After the repairs, specimens were painted white and the front sides randomly dotted black to form a stochastic pattern for the digital image corelation (DIC) recordings. The specimen's appearance and specifics can be found in Table 1, while the geometrical characteristics of both the frame and masonry infill wall unit can be found in Figure 1.

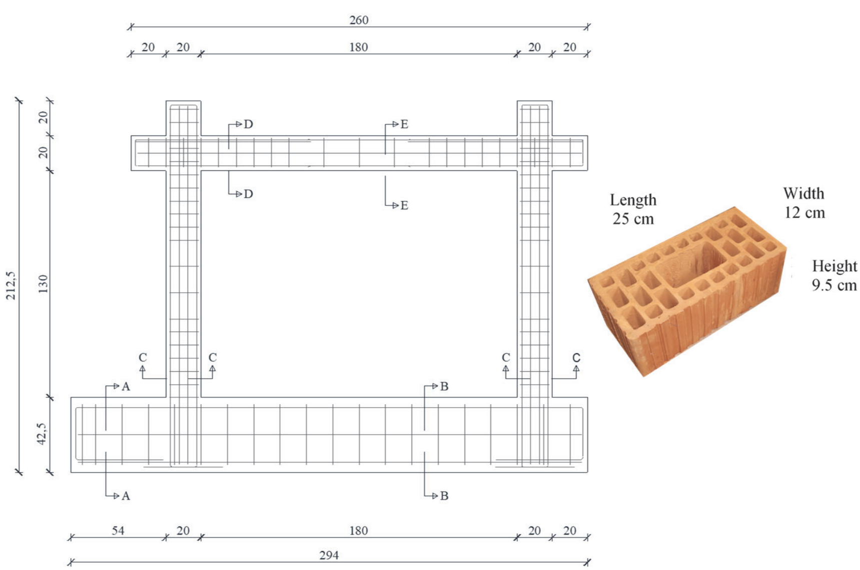
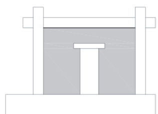
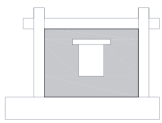
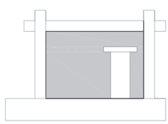
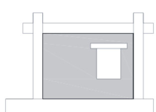
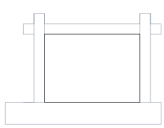
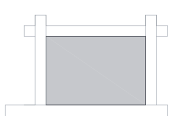


Figure 1. Geometrical characteristics of the frame and masonry unit

Table 1. Tested specimens

Mark	Appearance of the specimen	Opening	
		Type and area	Position
CD		Door	Centric
		l_o / h_o = 0.35 / 0.90 m	e_o = l_i / 2 = 0.90 m
		A_o = 0.32 m^2	
		A_o / A_i = 0.14	
CW		Window	Centric
		l_o / h_o = 50.0 / 60.0 cm	e_o = l_i / 2 = 0.90 m P = 0.40 m
		A_o = 0.30 m^2	
		A_o / A_i = 0.13	
ED		Door	Eccentric
		l_o / h_o = 0.35 / 0.90 m	e_o = h_i / 5 + l_o / 2 = 0.44 m
		A_o = 0.32 m^2	
		A_o / A_i = 0.14	
EW		Window	Eccentric
		l_o / h_o = 50.0 / 60.0 cm	e_o = h_i / 5 + l_o / 2 = 0.44 m P = 0.40 m
		A_o = 0.30 m^2	
		A_o / A_i = 0.13	
BF		Bare frame	
FI		Full infill	

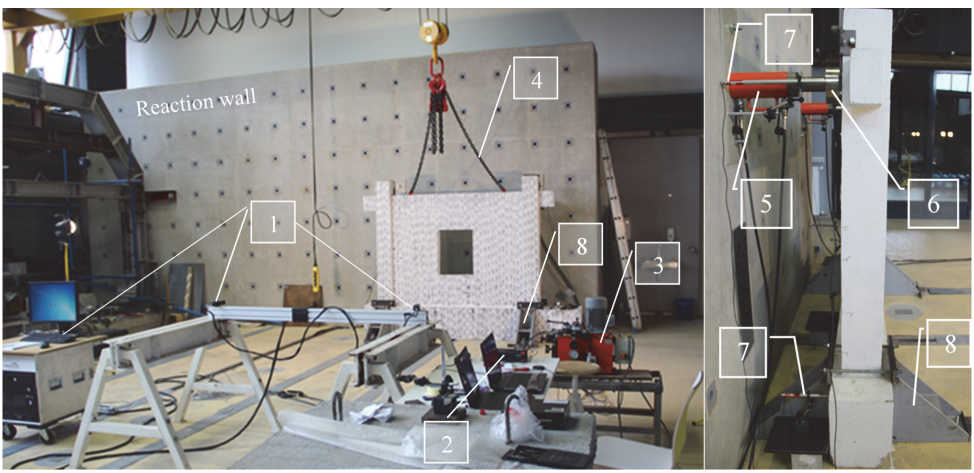
2.2 Experimental setup

The experimental setup is presented in Fig. 2. The brackets with numbers (#) within this subsection refer to the equipment as designated in Fig. 2. There were 2 systems of recording, one was optical (photogrammetry) using GOM ARAMIS (1), while the other was using hardware connected to the Dewesoft SIRIUS-HD-16xSTGS data acquisition system (DAQ) (2). The DAQ system was used as a primary acquisition tool, while ARAMIS to check with the DAQ and to capture incidents of accidental torsion, frame – infill wall interaction, stress accumulations, etc. The ARAMIS system used two 5MP cameras pointed at the specimens, which is required for stereophotogrammetry given that both

IP and OoP deformation was monitored (spatial deformation). The force transducers (6) were connected to the DAQ; so, for every load step an averaged force was calculated from DAQ and fed to the ARAMIS software.

The load protocol included loading and unloading the specimens at beam-column midline intersection in one direction with 5 kN step until yielding. Also, prior to yielding every load step was repeated twice. After yielding, the pushover, displacement control was used with +5 mm steps. The specimens were pushed to the maximum stroke of the piston, which is 10 cm or 9 % drift ratio.

The electrical-hydraulic pump (3) was operated manually and it was used to control both hydraulic presses (5). Hydraulic presses (5) and force transducers (6) were positioned so the load transmits at the midline intersection of the upper beam and the columns. There were 3 pairs of linear variable differential transducers (LVDT) (7) positioned on the specimen. One pair was set right beside the load input, second at the top, and last at the bottom of the lower beam. The LVDTs (7) at the lower beam were set to measure rotations and slipping that could occur.



1	ARAMIS	3	Hydraulic pump	5	Hydraulic press	7	LVDT
2	DAQ	4	Safety chains	6	Force transducer	8	Restrain

Figure 2. Experimental setup

The specimens were set in place by a pair of steel restrains (8) set at the lower beam beneath the columns. The restraints were placed on opposite sides of the lower beam and mutually connected by two M20 fully threaded studs. Additionally, the restrains were fixed in place by fastening them to the rails.

3 Results and discussion

The capacity curves (envelopes) of all specimens are plotted in Fig. 3, that includes averaged displacement of both columns as recorded by the ARAMIS system. Since force transducers were not connected to ARAMIS, forces were read from DAQ, averaged and multiplied by 2. From the figure, it is visible that the curves are relatively similar in terms of load-bearing capacity, initial stiffness and yielding point (at about 2 % drift). When OoP were compared to IP hysteresis from the test series described in [14] it was evident that OoP tests had more of a linear response. The same was observed in the dynamical study on a shaking table by [2]. Note that the FI specimen had the substandard capacity curve. This can be added to the fact that specimens had various levels of damages, repairing efficiencies and mechanical properties, rather than the infill wall – frame interaction.

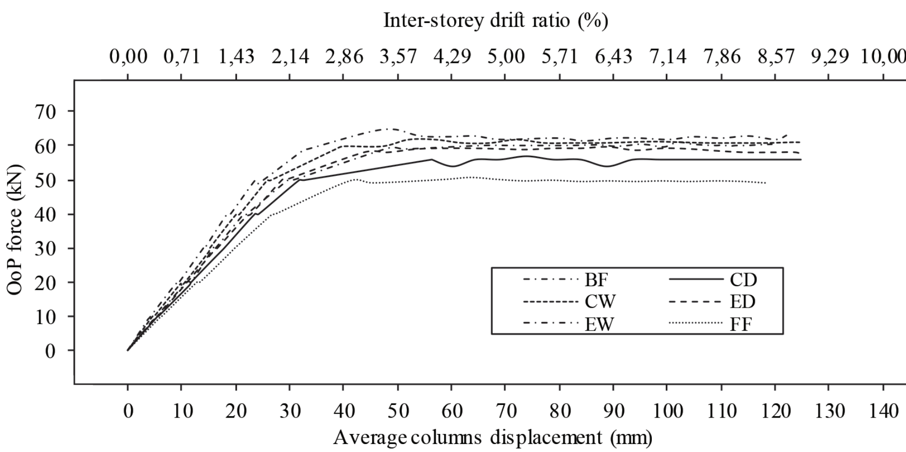


Figure 3. Capacity curves from ARAMIS

In Fig. 4, differences in rotation between elements and are plotted against the interstorey drift. The rotations were measured by ARAMIS optics, and they show differences between the two columns, opposite strips of the infill wall and between average rotations of both columns and infill wall. From the figure, it is observable that there is evidence of torsion and segregation between the frame and infill wall joint action at higher drift ratios. Also, both LVDTs on the lower beam and ARAMIS captured evidence of rigid-body movement, i.e. rotation. The results were corrected for the rigid body movement by determining relative displacements in relation to the frame base beam.

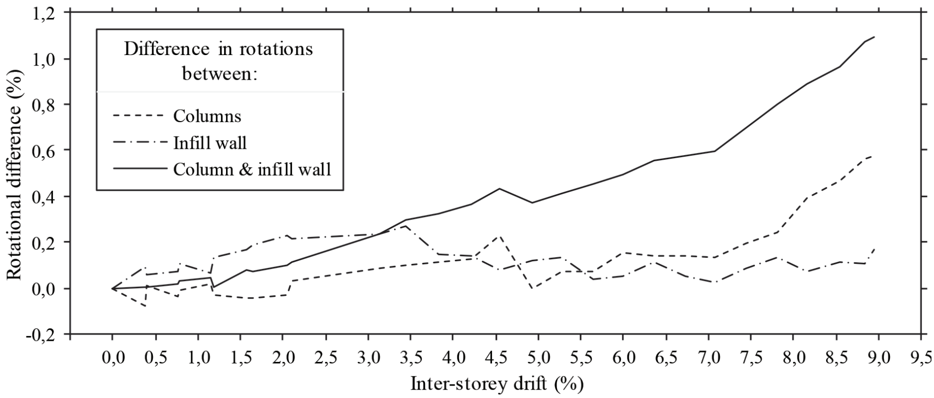


Figure 4. Differences in rotation between the specimen's elements of the ED model

In Fig. 5, cracks patterns of each specimen are plotted at the last step (approx. 10 % drift). The cracks on the tension side progressed from the bottom upwards, mostly covering bedjoints on the infill wall and columns. The cracks on the compression side were mostly due to the crushing of the columns concrete and along with the cracks on the tension side showing evidence of plastic hinge formation. Infill walls of all specimens started cracking at an inter-storey drift ratio of ≈1.25 %, the separation of infill wall from the columns occurred between 1.25 – 2.25 % likewise, detachment from the lower beam at about 1.25 – 2.50 %.

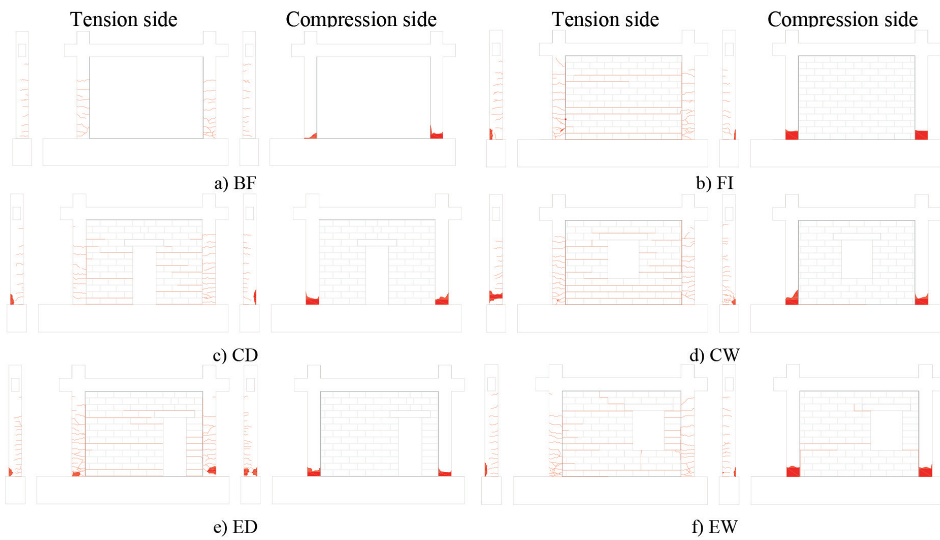


Figure 5. Crack patterns

Displacement map of ED model is presented in Fig. 6a, where it is visible that the frame and infill wall followed the same displacement patterns. In Fig. 6b, Von Mieses strains are plotted. Since clay blocks have heterogeneous mechanical properties in different directions, the values are not representative physically. Nevertheless, the figure provides a clue of stress accumulation, that is visible at frame infill wall connections and the bottom of the columns (crushing).

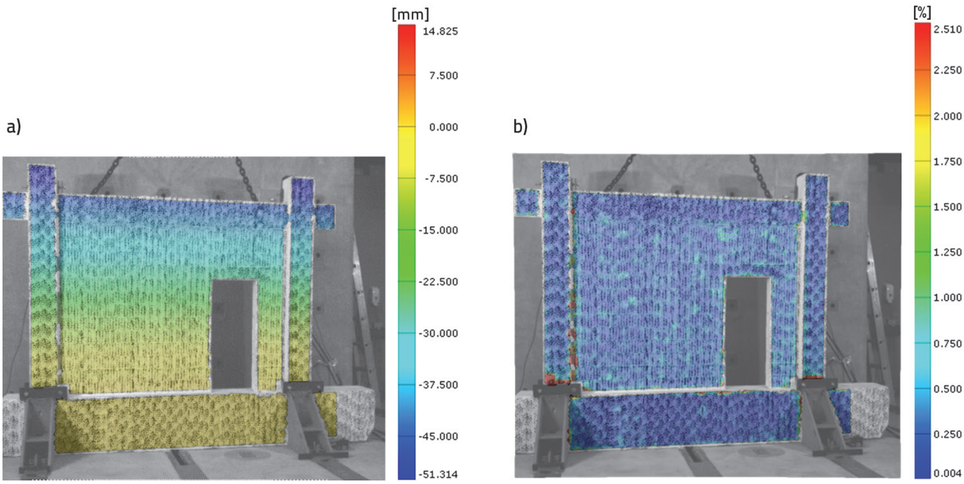


Figure 6. Overlay of results from ARAMIS optics on the ED model: a) Displacements, b) Von Mieses strain

4 Conclusions

During a seismic event, multistorey buildings are loaded by both the inter-storey drift and inertial forces. In the field of Out-of-Plane action on the structural systems made of frames with masonry infill walls, the research was mostly focused on using the inertial force methods. Therefore, the experimental campaign herein was concluded to cover the largely unexplored Out-of-Plane drift force action and to aid the previous In-Plane experimental campaigns done by [15]. All tests were concluded in the laboratory of the Faculty of Civil Engineering and Architecture Osijek.

The test series included 6 specimens as a bare and fully infilled frame, while also infilled frames with window and door openings positioned centrically and eccentrically. The specimens were loaded in a single direction by cyclic, quasi-static drift forces located at upper beam and columns midline intersections. Force control was used until yielding was reached; after which, pushover displacement control was used. Two systems of measurements were used, one was optical ARAMIS and the other physical DAQ.

Overall, the specimens showed great deformation capabilities, enduring up to 9 % drift ratios. Results showed a good amount of correlation between the other two inter-storey drift force [9,10] and dynamical [2] experiments. From the analysis of the results, it was visible that there was a one-way infill wall and frame interaction. That is, the infill wall did not significantly affect neither the overall behaviour of the specimens nor the frame. Rather, the frame only affected the infill wall's behaviour. The stated is observable in several points, being: the hysteresis was mostly linear; there were insignificant differences between the specimens capacity curves; the Von Mieses did not show significant accumulation of strain nor were there differences in displacements between the wall and the frame; the infill wall received a high amount of damages, i.e. cracks; at higher drift ratios the differences in rotation between the frame and infill wall increased. Furthermore, from the analysis of crack occurrences, it is expected that the infill wall with consideration of openings withstands light damage up to a 1.25 % storey drift, from 1.25 – 2.00 % heavy but usable damage and > 2.00 % heavy but unusable damage. Therefore, frames with masonry infill walls when subjected to purely Out-of-Plane drift forces still pose a life and socio-economical risks.

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