An experimental study on the seismic behavior of infilled RC frames with opening

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An experimental study on the seismic behavior of infilled RC frames with opening

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Abstract. Infill walls are generally not taken into account in structural analysis due to their complex behavior at seismic actions. As it is known, they increase the stiffness as well as the lateral load capacity of the system. Sometimes, infill walls may have window and door openings in their planes. In the present study, behavior of reinforced concrete (RC) frames with infill wall which have openings is investigated under cyclic lateral loadings. Location and size of the openings in the infill wall are selected as investigation parameters. Test specimens are constructed and experimentally analyzed. The infill wall changes the behavior of the frames under cyclic lateral loads significantly. Location and size openings in the infill wall are two main parameters which affect the behavior of the infill walls as well as on that of the frame. The test results clearly show that the contribution of the infill wall to the behavior of RC frame has diminished significantly when the opening ratio is larger than 9%. Therefore, the effect of the opening in the infill wall must be taken into account in the structural modeling when the opening ratio is larger than 9%.

Keywords: Infill wall; opening; reinforced concrete buildings; cyclic lateral loading; location and size of the openings

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1. Introduction

Reinforced concrete (RC) frames with masonry infill walls are widely used in structural systems in many parts of the world. It is known that influence of infill walls on the behavior of frames, which are subjected to earthquake loadings, is very important in some cases. If the infill walls are uniformly distributed throughout the structure, then they usually have a beneficial effect on the seismic response of the structure. On the other hand, negative effects can appear due to irregular positioning of the infill walls in plan, and especially in elevation [1]. Even with symmetric layout, irregularity can be expected due to partial failure of these walls.

Infill walls have attracted the attention of many researchers since the early 1950s. A large number of researchers have studied the behavior of infilled steel and RC frames subjected to in-plane and out-of-plane lateral loads. These studies have involved both experimental and numerical analysis.

Uva et al. [2] have investigated the role of masonry infill in the seismic behavior of RC frames, pointing out some relevant questions about the sensitivity to the material parameters and the choice the modelling approach. Chrysostomou and Asteris [3] have stated the in-plane behavior and in-plane failure modes of infilled frames and presented simplified methods for predicting these failure modes. Ricci et al. [4] have analyzed the effect on the elastic period of vibration of infill contribution to lateral stiffness of RC buildings. Shing and Mehrabi [5] have summarized some of the recent findings and developments on the behaviour and modelling of infilled structures. Koutromanos et al. [6] have investigated the behavior of masonry-infilled reinforced concrete frames under cyclic lateral loading by using nonlinear finite element models. Most of these studies have shown that use of masonry infill walls has a significant impact not only on the strength and stiffness but also on the energy dissipation mechanism of the overall structure. Celarec et al. [7] have investigated the sensitivity of the seismic response parameters to the uncertain modeling variables of the infill walls and frame. Campione et al. [8] have improved an equivalent diagonal pin-jointed strut model taking into account the stiffening effect of vertical loads on the infill in the initial state. Martinelli et al. [9] have proposed a simplified procedure based on NonLinear Static (NLS) analysis for evaluating the seismic response of masonry infilled RC frames.

Amanat and Hoque [10] and Kose [11] have investigated parameters affecting the fundamental period of RC buildings with infill walls. Asteris et al. [12] have presented a detailed and in depth analytical investigations on the parameters that affect the fundamental period of reinforced concrete structure. From the analysis of the results, it has been found that the number of storeys, the span length, the stiffness of the infill wall panels, the location of the soft storeys and the soil type are crucial parameters that influence the fundamental period of RC buildings.

Pujol and Fick [13] have reported experiments on a full-scale building structure were done to address questions about the potentially positive or negative effects of masonry infill walls. The study has focused on the assumption that measures are taken to prevent out-of-plane failure of masonry panels. Tu et al. [14] have conducted shaking table tests on four full-scale single-story structures to investigate the out of-plane behavior of unreinforced masonry (URM) panels in RC frames. They have presented an analytical model for the out-of-plane behavior of masonry panels in accordance with the rocking mechanism. Arulselvan et al. [15] have tested a frame having five stories and three spans with a central portion infilled with brick under cyclic loading simulating seismic action. Analytical studies have been carried out as well to study the stiffness, strength, and behavior of these types of frames.

Infill walls may have window and door openings. Asteris [16] has analytically investigated the influence of the masonry infill panel opening in the reduction of the infilled RC frames stiffness. A parametric study has been carried out by adopting location and size of the masonry infill panel opening as investigation parameters. Altin et al. [17] and Anil and Altin [18] have investigated the behavior of ductile reinforced concrete (RC) frames strengthened by addition of partial infills under cyclic lateral loading. Steel frames with masonry infills having openings have been tested by Tasnimi and Mohebkhah [19], and Liu and Manesh [20].

Experimental studies are carried out by Voon and Ingham [21], Kakaletsis and Karayannis [22], Mansouri et al. [23] related to walls with openings. Voon and Ingham [21] have presented test results of eight partially grout-filled perforated concrete masonry walls that were subjected to cyclic lateral loading. The eight walls had variations in lintel reinforcement detailing. Test results obtained from this research indicated that the size of openings and the length of trimming reinforcement significantly affected the lateral strength of perforated masonry walls. Kakaletsis and Karayannis [22] have investigated the influence of masonry openings on the seismic performance of infilled reinforced concrete frames, designed according to current code provisions. The investigated parameters have been selected as the shape and the size of the opening. In all the examined cases, the shear strength of columns was higher than the cracking shear strength of solid infill. The experimental results have shown the significance of various forms of openings on the reduction of strength, stiffness, and energy dissipation capability for all the examined cases of infilled frames. Mansouri et al. [23] have presented the influence of openings on lateral behavior of low-shear strength masonry infilled reinforced concrete frames. The design of the reinforced concrete frames have been aimed to reflect common seismic design deficiencies. Six half-scale single-storey, single-bay frame specimens were tested under in-plane lateral loading. The aspect ratio (h/l) of infill wall was equal to 0.62. The investigated parameters have been selected as shape (window and door), size (regular and large windows) and location of the openings (eccentric and central in horizontal direction). The results have indicated that presence of openings alters the failure mode, increases the damage level and reduces ductility, strength and stiffness of the infilled frame.

The failure mechanism of an infilled frame is quite complex and depends upon a large number of factors such as the relative strength and stiffness properties of the infill wall and the frame. Although the subject of infilled frames has been studied for a long time, there are still questions to be investigated and answered about their behavior and interaction with the frame. Generally, window and door openings are formed in the infill wall to satisfy architectural requirements of the buildings; however, they create various modelling difficulties. In FEMA 306 [24], it is stated that "In spite of the general success of modelling infilled frames with solid panels, major difficulties still remain unresolved regarding the modeling approach for infilled frames with opening". Despite of all these difficulties in the modeling of infill walls with and without openings, seismic behavior of infill walls is still a popular subject for experimental and numerical studies.

The seismic safety evaluation of masonry infill walled reinforced concrete buildings requires appropriate macro-models for infill walls that have been calibrated by experimental results. Because of restriction of experimental data, most of the existing models have been developed by finite element analyses and have not been verified by experimental results. Therefore, more experimental investigation is required for predicting the stiffness and strength of infilled frames with openings.

The purpose of this study is to investigate the effects of infill walls with openings on the behavior of the RC frames, and increase experimental results in literature deal with infill wall having opening. Thus, the macro model of infill wall having opening can be developed by using the experimental results. An experimental study has been carried out by using variables that relate to the location and the size of window opening in the infill walls. In the four specimens the opening is located in the middle of the infill wall, whereas in the other four specimens the opening is located on the upper left part of the diagonal. Openings of the infill walls are located on the diagonal of all specimens.

The design of the reinforced concrete frames in this study are aimed to reflect common seismic design deficiencies, such as insufficient transverse reinforcements at column and beam ends, lack of transverse reinforcement at beam-column joints, weak column-strong beam connections that are encountered frequently in practice. The results of the study including failure mode, lateral load capacity, energy dissipation, and the lateral stiffness of the frame with infill walls are investigated and the results are given in figures comparatively.

2. Experimental work

2.1. Description of the test specimens

Ten test specimens are constructed with 1/3 scale and tested under cyclic lateral loading. Span length and height of the frame in all specimens are kept constant as 1500 mm and 1200 mm, respectively.

Cross section dimensions of columns and beams are given in Fig. 1. Longitudinal reinforcements of columns and beams consist of 10 mm bars. Stirrups are provided to the columns and beams as 6 mm diameter bars with 135° hooks. Spacing between the stirrups is 80 mm. The design of the reinforced concrete frames in this study are aimed to reflect common seismic design deficiencies, such as insufficient transverse reinforcements at column and beam ends, lack of transverse reinforcement at beam-column joints, and weak column-strong beam connections that are encountered frequently in practice. A typical layout of the beam and the column along with reinforcing details is presented in Fig. 1. Properties of the reinforcement used in the study are listed in Table 1.

Tests for evaluation of concrete compressive strength (f_c) are carried out on 150 mm×300 mm concrete cylinders, and average strength values (f_c) at 28-day for each frame are given in Table 2. Three types of frames are constructed for the experimental tests. The first type does not have any infill wall (bare frame), the second has a solid infill wall (without opening), and the third includes partial openings at different locations of the infill wall. Table 2 summarizes the properties of each specimen.

The infill walls in the frames are constructed by using one-third scale hollow clay tiles with dimensions 55 mm × 100 mm × 100 mm after finishing the construction of the frame. The aspect ratio (h/l) of infill wall is equal to 0.83. A rough plaster has been applied on the both sides of the infill walls where regular masonry units are connected to each other by a regular mortar. The thickness of the plaster used at the two faces of the brick walls is 10 mm, and total thickness of infill wall is 120 mm. The infill walls were not constructed on the symmetric axis of the frame to simulate the exterior walls of the building. The mortar and plaster mixture contained one part cement, one part lime, and four parts sand according to common construction practice. The sand used had a maximum aggregate size of 3 mm. The average compressive strengths of the mortar and plaster used in the construction of the masonry walls of the specimens were found to be around 3.5 MPa.

Openings of the infill walls are located on the diagonal of all specimens, where strut is expected to appear, when the frame is subjected to a lateral load. In the four specimens the opening is located in the middle of the infill wall, whereas in the other four specimens the opening is located on the upper left part of the diagonal (Fig. 2). Ratio of the opening area to the infill wall area is selected as 4%, 9%, 16%, and 25%, where the rectangular openings are chosen as 240mm×200mm, 360mm×300mm, 480mm×400mm and 600mm×500mm, respectively, where dimensions represent the length and height of the opening on the x and y directions, respectively (Fig. 2).

The compressive strength of the infill wall is found to be as 5.0 MPa. All samples are painted with lime whitewash in order that cracking in the RC frame and in the infill wall can be observed clearly during the test.

2.2. Test setup

Test setup is shown in Fig. 3. After the specimens have been bolted to the rigid floor by the foundation beam at the bottom, tests are carried out by applying reversed cyclic lateral loading. Each load cycle consisted of push and pull loading steps. The lateral load is applied at the beam level and increased as 5 kN at each loading step. Loading in the tests are continued until the infilled frame reached its lateral load capacity in load control manner. Then the test is continued in displacement control in order to obtain the load-displacement curve until a decrease of 15% at the maximum load is reached. Furthermore, in order to provide a right angle (90 degrees) between the load cell and the frame during the loading, a hinge was used as shown in Fig. 3. The lateral displacements were measured by using LVDTs (linear variable differential transformers). The locations of LVDTs are also shown in Fig. 3. After each loading cycle, cracks and damage mechanisms in the specimens are observed and recorded. A bracing system is employed to prevent out-of-plane movement of the specimens, as shown in Figure 4.

3. Experimental results

3.1. Observed damage in the specimens

Distributions of the damage in the specimens are observed and recorded throughout the experiment. Fig. 5 shows damage variation in Specimen-1 and Specimen-2. Specimen-1 which represents the bare frame failed due to the column mechanism, i.e., due to plastic hinges developed at both ends of the columns as it is expected due to strong beam/weak column configuration. In Specimen-2, the separation cracks are firstly observed at the interface between the frame and the–infill wall due to deformation dissimilarity. While vertical cracks are formed at the bottom and top of the infill wall, horizontal cracks are formed in the middle of the infill wall**.** Propagation of the horizontal cracking in the middle of the infill wall developed a diagonal crack under increasing lateral load. After the formation of a great number of hairline cracks on the infill wall, an increase in their widths is observed, as well. The diagonal cracks in the infill wall were followed by shear failure at the bottom and top of the columns. This is due to the shear force applied by the strut developed in the infill wall. This fact indicates an increase of the design shear force at the columns as the horizontal component of the strut, to avoid brittle shear failure at the columns.

Crack configurations observed in all specimens with the infill walls having openings are given in Fig. 6. As seen, the first cracks occurred obliquely on the corner of the openings, where a stress concentration is expected. Failure mechanisms of Specimens 3 and 4 are quite similar to that seen in Specimen 2. Probable reason for this is that the size of the opening in the infill wall is quite small.

In Specimen 5, a crack was formed from the bottom corner of the opening up to the upper corner of the frame. Later, the crack was widened under the increasing lateral load. The crack in the infill wall was extended to the column at the frame corner and caused a shear failure at the top and bottom of the column, as observed in Specimen 2.

Cracking in the infill walls took place outside the diagonal strip of the frame in Specimens 7 and 9, while cracking took place along the diagonal of the frame in Specimens 6 and 8. Detailed inspection shows that cracking in Specimen 7 took place in the area of the wall besides the opening obliquely whereas a diagonal crack was formed in the area of the infill wall under the window opening in Specimen 9. As a result of the increase in the crack width in these specimens, the infill walls were failed by losing their load carrying capacity. In Specimen 10, the starting point of the crack was at the window's corner and the crack continued horizontally towards the column. From the experiments, it is observed that the opening in infill walls has changed the basic behavior of the frame and created a new failure mechanism, when the opening ratio is larger than 9%.

Generally it is observed that the failure mechanism of frames that include the infill walls with opening depends mostly on the location and ratio of the openings.

3.2. Lateral load capacity of the specimens

Lateral load-displacement hysteretic curves that were obtained during the testing are illustrated in Fig. 7. The tests show clearly that strength and stiffness of the frames increase significantly by the presence of infill walls. The largest lateral load capacity has been obtained as 115 kN from Specimen-2, whereas the lowest lateral load capacity has been obtained as 50 kN from Specimen-1. Lateral load capacity of the specimen with the solid infill wall has increased by almost 130% as compared to the specimen without infill wall. Envelope curves obtained from the lateral load–displacement hysteretic curves are shown in Fig. 8. Lateral load capacities obtained from the tests are given in Fig. 9 comparatively.

Lateral load capacity values in the pull and push directions are quite close to each other in the specimens (Specimens 4, 6, 8, and 10) having opening in the middle of the infill wall. In contrast, in the specimens (Specimens 3, 5, 7, and 9) having opening on the upper left part of the infill wall, the lateral load capacities in the push direction are generally larger than the lateral load capacities in the pull direction. A comparison of the two tests which have the same ratio of opening in the middle and on the upper left part of the infill wall yields that the lateral load capacity of the former is generally larger than the latter.

The lateral load capacities of Specimens 3 and 4 are almost equal to that of Specimen 2. As expected, the test results yield that as the opening ratio increases, the lateral load capacity of the specimen decreases, i.e., openings of 4, 9, 16 and 25 %, leads to a decrease in the lateral load capacity of 1%, 10%, 20%, and 30%, respectively. It is worth noting that these values represent averages in different opening locations and different loading directions. The results obtained from tests show that the contribution of the infill walls to the lateral load capacity of the frame decreases significantly, when the opening ratio is larger than 9%.

3.3. Story drift ratios

Story drift ratios are obtained for the all specimens in two different ways. Firstly, story drift ratios are calculated for all specimens corresponding to a lateral load capacity (50 kN) of the bare framed specimen. The highest and the lowest story drift ratios are observed in the bare frame and solid infill walled specimen as 1.1% (0.86%) and 0.1% (0.13%), respectively under pull (push) lateral loadings. The obtained results show that the story drift ratios increase as the openings on the infill walls increase.

Secondly, story drift ratios corresponding to the ultimate load capacity of each specimen are obtained. Except the specimens with the opening of 25%, the highest value for the story drift ratio has been observed in bare frame while the lowest value has been observed in solid infill walled frame. These corresponding drift values are at the order of 0.9-1.1% (0.7-0.9%) under pull (push) lateral loadings except the specimens with the opening of 25%. In the specimens with the opening of 25%, the story drift ratio is higher than the bare frame under both push and pull loading. For example, Specimen 10 (with openings of 25%) has experienced with 80 kN total load capacity, 1.4% story drift ratio and lateral stiffness of 5.05 kN/mm whereas, these values for bare frame are at the order of 50 kN, 1.1% and 4.16 kN/mm, respectively. This observation is due the fact that maximum story drift ratios are proportional with the corresponding ultimate lateral load capacities of the Specimen 10 and 1. Infill walls with openings contribute to the lateral stiffness and lateral load capacity of the frames. However, if the opening in the infill wall is higher than 16%, story drift ratio corresponding to the lateral load capacity of specimen is observed to increase with respect to the bare frame. The obtained results clearly show that the effect of openings on story drift ratios is noteworthy. Increment on the story drift ratio becomes significant when the opening ratio is larger than 16% for both push and pull loading. The opening becomes more effective, when they are located in the middle part of the infill wall.

3.4. Stiffness and energy dissipation

Lateral stiffnesses of the specimens are calculated as the ratio of the lateral load to the lateral displacement at each cycle and presented in Fig. 10. Specimen 2 exhibits the highest stiffness among of all specimens while Specimen 1 has been the lowest. The specimens which have openings in the middle of infill wall exhibit approximately equal stiffness values for lateral loads in the pull and push directions. The results show that the stiffness of the specimens decreases as the opening ratio increases. The lateral stiffnesses for the push loading in the all specimens having openings on the upper left part of the infill wall are generally larger than the stiffnesses for the pull loading.

Energy dissipation is determined by calculating the areas inside the hysteretic load-displacement loops for each cycle, whereas the cumulative dissipated energy is evaluated as the sum of the area of all previous hysteresis loops and cumulative energy dissipations are depicted in Fig. 11.

It is apparent from Fig. 11 that the lowest energy dissipation is observed in Specimen 1 within all specimens. Among the all infill walled specimens, Specimen 2 displays the largest amount of energy. When the opening ratio is less than 9%, the amount of the energy dissipation is almost equal to that of the solid infill walled specimen.

4. Conclusions

In this study, the behavior of RC frames with infill walls having opening are investigated experimentally under cyclic lateral loadings. Location and ratio of the opening in the infill wall are selected as test parameters. RC frames with infill wall having opening are tested under reversed cyclic loading. Failure mode, lateral load capacity, energy dissipation and stiffness of each specimen are obtained from the experimental results. The following conclusions can be derived from this study:

(1) Presence of infill walls having openings changes the behavior of the frame significantly. It also modifies the failure mechanism, as opening ratio increases, especially when it is larger than 9%.

(2) The obtained results have shown that infill walls lead to significant increases in strength and stiffness in relation to bare RC frames. Lateral load capacity of the solid infill walled specimen increases about 130% as compared to the specimen without infill wall. The test results show that as the opening ratio increases, the lateral load capacity of the specimen decreases. When the opening ratio of the infill wall is 4, 9, 16, and 25 %, the lateral load capacity decreases approximately 1, 10, 20, and 30%, respectively. Furthermore, the test results yield that the contribution of the infill wall to the lateral load capacity of the frame decreases significantly, once the opening ratio is larger than 9%.

(3) Story drift ratios are obtained for the all specimens in two different ways. Firstly, story drift ratios are calculated for all specimens corresponding to a lateral load capacity of the bare framed specimen. The highest and the lowest story drift ratios are observed in the bare frame and solid infill walled specimen. The obtained results show that the story drift ratios increase as the openings on the infill walls increase.

(4) Secondly, story drift ratios corresponding to the ultimate load capacity of each specimen are obtained. In the specimens with the opening of 25%, the story drift ratio is higher than the bare frame under both push and pull loading. This observation is due the fact that maximum story drift ratios are proportional with the corresponding ultimate lateral load capacities of the Specimen 10 and 1.

(5) Infill walls with openings contribute to the lateral stiffness and lateral load capacity of the frames. However, if the opening in the infill wall is higher than 16%, story drift ratio corresponding to the lateral load capacity of specimen is observed to increase with respect to the bare frame. The obtained results clearly show that the effect of openings on story drift ratios is noteworthy. Increment on the story drift ratio becomes significant when the opening ratio is larger than 16% for both push and pull loading. The opening becomes more effective, when they are located in the middle part of the infill wall.

(6) Energy dissipation and stiffness of the specimen is significantly reduced with the increase in the ratio of the opening on the infill wall. Furthermore, the amount of energy dissipation is almost equal to that of the solid infill walled specimen, when the opening ratio is more than 9%.

(7) Behavior of the specimen under pull and push loading are quite close to each other, when the opening is located in the middle of the infill wall. However, the pull loading is generally more critical than the push loading, when the behavior of the specimen is considered, especially and when the opening is located on the upper left part of the infill.

(8) The test results clearly show that the contribution of the infill wall to the behavior of RC frame has greatly reduced, when the opening ratio is larger than 9%. Therefore, the effect of the opening in the infill wall must be taken into account in the structural modeling, when the opening ratio is larger than 9%.

(9) In order to avoid brittle shear failure at the top and bottom of the columns of the frames with infill, the design shear force should be increased by the horizontal component of the strut developed in the infill wall.

(10) Experimental tests have shown that presence of openings significantly change the behavior of infilled frames. The macro model of infill wall with opening can be developed by using the experimental results. Empirical equations can be proposed for estimating changes in lateral load capacity, energy dissipation, and the lateral stiffness of infill walled frames because of the presence of openings.

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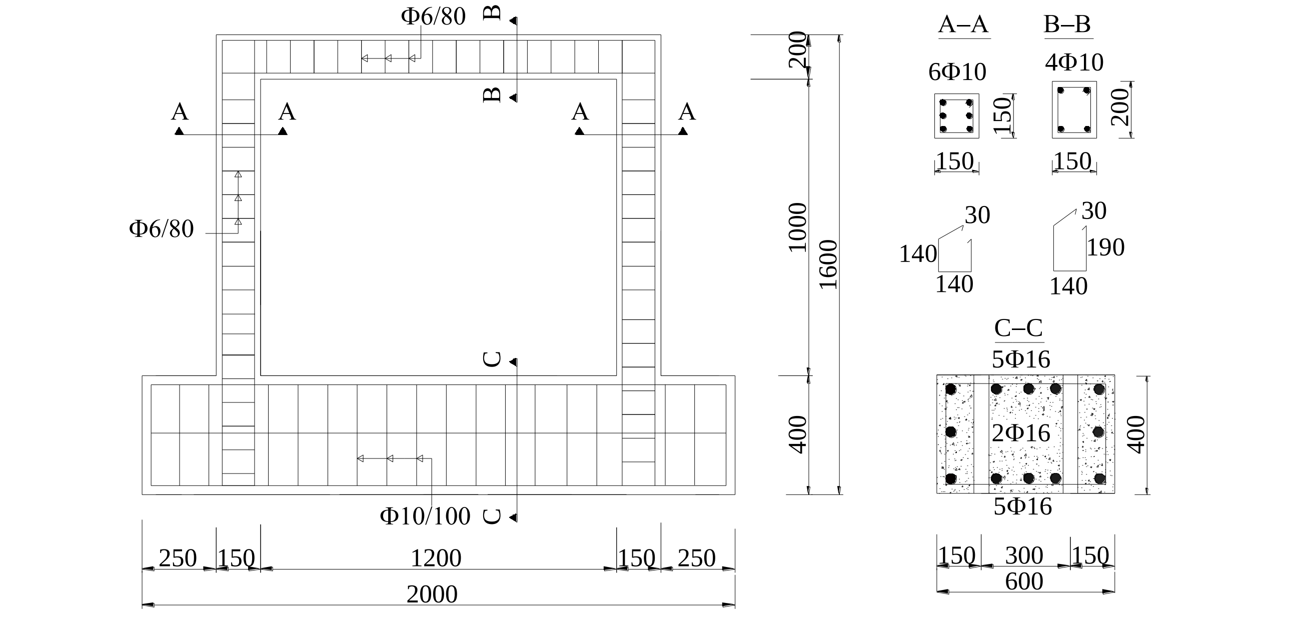
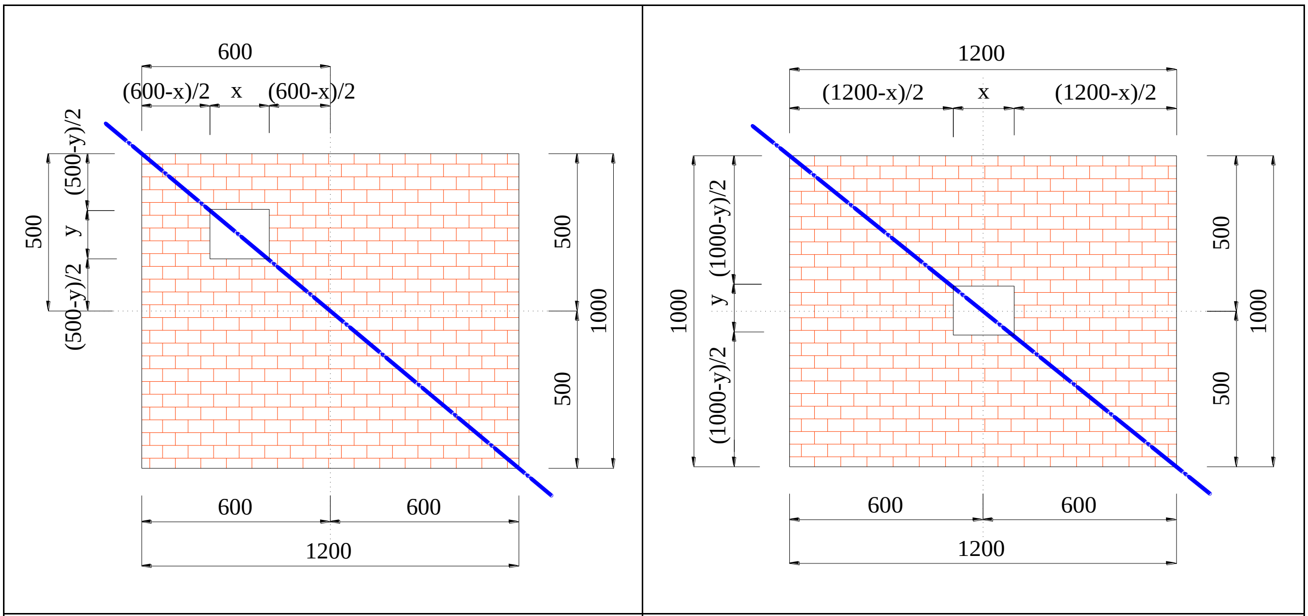


Fig. 1. Dimensions and reinforcement details of the specimens (mm)



(a) (b)

Fig. 2. Location of the openings on the infill wall (mm)

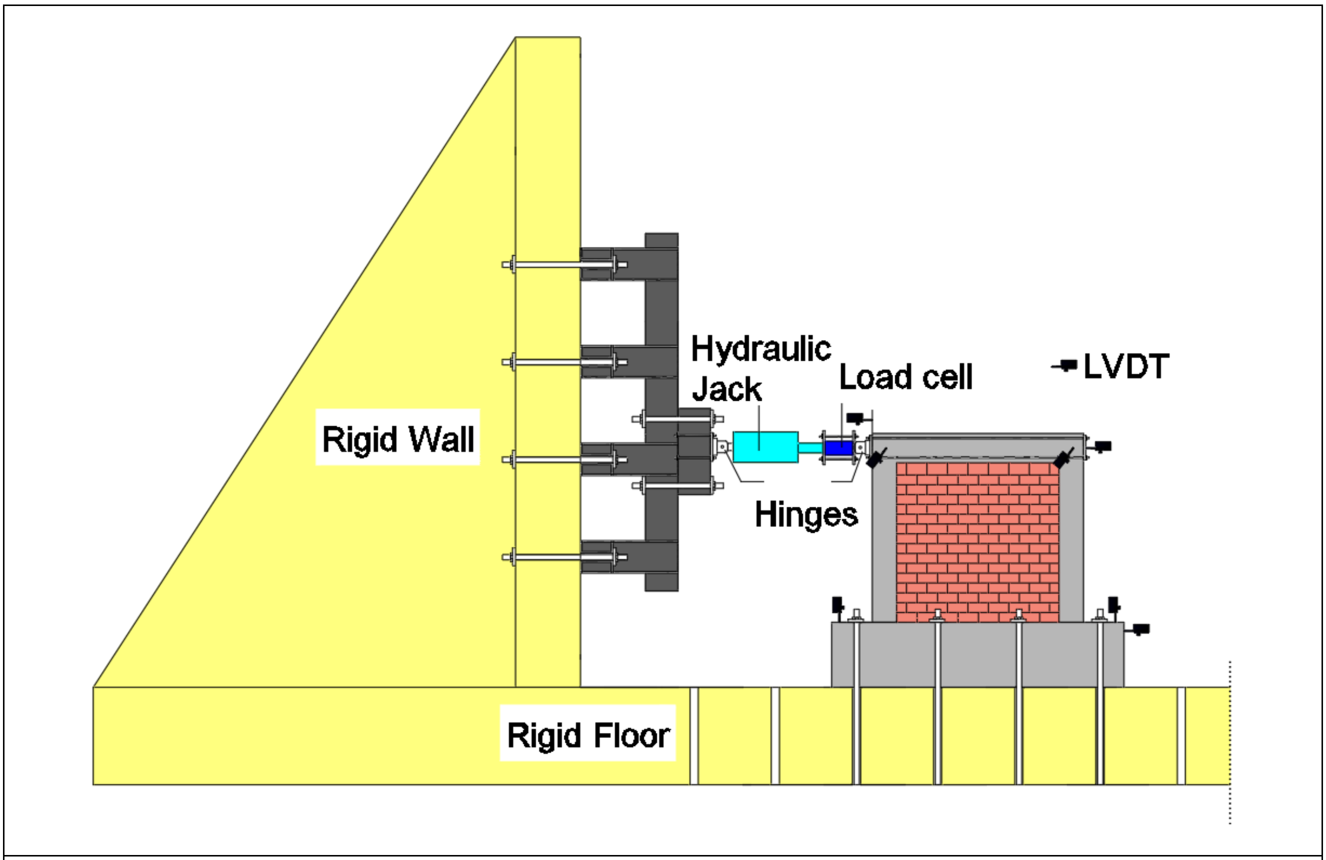


Fig. 3. Test setup

Fig. 4. Bracing system against out-of-plane movement of the specimens

	
(a) Specimen-1	(b) Specimen-2

Fig. 5. Damage observed in Specimen-1 and Specimen-2

(a) Specimen 3

(b) Specimen 4

(c) Specimen 5

(d) Specimen 6

(e) Specimen 7

(f) Specimen 8

(g) Specimen 9

(h) Specimen 10

Fig. 6. Damage observed in all specimens with the infill wall which have opening

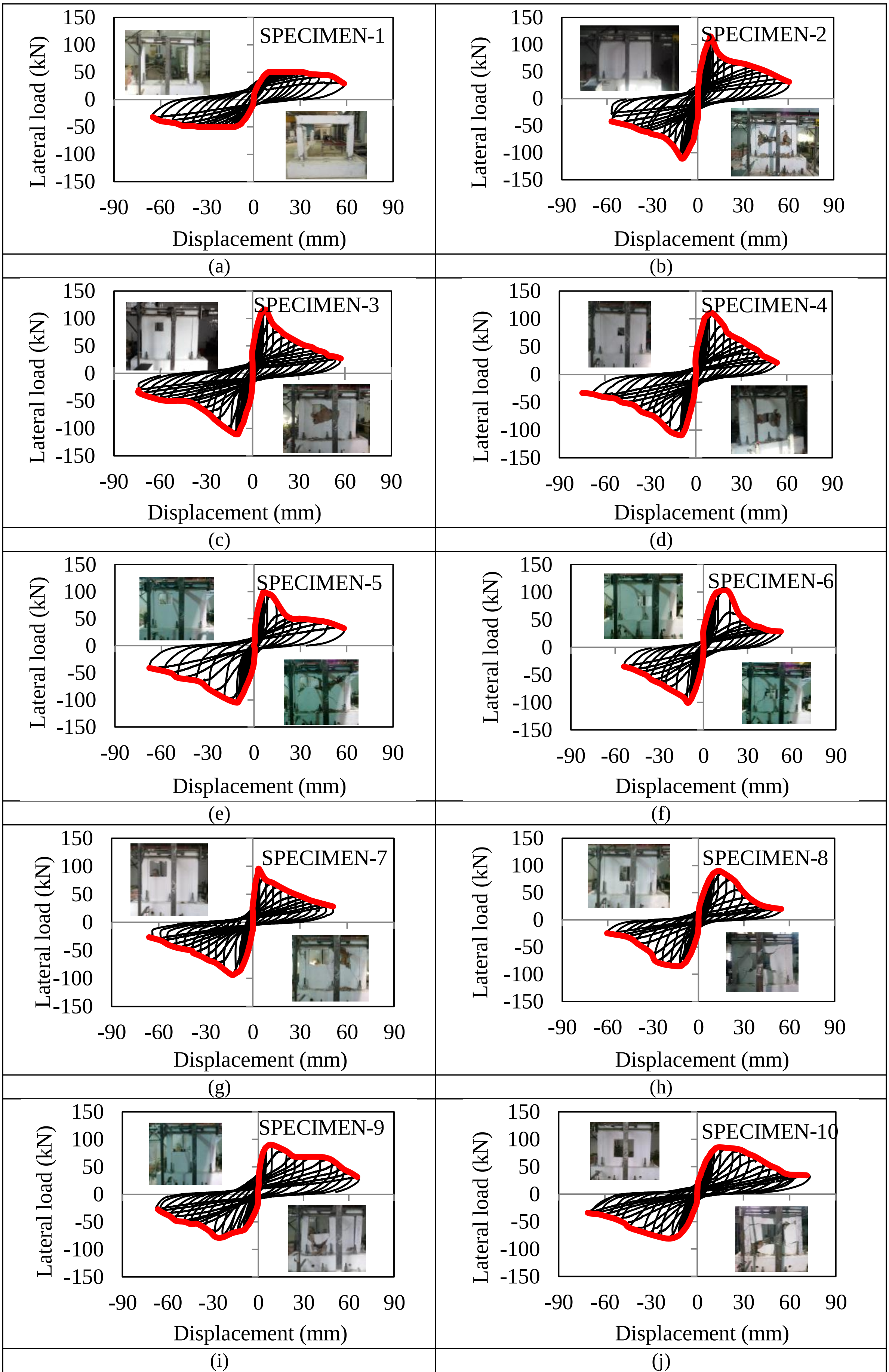
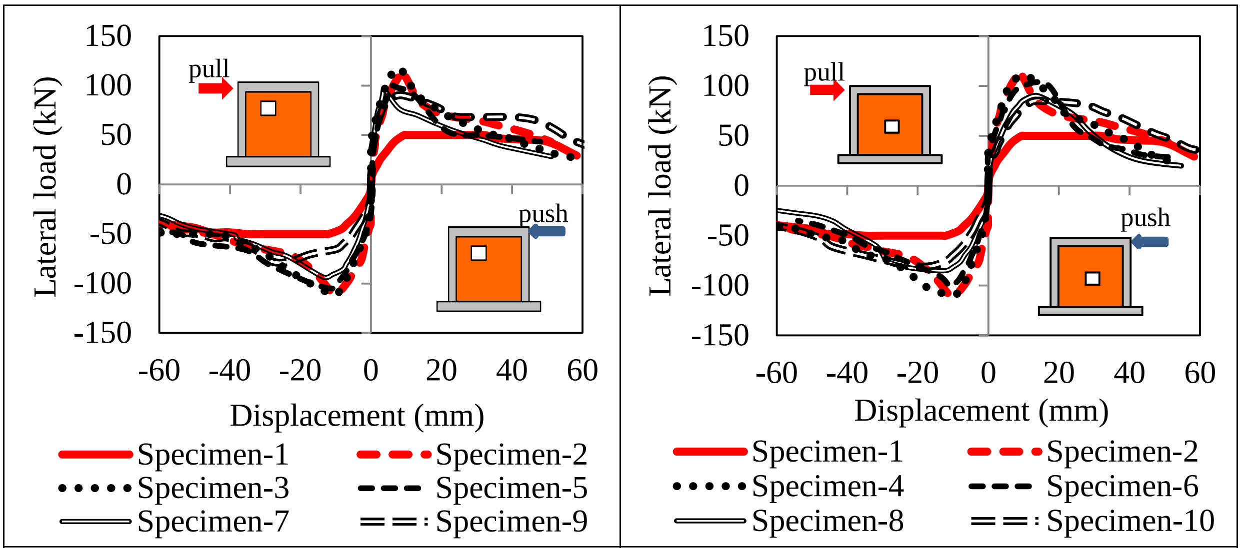
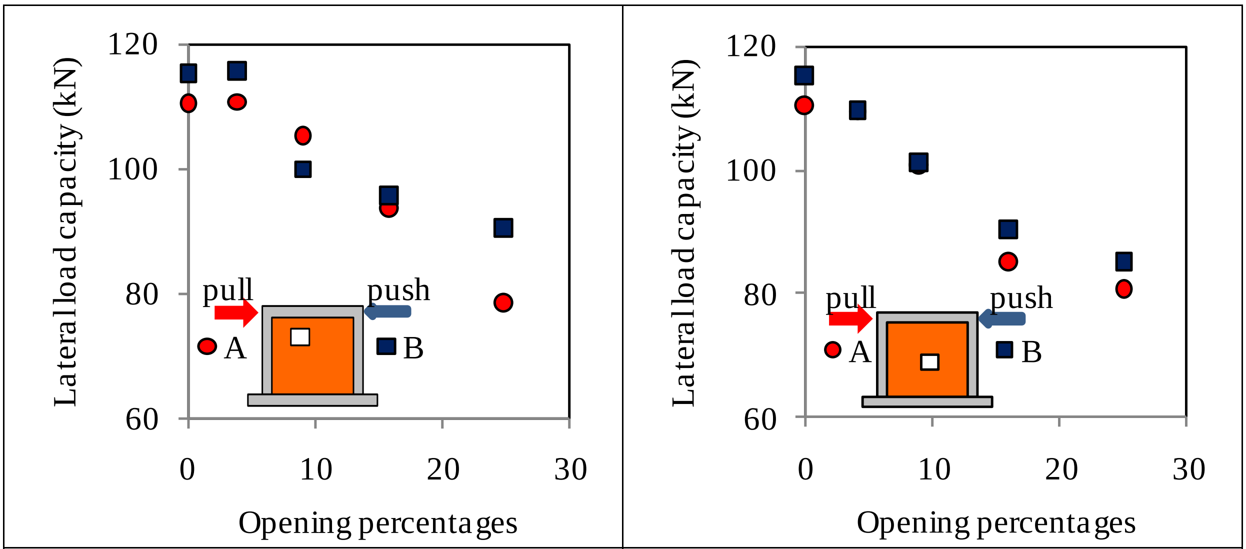


Fig. 7. Lateral load–displacement hysteretic curves of all specimens



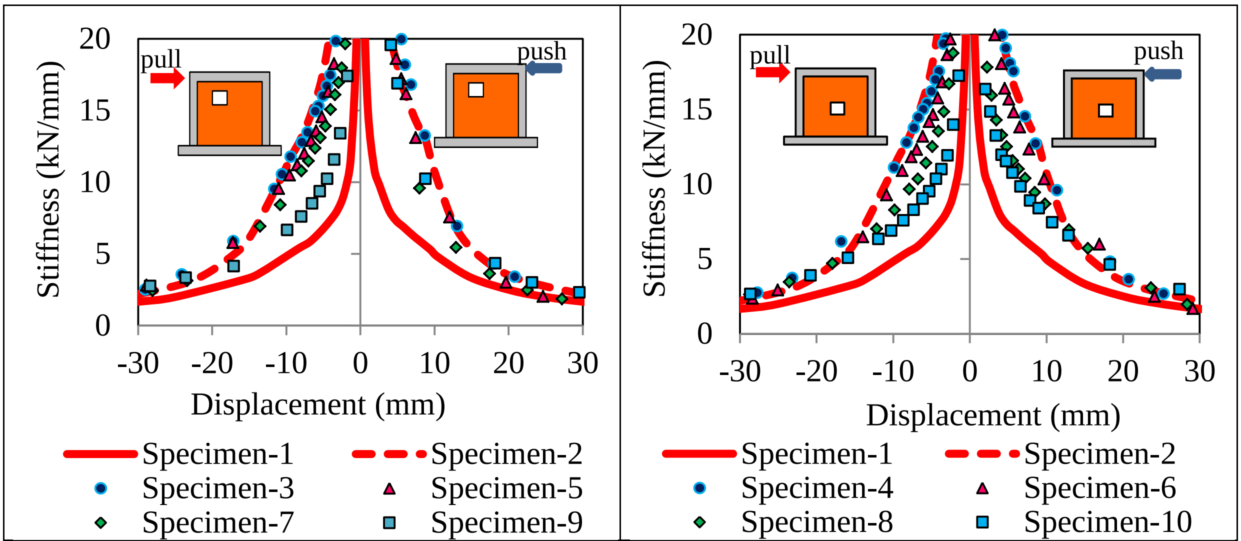
(a) (b)

Fig. 8. Envelope curves for all specimens



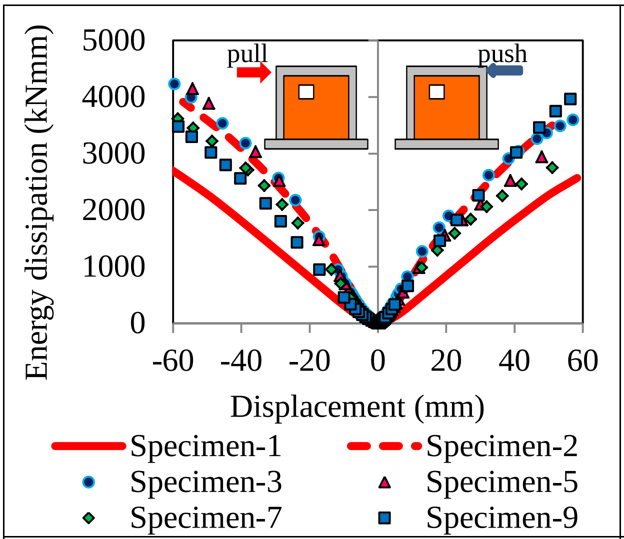
(a) (b)

Fig. 9. Lateral load capacities of all specimens

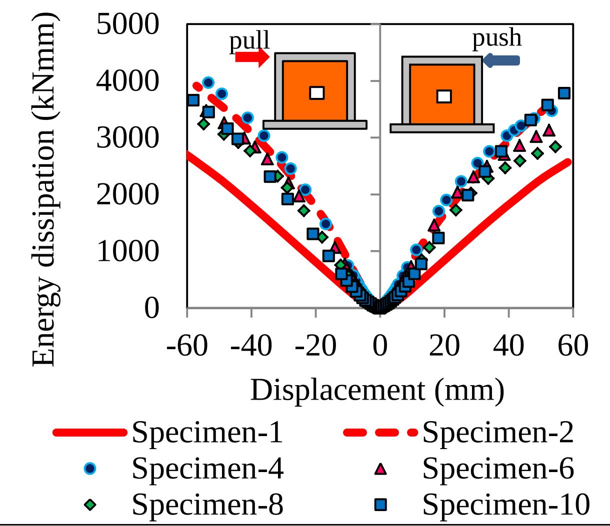


(a) (b)

Fig. 10. Variation of stiffness depending on displacement for all specimens



(a)



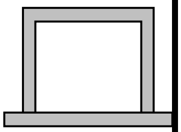
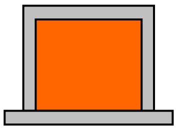
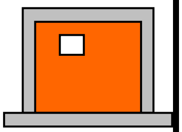
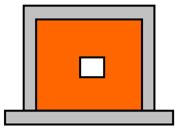
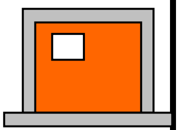
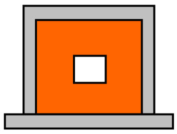
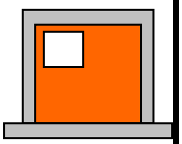
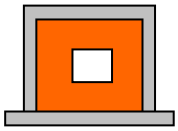
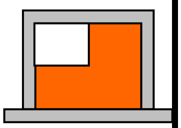
(b)

Fig. 11. Energy dissipation depending on displacement for all specimens

Table 1. Average values of the yield stress of the reinforcing bars

Bar diameter (mm)	f_{sy} (MPa)	f_{su} (MPa)
6	374	476
10	449	524
16	452	536

Table 2. Location and ratio of the opening on infill wall

Specimen ID	f_c (MPa) Frame	Opening percentage %	Opening position	Specimen ID	f_c (MPa) Frame	Opening percentage %	Opening position
Specimen-1	21	100		Specimen-2	20	0	
Specimen-3	23	4		Specimen-4	21	4	
Specimen-5	21	9		Specimen-6	21	9	
Specimen-7	22	16		Specimen-8	20	16	
Specimen-9	20	25		Specimen-10	22	25