Experimental Study of Masonry Infilled R/C Frames with Opening

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SUMMARY:
This paper presents results of a part of the Croatian research project "Seismic design of infilled frames". Within this part we have investigated the influence of different types and positions of opening in masonry infill, with and without tie-columns surrounding them, on the seismic response of R/C frames. Ten equal single R/C frames, designed and constructed according to Eurocode 2 and Eurocode 8, were built in a scale 1:2.5 and infilled with masonry walls. They were tested under constant vertical and a sequence of lateral load reversals till the infill failure (IDR =1%). The results showed that strength and stiffness properties were only slightly affected by opening position and type. Presence of the opening lowered energy dissipation capacity of the system. Without tie-columns an opening caused the infill subdivision and its sequenced failure mechanism. Tie-columns affected the infill's mechanism of failure, ductility, equalized the behaviour and prevented its out-of-plane failure.

Keywords: Opening, Masonry infill, R/C Frame, Cyclic Response, Experiment

1. INTRODUCTION

The application of r/c frames with masonry infill built after the frame is hardened, is classical in construction of low- and medium-rise buildings in South-eastern Europe. The knowledge, so far, on the influence of masonry infill, is contradictory and design guidelines take into account the negative contribution, while the positive contribution is neglected. Presence of openings in infill, with and without tie-columns surrounding them, and their influence to the seismic response of r/c frames with infill is the theme requiring special attention.

Kakaletsis et all, (2008) suggested that infill affected by opening could be resolved on subcomponents to be observed through rules for masonry, i.e. height to length ratio hints the type of failure. The opening in masonry infill could be executed with- or without surrounding ties. Influence of the ties brings additional questions in attempts to predict the response of "framed-walls", if the infilled-frames could be observed as one system. Taking the infill into account would be more realistic to the actual behaviour of buildings and a rationalization of the design could be achieved.

Within this study we have experimentally investigated the influence of different types and positions of opening in masonry infill, with and without tie-columns surrounding them, on seismic response of R/C frames, designed and constructed according to Eurocode 2 and Eurocode 8, tested under constant vertical and cyclic horizontal loading until the infill failure. Test results concern strength and stiffness properties in relation to storey drift in relation to bare frame specimen, and failure mechanism and crack distribution of the masonry infill.

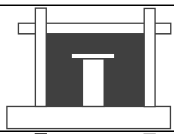
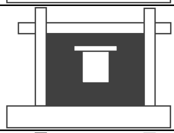
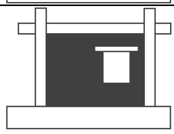
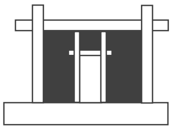
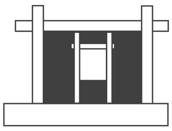
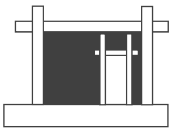
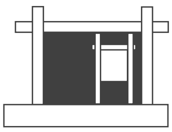
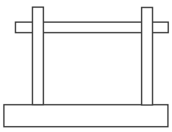
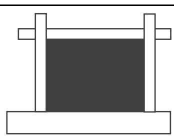
Reviewed experimental studies from the literature do not include the presence of the tie-columns around the opening in masonry infill, although design guidelines are recommending their construction when opening area is greater than 1,5 m^2.

2. EXPERIMENT

2.1. Test specimens and material properties

Ten reinforced-concrete one-story one-bay equal frame specimens were designed according to EC2 and EC8 produced and infilled with masonry. They represented a middle span of 7-storey R/C prototype structure scaled to 1:2.5 on the basis of a true model according to the complete similarity rule. The masonry infill in all specimens had the same mechanical properties and the opening size and position were used as parameters. The specimens were classified into three groups: Group I without confining elements around opening, Group II with confining elements around opening and Group III were reference specimens with- and without infill (Table 2.1).

Table 2.1 Overview of the test specimens

Test specimen			**Appearance of the Test Specimen**	**Type of Opening and Dimensions** l_o/h_o **(m)**	**Position of Opening and Distance** e_o **(m)**	**Confinement of Opening**
Group	**No.**	**Mark**				
I	1	Type (1/I)		Door (0,35/0,90 m)	Centric (0,90 m)	Without confining elements
	2	Type (2/I)		Window (0,50/0,60 m)	Centric (0,90 m) Parapet wall height is 0,40 m	
	3	Type (3/I)		Door (0,35/0,90 m)	Eccentric (0,44 m)	
	4	Type (4/I)		Window (0,50/0,60 m)	Eccentric (0,51 m) Parapet wall height is 0,40 m	
II	1	Type (1/II)		Door (0,35/0,90 m)	Centric (0,90 m)	With confining elements
	2	Type (2/II)		Window (0,50/0,60 m)	Centric (0,90 m) Parapet wall height is 0,40 m	
	3	Type (3/II)		Door (0,35/0,90 m)	Eccentric (0,44 m)	
	4	Type (4/II)		Window (0,50/0,60 m)	Eccentric (0,51 m) Parapet wall height is 0,40 m	
III	1	Type (1/III)		-	-	Reference specimens
	2	Type (2/III)		-	-	

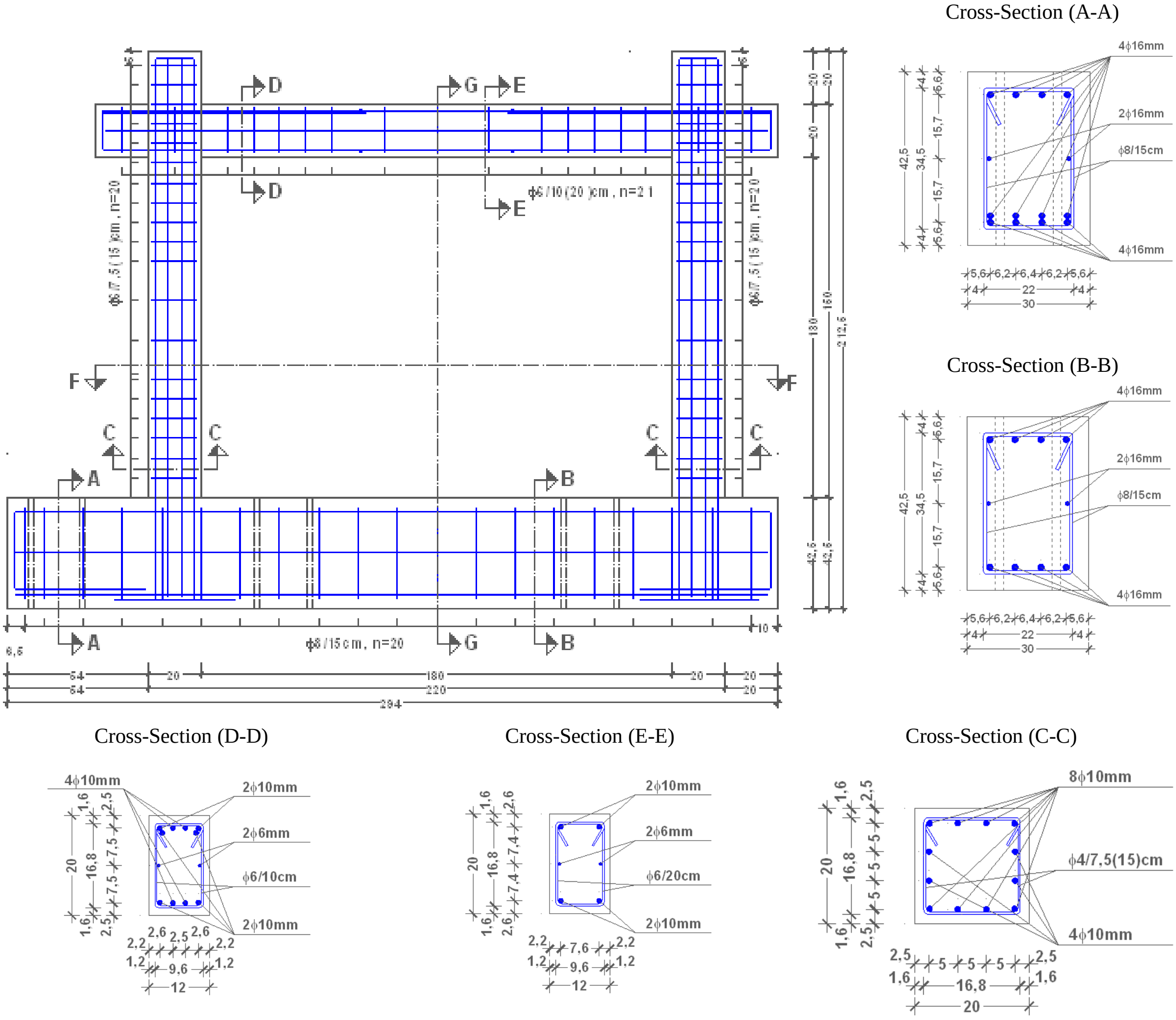


Figure 2.1 Dimensions and reinforcement of r/c frame elements and cross-sections

Geometry of the R/C frame specimens along with the reinforcement are given in Figure 2.1.

Vertical r/c ties (when present) were reinforced with two longitudinal bars of diameter ø8 mm, each. Those bars where anchored in r/c beam elements with anchoring depth of 10 cm. The ties were connected with masonry by dowels ø4 mm anchored in masonry mortar joints every 20 cm.

Lintel, in both opening's cases (door or window), was reinforced with four longitudinal bars ø6 mm and with ø6 mm spaced at 9 cm.

Mechanical properties of the constituent materials were determined experimentally (Table 2.2). Properties of concrete, mortar, masonry blocks and infill walls were obtained according to European codes. Masonry units belonged to group IIb according to Eurocode 6 and mortar compressive strength was M5.

Table 2.1 Mechanical properties of the constituent materials

Material	Property		Value	Units
Hollow-clay-tile	Normalized compressive strength in vertical direction	f_b	15,9	N/mm^2
	Normalized compressive strength in horizontal direction	f_{bh}	2,6	N/mm^2
General purpose mortar	Compressive strength	f_m	5,15	N/mm^2
	Bending-tensile strength	f_{mt}	1,27	N/mm^2
Masonry	Characteristic compressive strength	f_k	2,7	N/mm^2
	Elastic modulus	E	3900	N/mm^2
	Ultimate strain	ε_u	0,57	‰
	Characteristic initial shear strength	f_{v0k}	0,7	N/mm^2
	Characteristic angle of friction	$\tan\alpha_k$	0,8	N/mm^2
Frame concrete	Characteristic compressive strength	$f_{ck,cube}$	45	N/mm^2
Longitudinal and transversal reinforcement	Characteristic yield strength	f_{yk}	600	N/mm^2
	Characteristic ultimate strength	f_{uk}	700	N/mm^2
	Elastic modulus	E_s	210000	N/mm^2
Tie-column concrete	Characteristic compressive strength	$f_{ck,cube}$	30	N/mm^2

2.2. Testing procedure and equipment

The arrangement of measuring and loading equipment and boundary conditions for all test specimens are presented in Figure 2.2. Vertical loading was applied on top of the columns and horizontal at the beam ends. Displacement of r/c columns in vertical upward direction was prevented by steel support beam, while it remained possible for them to move horizontally through rolling supports. The base beam was anchored to the strong floor. Tests were conducted under constant vertical and cyclic horizontal loading with an increment of ΔF_H=10,0 kN. Vertical load was kept constant at the value of F_V=365,0 kN, by means of a pressure valve, throughout the test. The test was run as force controlled until the specimen became flexible and then was switched to displacement controlled until the infill's failure occurred. The force and displacement values were constantly monitored using the transducers located in front of the press and on the beam ends.

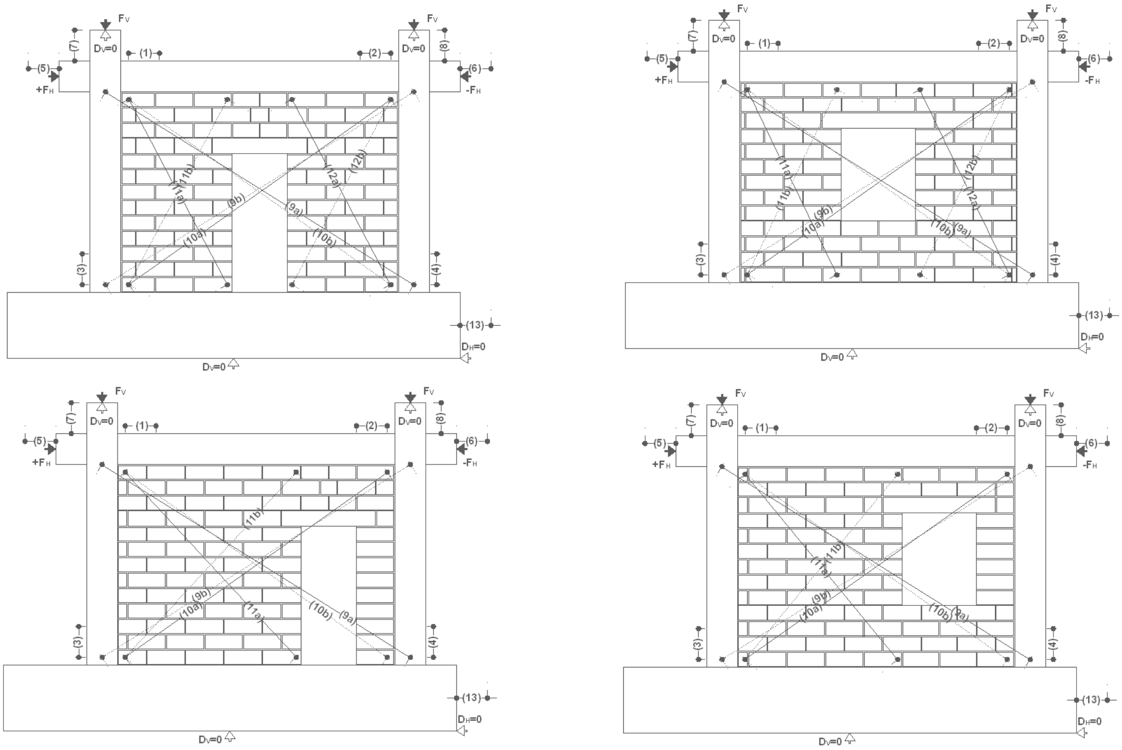


Figure 2.2 Arrangement of testing equipment and boundary conditions

Measured were forces, horizontal displacements on the left (mark 5) and right end of the beam (6), vertical displacements (7 and 8), diagonal elongations of the frame (9a and 9b) and of the masonry infill (10a and 10b). The indexes (a) and (b) denote front and back of the specimen. On the specimens with openings additionally were measured diagonal elongations of the masonry piers on one (11a and 11b) and/or other side of the opening (12a and 12b). In the case of eccentric opening measuring devices 12a and 12b were not placed. Local deformations were measured at the column's bottom and at the expected beam's hinge location (1-4). Possible movement of the base beam was additionally monitored and taken into account for analysis results. Visually were observed and registered cracking of the masonry and of the frame, as well as, all other significant phenomena occurring during the testing.

3. EXPERIMENTAL RESULTS

The failure type of each model is described by basic modes of failure: bending, shear (diagonal) and horizontal shear failure. Failure was concentrated to the infill and during all tests no shear cracks or any other significant cracks on r/c frames were observed. The observed damage was described according to the FEMA 306 damage classification guide for masonry infill panels as insignificant, moderate and heavy (Table 3.1).

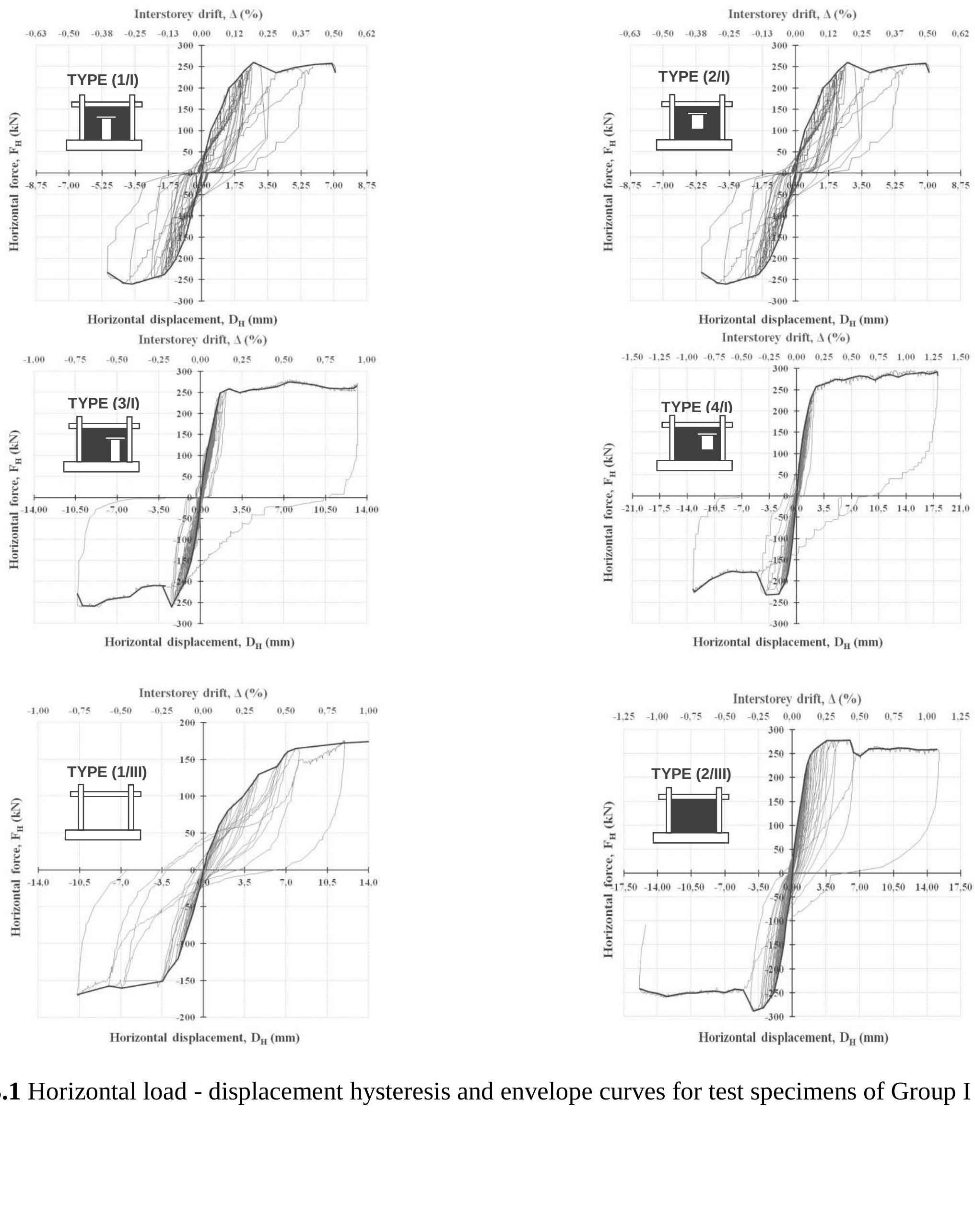


Figure 3.1 Horizontal load - displacement hysteresis and envelope curves for test specimens of Group I and III

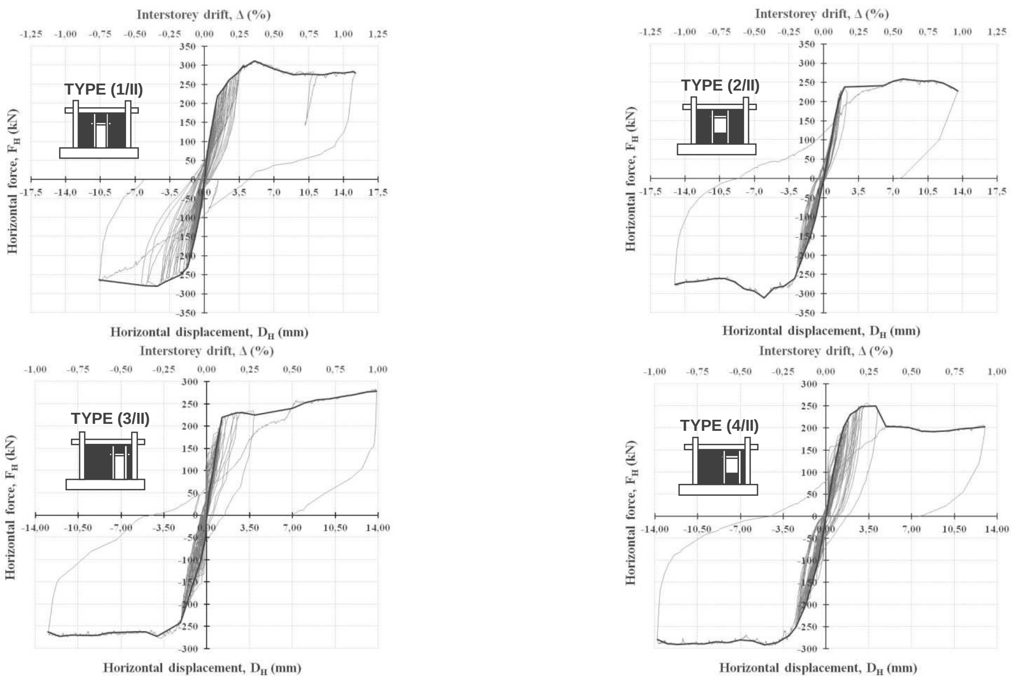


Figure 3.2 Horizontal load - displacement hysteresis and envelope curves for test specimens of Group II

The overall results, in terms of the Inter-story drift ratio (Δ%), Lateral load (V), and Failure mechanism, are presented in Table 3.1 for every specimen.

Table 3.1 Overview of the test specimen damage and failure mechanism

Test specimen type	Insignificant damage		Moderate damage		Heavy damage		Collapse		Failure mechanism
	Δ_L (%)	V_L (kN)	Δ_M (%)	V_M (kN)	Δ_H (%)	V_H (kN)	Δ_U (%)	V_U (kN)	
1/I	0,10	200,0	0,19	260,0	0,35	248,0	0,50	236,0	Two piers and spandrel were formed due to bed-joint sliding in the plane bellow lintel. Pier had dominant bending failure.
2/I	0,11	180,0	0,18	280,0	0,49	310,0	1,29	250,0	Two piers and two spandrels were formed due to bed-joint sliding in the plane above and below opening. Pier had dominant shear failure.
3/I	0,09	180,0	0,18	258,0	0,57	272,0	0,93	260,0	Two piers and two spandrels were formed due to bed-joint sliding in the plane above and below opening. Pier had dominant shear failure.
4/I	0,10	200,0	0,22	261,0	0,58	283,0	1,30	292,0	Two piers and two spandrels were formed due to bed-joint sliding in the plane above and below opening. Pier had dominant shear failure.
1/II	0,10	220,0	0,16	261,0	0,57	283,0	1,07	283,0	Pier had dominant bending failure.
2/II	0,09	170,0	0,16	239,0	0,43	242,0	1,07	275,0	The bending failure of the pier was predominant.
3/II	0,10	220,0	0,21	230,0	0,50	240,0	0,99	279,0	The pier had dominant shear failure
4/II	0,08	150,0	0,15	230,0	0,36	292,0	0,99	280,0	The pier had dominant shear failure
1/III	-	-	-	-	-	-	-	-	The r/c frame yielded at the lateral load of 172,0 kN
2/III	0,09	150,0	0,16	257,0	0,42	278,0	1,09	288,0	Bed-joint sliding failure occurred. The r/c frame yielded at the lateral load of 260,0 kN

4. BILINEAR IDEALISATION

In order to simplify the results, the actual hysteresis envelope curves of the specimens subjected to the constant vertical and a sequence of lateral load reversals was represented by the bilinear envelope. The envelope was obtained by equalizing the area above and below the hysteresis envelope curve for the positive and negative loading cycle. The key parameters were: lateral cracking load and displacement at infill collapse (case dependent). Both curves are presented in Figures. 4.1. and 4.2.

4.1. Effective lateral loads

The effective crack (V_{cr}), yield (V_y) and ultimate (V_u) lateral load and corresponding drifts are given in Table 4.1.

Table 4.1 Effective lateral loads and drifts

Test specimen type	Positive cycle						Negative cycle					
	V_{cr} (kN)	Δ_{cr} (%)	V_y (kN)	Δ_y (%)	V_u (kN)	Δ_u (%)	V_{cr} (kN)	Δ_{cr} (%)	V_y (kN)	Δ_y (%)	V_u (kN)	Δ_u (%)
1/I	153	0,08	255	0,14	247	0,50	-153	-0,07	-255	-0,11	-237	-0,35
2/I	173	0,07	288	0,12	310	0,52	-176	-0,08	-293	-0,14	-262	-1,29
3/I	157	0,06	261	0,10	265	0,93	-124	-0,04	-206	-0,07	-254	-0,75
4/I	157	0,07	262	0,11	291	1,29	-99	-0,04	-165	-0,06	-229	-0,93
1/II	168	0,07	280	0,11	283	1,07	-145	-0,06	-242	-0,11	-264	-0,76
2/II	153	0,08	256	0,13	227	0,97	-165	-0,11	-275	-0,19	-275	-1,07
3/II	124	0,04	207	0,07	280	0,99	-162	-0,09	-270	-0,14	-262	-0,93
4/II	131	0,06	218	0,09	201	0,93	-172	-0,10	-286	-0,16	-281	-0,98
1/III	84	0,20	141	0,33	172	1,00	-86	-0,11	-144	-0,18	-167	-1,00
2/III	163	0,07	271	0,12	253	1,09	-161	-0,07	-268	-0,12	-242	-1,13

4.2. Effective stiffness and energy dissipation capacity

The effective lateral stiffness (K_e) was calculated as initial slope of the idealised bilinear curve and post-yield stiffness (αK_e) as slope of the second part. Energy dissipation capacity was calculated as the hysteresis damping of experimentally obtained hysteresis curves for a certain drift (yield drift > $E_{i,y}$ and ultimate drift > $E_{i,u}$).

Table 4.2 Effective stiffness and energy dissipation capacity

Test specimen type	Positive cycle		Negative cycle		Positive cycle		Negative cycle	
	K_e (kN/mm)	αK_e (kN/mm)	K_e (kN/mm)	αK_e (kN/mm)	$E_{i,y}$ (kN-mm)	$E_{i,u}$ (kN-mm)	$E_{i,y}$ (kN-mm)	$E_{i,u}$ (kN-mm)
1/I	133,89	-1,55	167,07	-5,39	774,42	6757,90	609,43	5706,25
2/I	168,12	3,86	151,76	-1,93	2030,64	7139,53	2283,41	10269,34
3/I	193,23	0,30	202,63	5,12	107,13	3531,97	69,84	6206,13
4/I	163,05	1,81	188,93	5,23	1370,90	7658,51	1099,39	10343,99
1/II	176,86	0,17	159,91	2,44	863,79	8844,96	912,51	10574,33
2/II	143,74	-2,42	105,59	0,05	1453,10	8386,29	1580,47	5124,62
3/II	200,31	5,66	135,69	-0,70	397,71	5151,64	427,32	2444,88
4/II	166,53	-1,45	126,35	-0,48	111,25	7341,45	164,97	4975,58
1/III	28,14	2,14	57,07	2,88	700,64	4235,72	1022,10	4436,45
2/III	167,45	-1,37	162,05	-1,81	465,80	9177,11	1657,50	13176,72

The effective lateral stiffness of the r/c frames with infill was 4 to 6 times higher and the capacity was 40 to 80% higher than that of the bare frame.

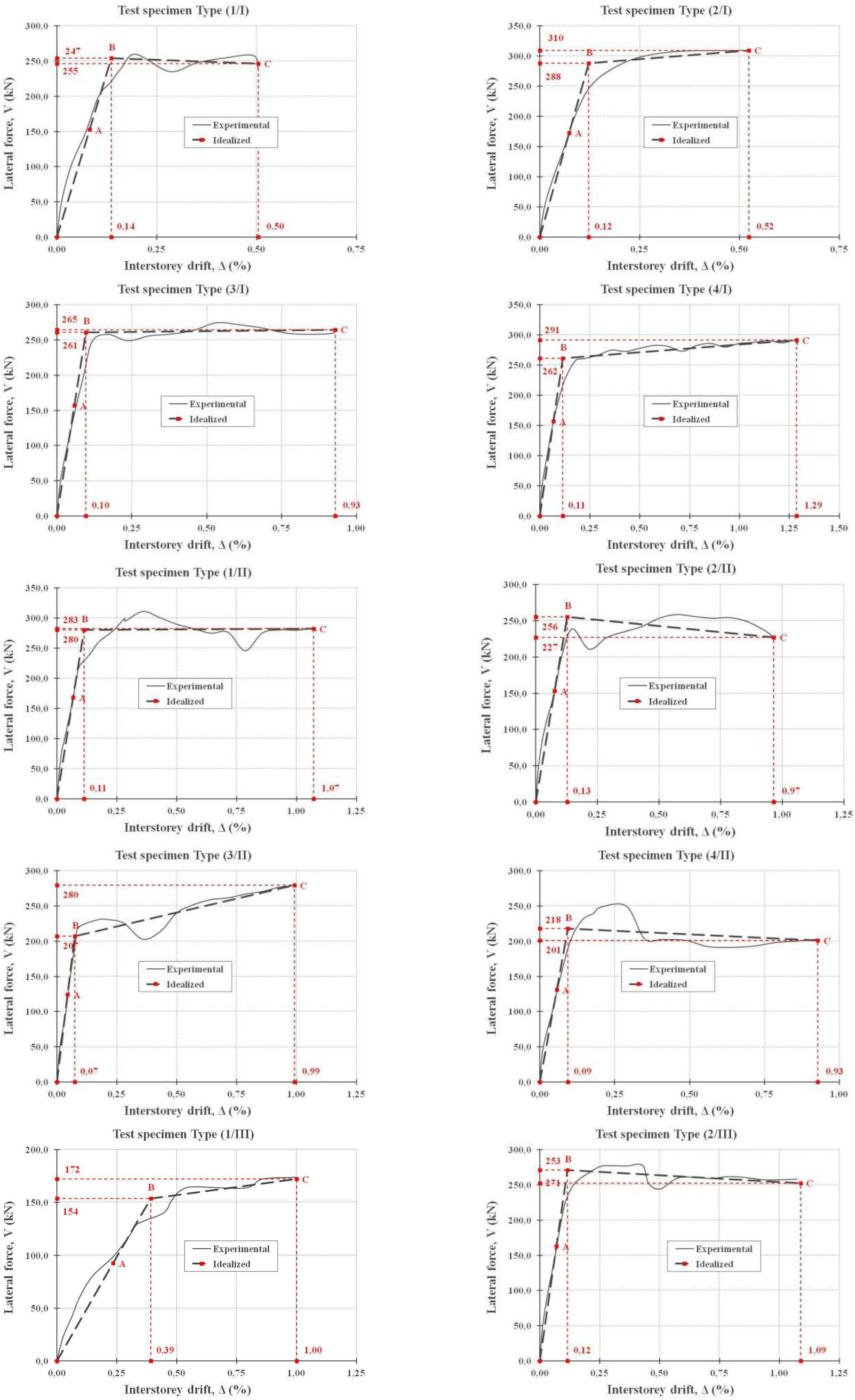


Figure 4.1 Bilinear idealisation of the positive cycle envelope curves

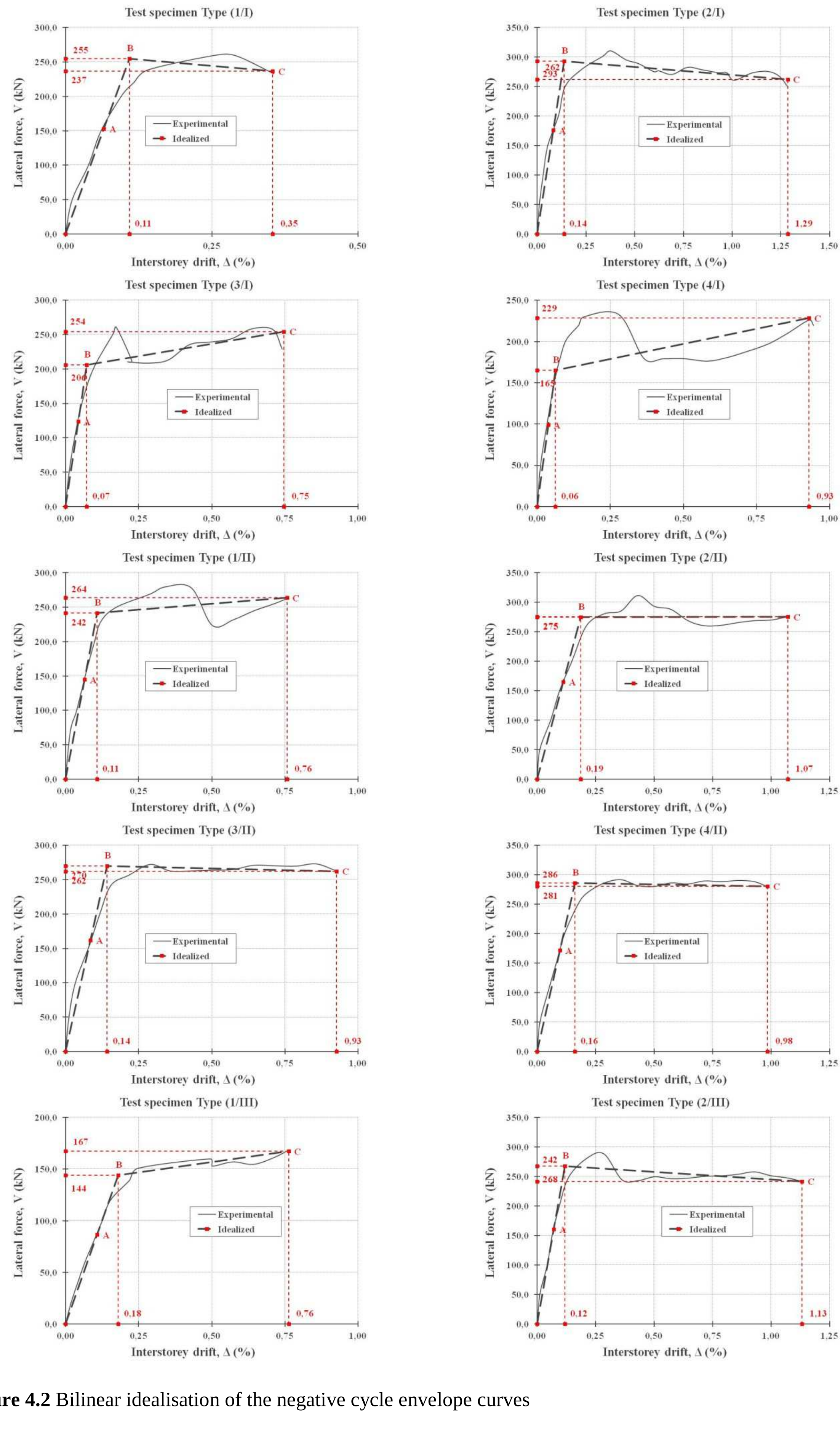


Figure 4.2 Bilinear idealisation of the negative cycle envelope curves

5. CONCLUSIONS

All reinforced-concrete frame specimens with masonry infill (“Framed-wall”), with and without opening, in the observed deformation range (IDR<1,0%) had higher strength and stiffness compared to the bare r/c frame specimen. The stiffness and capacity of specimens with opening in masonry infill was not much different to the one without opening. Presence of the opening lowered hysteresis dissipation capacity of the system. Failure mode of the infill was determined by failure of the pier. The specimens with openings in infill without vertical confining elements, showed a sequence of multiple failure modes influenced by the opening’s dimensions (especially height). Addition of the tie-columns prevented sudden and out of plane failure of the infill piers. Addition of the tie-columns around opening did not influence the overall stiffness and capacity of the “framed-masonry” specimens. Tie-columns affected the mechanism of failure and ductility and equalized the behaviour of the infill.

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