Influence of masonry strength and rectangular spiral shear reinforcement on infilled RC frames under cyclic loading

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Abstract

The effect of two types of shear reinforcement of the concrete members and two types of masonry infills on the seismic performance of reinforced concrete (RC) frames was experimentally investigated. Six single-story, one-bay, 1/3-scale frame specimens were tested under cyclic horizontal loading, up to a drift level of 40‰. Bare frames and infilled frames with weak and strong infills were sorted into two groups: Specimens of group A had stirrups while specimens of group B had spirals respectively, as shear reinforcement. The frames were designed in accordance with modern codes provisions. The types of masonry infills had different compressive strength but almost identical shear strength. Infills were designed so that the infill lateral cracking load is less than the available column shear resistance. The results from the specimens of group A were compared with the results from specimens of group B, in terms of hysteretic response, ductility and energy absorption. From the observed responses of the tested specimens it can be deduced that the use of rectangular spiral reinforcement in the beam and columns, even in the case of strong infills, improved the seismic capacity of the examined infilled RC frames.
Keywords: infilled R/C frames, masonry strength, spiral shear reinforcement.

1 Introduction

From the experimental investigations that were carried out by several researchers, [1–4], it has been shown that the presence of infill panels improves the seismic performance of a frame. The stronger the infill and the frame is, the higher is the seismic resistance (Mehrabi *et al* [5]). However the brittle shear failure of columns which might jeopardise the stability and repairability of a

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structure must be avoided. The results also suggest that infill panels can be used for retrofitting existing RC structures. In this case, new panels must be designed in such a way that their strength will be compatible with those of the columns (Klingner and Bertero [6]). Therefore, the infilled frame is suggested to be designed to prevent or delay shear failure of the frame members, by designing them for high resistance to cycles of shear reversal, and by examining closely the relationship between column shear resistance and infill panel strength. The above demands must be satisfied by high percentages of transverse steel used in the beams and columns in excess of the proper concrete section and panel thickness. Henceforth, it is obvious that the improvement of the concrete response in terms of the confinement of frame members would help to the improvement of the total seismic response of the infilled frame.

On the other hand it is generally accepted that the use of continuous spiral reinforcement in concrete elements with cyclic cross section can substantial improve the strength and the ductility of the concrete and henceforth the total seismic response and capacity of the structural element (Park and Paulay [7]). International codes in these cases propose increased performance factors for the concrete confinement (ACI 318, EC8). The extension of the use of continuous spiral reinforcement in elements with rectangular cross sections is a new promising technology that is believed it can improve the seismic capacity of structures. Considering that the application of the Rectangular Spiral Reinforcement (RSR) could contribute to the improvement of the external beam-column joint properties (Karayannis *et al* [8]) it is expected to contribute to the total improvement of the response of infilled frames.

In this paper the experimental results that are presented are a part from an experimental program that has the aim to investigate the performance of masonry – infilled RC frames under in-plane lateral cyclic loads. The objects of the present paper were mainly of: (a) Finding the effect of two types of shear reinforcement that is spirals and equally spaced stirrups, on the hysteretic characteristics of infilled frames. (b) Examining the behavior of two types of masonry infills that is weak and strong, under identical geometry and loading conditions.

2 Experimental program

2.1 Test specimens

The experimental program as shown in table 1 consisted of testing six single-story, one-bay, 1/3-scale specimens of reinforced concrete frames. Specimens B and BS were bare frames, one with transverse steel in the form of common stirrups and one with continuous rectangular spiral reinforcement of the same spacing. Specimens S and SS were infilled frames with a solid weak infill of clay bricks, one with transverse steel in the form of common stirrups and one with continuous rectangular spiral reinforcement of the same spacing. Specimens IS and ISS were infilled frames with a solid strong infill of vitrified ceramic bricks,

Table 1: Test specimens.

Group	Specimen	Masonry type			Shear reinforcement type	
		Bare frame	Weak	Strong	Common stirrups	Rectangular spirals
A	B	■			■	
	S		■		■	
	IS			■	■	
B	BS	■				■
	SS		■			■
	ISS			■		■

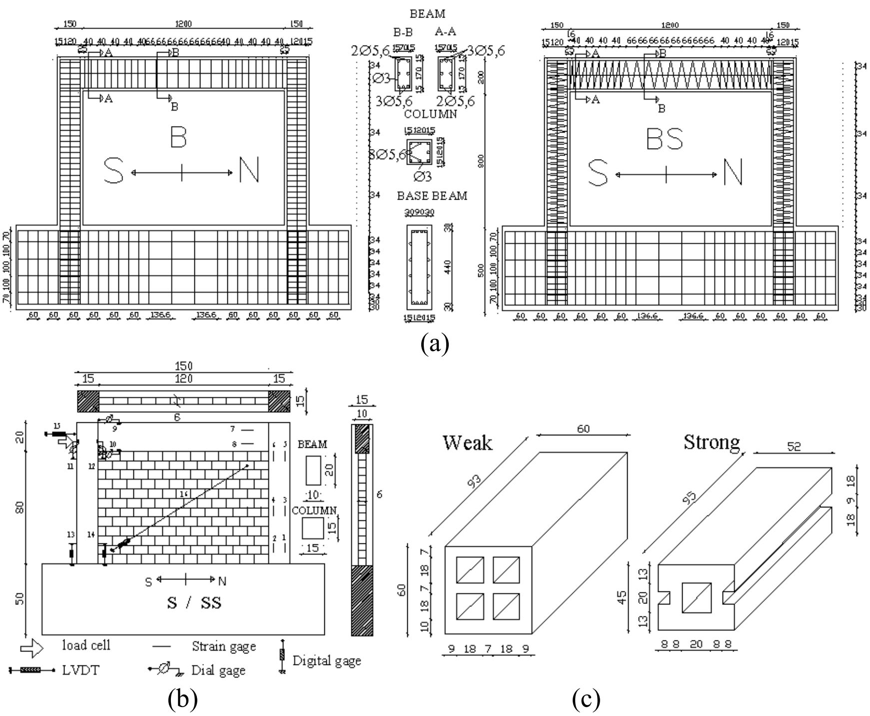


Figure 1: Description of infilled frame specimens: (a) Reinforcement detailing of the RC frame models (mm); (b) Infilled frame and instrumentation (cm); (c) Weak and strong brick units (mm).

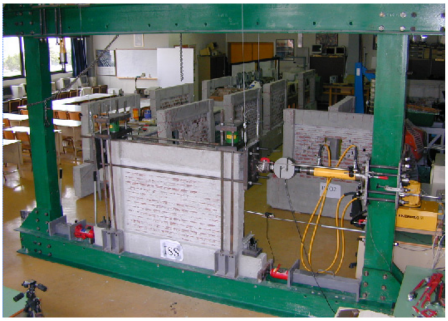
one with transverse steel in the form of common stirrups and one with continuous rectangular spiral reinforcement of the same spacing. The geometric characteristics of the RC frames were the same for all specimens. The elevation, the corresponding cross-sections of the members and the design details for the RC frame specimens are shown in figs. 1a, b. The reinforced concrete frame represented typical ductile concrete construction, particularly structures built in accordance to currently used codes and standards in Greece. Masonry infills had a height/length ratio h/*l* = 1/1,5 and were constructed with two selected brick types cut into two halves for complete simulation to the test scale. Their configuration is shown in fig. 1c. The former "weak" common clay brick usually used in Greece had a thickness 60 mm, while the latter "strong" vitrified ceramic brick that felt to be important for the specimen behavior had a thickness 52 mm. A representative mortar mix was used for the two types of infills contained the portions 1:1:6 (cement: lime: sand) and produced mechanical properties similarly to type M1 mortar according to EN 998-2 standard. Masonry properties were chosen in such a way to produce the desired lateral strength of the two types in a magnitude $V_{w,u}$ = 27.36 or 25.58 KN lower than that of the lateral strength of the frame $V_{f,u}$ = 40.28 KN as presented in the following paragraph. This closely represents actual construction in Greece.

2.2 Material properties

Material tests were conducted on concrete, reinforcing steel and masonry samples. The mean compressive strength of the frame concrete was 28.51 MPa. The yield stress of longitudinal and transverse steel was 390.47 and 212.2 MPa respectively. The main results of mortar, bricks and infill masonry tests are presented in table 2. It can be noted from the table that the compressive strength of the "weak" masonry prisms was considerably lower than those of the "strong" while the shear strength of the bed joints in the "weak" and "strong" specimens with the same to the full size infills length / height ratio (l/h = f_v/f_n = 1.5/1) was almost identical.

Table 2: Mechanical properties of the materials used (MPa).

Material Properties		Masonry type	
		Weak t = 6 cm	Strong t = 5.2 cm
MORTAR			
Compressive Strength	f_m	1.53	1.75
BRICK UNITS			
Compressive Strength	f_{bc}	3.1	26.4
MASONRY			
Compressive Strength ⊥ to hollows	f_c	2.63	15.18
Elastic Modulus ⊥ to hollows	E	660.66	2837.14
Compressive strength // to hollows	f_{c90}	5.11	17.68
Elastic Modulus // to hollows	E_{90}	670.3	540.19
Friction Coefficient	μ (rads)	0.77	0.957
Shear Modulus	G	259.39	351.37
Shear Strength without normal stress	f_{vo}	0.08	0.12
Shear Strength with normal stress	f_v/ f_n	0.38*/0.25*	0.41*/0.27*
* *On full size infills*		0.33/0.22	0.26/0.17
		0.39/0.30	0.60/0.61
		0.21/0.37	0.39/0.72
		0.20/0.73	0.41/1.55



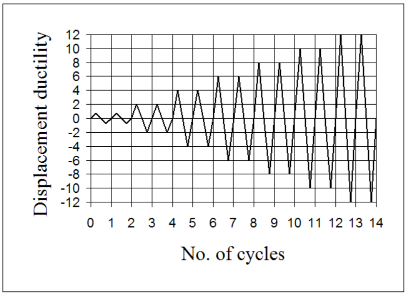


Figure 2: Test setup of specimen SS and loading program.

2.3 Test setup and instrumentation

The test setup is shown in fig. 2. The lateral load was applied by means of a double action hydraulic actuator. The vertical loads were exerted by manually controlled hydraulic jacks that were tensioning four strands at the top of the column whose forces were maintained constant during each test. The level of this axial compressive load per column was set 50 KN (0.1 of the ultimate). One LVDT measured the lateral drift of the frame and a load cell measured the lateral force of the hydraulic actuator. The loading program included full reversals of gradually increasing displacements. Two reversals were applied for each displacement level. The cycles started from a ductility level 0.8 corresponding to an amplitude of about ±2 mm (the displacement of yield initiation to the system is considered as ductility level μ=1) and were followed gradually by ductility levels 2, 4, 6, 8, 10, 12 corresponding about to amplitudes 6, 12, 18, 24, 30, 36 mm (fig. 2).

3 Experimental results

The main output of the experimental investigation was a load – displacement curve for each frame (figs. 3, 4, 5a). The initial stiffnesses, critical loads, energy dissipation capacities and critical displacements attained during the tests of the six specimens were derived. It must be pointed out that the hysteretic characteristics of the weak masonry infill were some times larger because of the larger net bedded area for the weak masonry units. The appearance and propagation of cracking was also recorded for both infill and frame throughout each test (figs. 3, 4).

Specimens “B” and “BS” were bare reference frames. Flexural cracks and corresponding plastic hinges occurred at predicted critical locations at the bottom and the top of the columns and the ends of the beam – at a drift 4-6‰ – (figs. 3a, 4a).

Specimens “S”, “SS” and “IS”, “ISS” had solid weak and solid strong infill respectively. The nonlinear behavior was initiated by the cracking of the infill. Then developed plastic hinges at the top and the bottom of the columns – at a drift 4-11‰ –. However, as shown by the damage patterns of specimens, the failure of the specimens “S” and “SS” with the weak solid infill (figs. 3d, 4d) was dominated by internal crushing in the infill – at a drift 19‰ – while the failure of the specimens “IS” and “ISS” with the strong solid infill (fig. 3f, 4f) was dominated by sliding of the infill along its bed joints – at a drift 14‰ –.

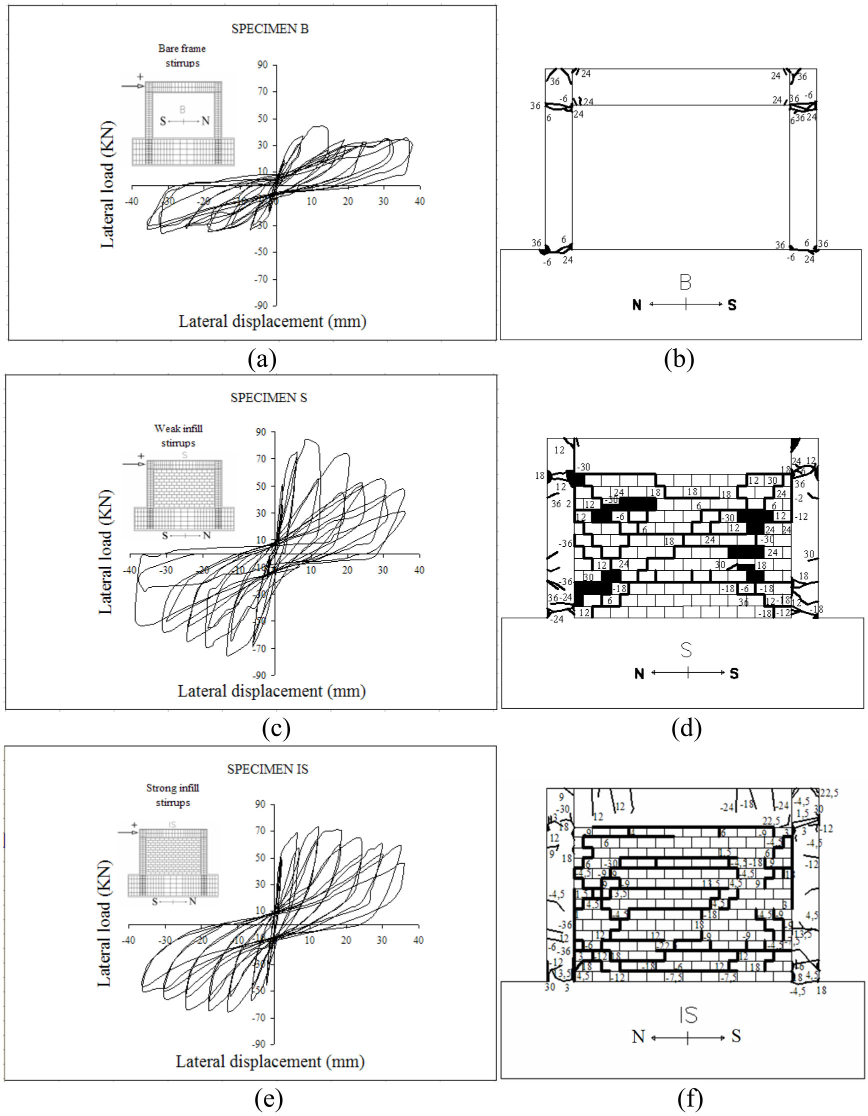


Figure 3: Lateral load – displacement hysteresis curves and failure modes of specimens of group A with stirrups: (a), (b) Bare frame; (c), (d) Weak solid infill; (e), (f) Strong solid infill.

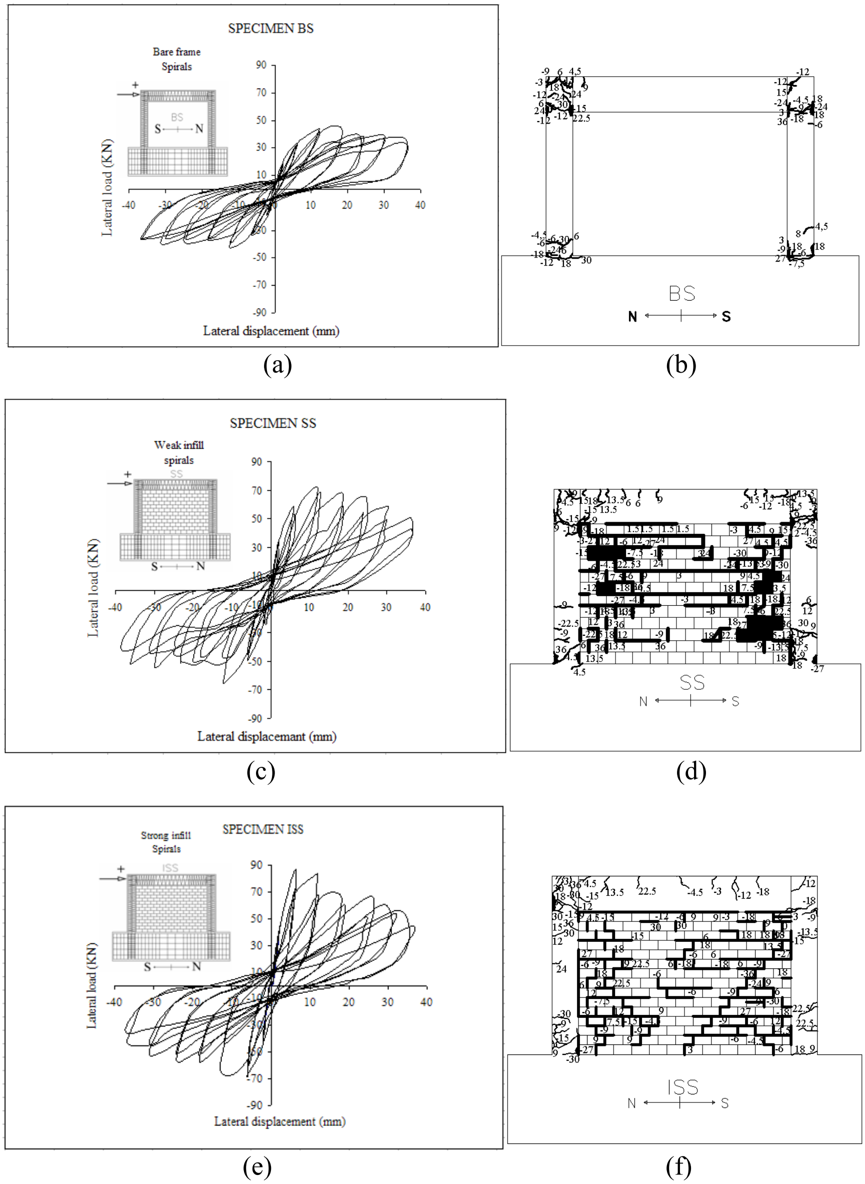


Figure 4: Lateral load – displacement hysteresis curves and failure modes of specimens of group B with spirals: (a), (b) Bare frame; (c), (d) Weak solid infill; (e), (f) Strong solid infill.

In all infilled specimens the cracking of the beam occurred far from the column face towards the mid – span vicinity of the beam. Plastic hinges were developed at drifts higher than 11‰ or they did not developed at all. Generally the infills restrained the beams from bending and, there by, postpone the development of plastic hinges in the beams. In the case of the present project shear failure of the columns was not observed.

4 Interpretation of experimental results

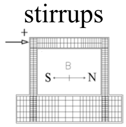
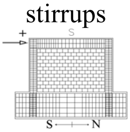
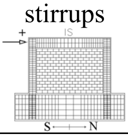
From the data shown in Table 3 it can be concluded that:

For all cases lateral resistance (v) of infilled frames was from 1.63 up to 1.94 times that of the corresponding bare frames. Spirals increased resistance as far strong infills only. The residual resistance (β_{res}) was observed to be increased in the case of strong infills. Spirals did not influence very much residual resistance. The presence of strong infills increased considerably the initial stiffness (k) of the system. Spirals decreased the initial stiffness. It should be noted that the confinement type of the surrounding frame members, did not influence considerably the limit states which had been regarded corresponding to the drifts (γ_y) and (γ_u). Only the specimen with strong infill of group B had ultimate limit occurring at a much lower drift level than that of group A. The presence and behavior of spirals increased the ductility factor ($\mu_{0,85}$), corresponding to a lateral force response equal to 85% of the maximum, only in the bare frame while the specimens with infills exhibited higher ductility than that of the bare frames. The total energy dissipation capacity (ΣW) of the infilled frames was of order 1,44 up to 1,64 times the capacity of the corresponding bare frames. It must be pointed out that infill strength and type of shear reinforcement did not influence very much the values of dissipation ratio. Specimens with strong infills and spirals seemed to loose a larger amount of strength and energy during the second loading cycle.

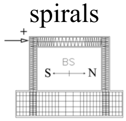
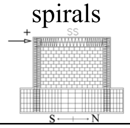
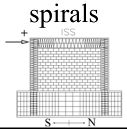
From fig. 5b, it can be concluded that in all specimen cases spirals lessened the loss of stiffness. Strong infills increased the loss of stiffness because of different failure mechanism respectively to that of weak infills. From fig. 5c and fig. 5f it can be concluded that strong infills resulted in higher values of average added strength and average added energy dissipation to the system due to infills, especially at low displacement ranges, because those infills developed a better distribution of cracking than weak infills. Almost in all specimen cases, spirals lessened the effectiveness of an infill in increasing the lateral strength and the energy dissipation capacity of a frame. From the cumulative energy dissipated per cycle shown in fig. 5d it can be concluded that the contribution of spirals to energy dissipation capacity of the system seems to be slightly greater than the contribution of stirrups only at very high distortions and only in bare frame and frame with strong infill. Infill strength did not influence very much the dissipation capacity. From fig. 5e it is evident that the energy dissipation during a given cycle normalized by the total peak-to-peak displacement variation for that cycle was greatest just prior to crushing of the critical equivalent compression struts at about γ=13‰-20‰ in weak infills and prior to shear sliding at about γ = 7‰ in strong infills coinciding with the formation of plastic hinges in frame elements. After this, dissipation dropped with a steeper branch in the case of weak infills or with a smoother branch in the case of strong infills and continued to decrease gradually with increasing deflections, tending to reach the values of the corresponding bare frame. Spirals in bare frame at high distortion levels resulted in higher normalized energy dissipation capacity.

Table 3: Comparison of hysteretic characteristics for test specimens.

(a)

Spec.	Structural Morphology	v	γ_y (‰)	γ_u (‰)	k	v_{lim}	$\mu_{0,85}$	β_{res}	V_2/V_1 (m. v.)	W_2/W_1 (m. v.)	$\Sigma W/\Sigma W_B$
B	Bare frame stirrups 	1.00	5.06	12.09	1.00	0.74	2.81	1.00	0.89	0.84	1.00
S	Weak infill stirrups 	1.84	2.82	9.23	2.88	0.65	4.24	1.40	0.87	0.85	1.64
IS	Strong infill stirrups 	1.65	3.10	13.69	3.04	0.84	6.31	1.75	0.87	0.70	1.48

(b)

Spec.	Structural Morphology	v	γ_y (‰)	γ_u (‰)	k	v_{lim}	$\mu_{0,85}$	β_{res}	V_2/V_1 (m. v.)	W_2/W_1 (m. v.)	$\Sigma W/\Sigma W_{BS}$
BS	Bare frame spirals 	1.00	3.44	15.50	1.00	0.54	3.97	1.00	0.90	0.70	1.00
SS	Weak infill spirals 	1.63	2.77	13.33	1.92	0.51	4.09	1.47	0.87	0.79	1.46
ISS	Strong infill spirals 	1.94	3.33	6.81	2.36	0.65	3.36	1.56	0.87	0.70	1.44

v: Lateral norm. resistance, β_{res}: Residual nor. resistance, γ_y: Serviceability limit, γ_u: Ultimate limit, k: In. norm. stiffness, $\mu_{0,85}$: Ductility factor, ΣW: cumulative energy, V: max. Recorded force, W: Energy dissipation, 1/2: $1^{st}/2^{nd}$ cycle.

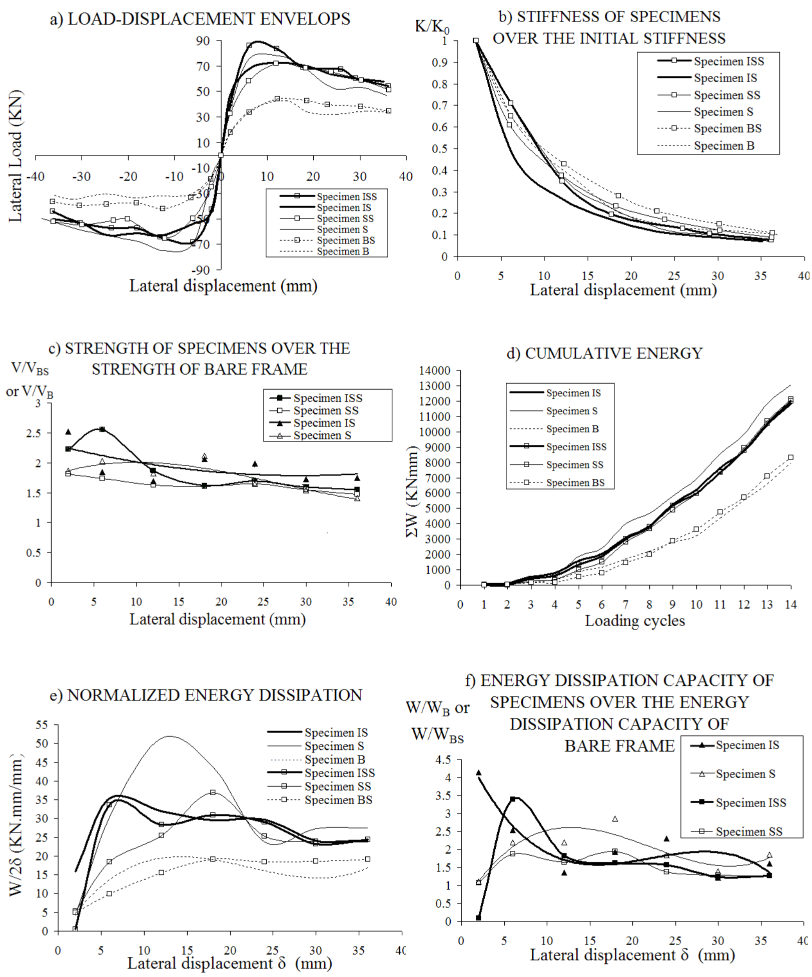


Figure 5: Comparison of hysteretic characteristics versus imposed displacements.

5 Conclusions

The authors have carried out investigations on several bare frames and infilled frames with weak and strong infills that were sorted into two groups based on the shear reinforcement, providing data for a parametric evaluation of different shear reinforcement and different infill compressive strengths.

The experimental results indicated that the presence, behavior and failure of the infills can significantly improve the performance of RC frames. As long as the infilled frames are designed so that the infill cracking resistance will be less than the combined available shear resistance of the columns, the use of infills does not cause a brittle frame failure.

Furthermore specimens with strong infills exhibited a better performance than those with weak infills in terms of the load resistance, stiffness, ductility and energy – dissipation capacity. Strong infills exhibited a better distribution of cracking than weak infills and, thereby, a more drastic mechanism of energy dissipation.

The extension of the use of continuous spiral reinforcement in elements with rectangular cross sections is a new promising technology that is believed it can improve the seismic capacity of structures. However, considering that the application of the Rectangular Spiral Reinforcement was not observed to offer a clear total improvement of the response of infilled frames, it is recommended that more refined experimental techniques be pursued in future research.

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