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SEISMIC RESPONSE OF INFILLED RC FRAMES STRUCTURES

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ABSTRACT

The effect of infills on the global seismic response of RC frame structures is studied numerically through nonlinear dynamic response analyses. Parametric analyses are performed: a) on SDOF models of the infilled frame, to study the effect of the elastic natural period of the frame and of the strength, stiffness and energy dissipating characteristics of the infills; b) on a 4-story RC frame structure with various degrees and configurations of infilling, to study the effect of motion intensity and of the strength, stiffness and regularity in elevation of the infills; and c) on various RC frame structures, to study the effect of structural configuration and of the design of the structure for earthquake resistance, including or neglecting the presence of infills.

KEYWORDS

Eurocode 8, inelastic seismic response, infilled frames, masonry infills, nonlinear dynamic analysis.

GLOBAL EFFECTS OF INFILLS ON THE SEISMIC RESPONSE OF SIMPLE STRUCTURES

In masonry-infilled Reinforced Concrete (RC) frames, the infills usually control the global response and often determine performance and failure or not of the frame. Experience from earthquakes suggests that strong infills, although non-engineered and non-structural, often provide most of the earthquake resistance and prevent collapse of relatively flexible and weak RC structures. Nevertheless, because failure of infills is rather brittle and may cause formation of a soft-story, most codes penalize infilled frames in comparison to bare ones.

Due to their high in-plane stiffness and strength, infills affect the global 3D structural response to bidirectional ground motions mainly in the horizontal direction parallel to their plane. Their out-of-plane dynamic response is of interest only to the extent that it may lead to loss of infills due to out-of-plane collapse and hence may influence the global response in the orthogonal direction. For this reason the present paper only focuses on the primary effect of infills on the global seismic response in their in-plane direction. The infill model used for this purpose is a relatively simple nonlinear macromodel of the diagonal strut type, with the hysteretic interstory shear (F) - interstory drift relationship shown in Fig. 1(a) (Panagiotakos and Fardis, 1994). The model has a multilinear curve in monotonic or virgin loading, with an initial stiffness K_1 equal to GLt/H and a cracking force equal to $\tau_{cr}Lt$ (L, H and t are the length, height and thickness of the infill panel and G and τ_{cr} are its shear modulus and cracking stress, as measured in a diagonal compression test of the masonry), a post-cracking hardening branch at a slope $K_2=pK_1$ to an ultimate strength $F_u=1.3\tau_{cr}Lt$, and a post-ultimate falling branch at a slope $-K_3=-p_1K_1$, leading to a residual strength horizontal branch. The hysteresis model is an extension of that proposed by Tassios (1984): Unloading takes place at a slope K_1 up to force equal to βF_u, while the shape and the width of full unloading-reloading loops is controlled by parameters γ and α in Fig. 1(a). The best overall fit to available test results is provided by the parameter values $\alpha=0.15$, $\beta=0.1$ and $\gamma=0.8$.

The resulting hysteretic damping ratio of the infill for its first excursion to a displacement μ times that at cracking equals $(1-p)(1+0.5p(\mu-1))(\mu-1)/\pi\mu(1+p\mu-p)$ and assumes values close to 30%, while that for full unloading-reloading cycle equals $(\mu-1)(1-p-\gamma)[(2-\alpha)(1+p\mu-p)+2\beta]/4\pi(1+p\mu-p)\mu$ and for the selected set of values for α, β and γ assumes values between 2.5% and 3%.

The peak displacement S_d and the spectral acceleration S_a, of an elastic frame with mass-proportional damping 5% of critical, infilled with a panel of initial elastic stiffness K_1 equal to 4-times the lateral stiffness of the bare frame, is shown in Fig. 2 as a fraction of the natural period of the frame T_{fr}. Results shown are mean values of the peak response to 10sec. long artificial motions, compatible with the Eurocode 8 5% damped elastic response spectrum for soil type B. The post-cracking stiffness ratio of the infills $p=K_2/K_1$, is taken equal to the representative value of 3%, while two values of the post-peak softening ratio $p_1=K_3/K_1$ are considered: The unrealistically high value of 10%, signifying a very brittle infill which loses completely its resistance at a lateral displacement about double that at ultimate strength in Fig. 2(a) and a more realistic yet still conservative value of 1%, representative of a well constructed infill panel which sheds its load gradually in Fig. 2(b). The ultimate strength of the infill, F_u, is taken as a multiple f_u of the product of the mass m of the system times the peak input motion acceleration a_g: $f_u=F_u/ma_g$. Four values of f_u are considered: $f_u=0.5$, 1.0, 1.5 and 2.0. The results in Fig. 2 allow the conclusion that, with one exception, infills reduce the peak force and displacement response of the frame. In other words, the often quoted shortening of the effective period of the system due to the stiffening effect of the presence of infills does not increase the peak force and deformation demands on the frame, even when its elastic natural period is in the constant-velocity falling branch of the input spectrum and the shifting is towards the constant spectral acceleration plateau. Of course the peak force of the infill-frame system is higher than that of the bare frame, but the shear force taken by the infill more than compensates this increase. The exception noted above refers to relatively stiff frames with light and very brittle infills, i.e. infills with $p_1=K_3/K_1=0.1$ and $f=0.5$ or 1.0. The peak displacement response of such systems is such that the infills shed all their force, for $T\leq1.5$s. if $f_u=0.5$, of for $T<0.7$s. if $f_u=1.0$. As a result peak shears in these infilled frames are almost equal or even higher than those in the bare ones. Therefore, with the exception of premature disintegration of the infills, something which may happen only in stiff frames with light and brittle infills, the presence of infills reduces peak demands on the frame.

To study the effect of the initial stiffness, K_1 and of the hysteretic characteristics of the infills, the idealized infill model in Fig. 1(b) (rigid-perfectly plastic in loading or reloading, zero resistance in unloading) is also considered. The equation of motion of the system is simply:

$$\ddot{u}+2\zeta\omega\dot{u}+\omega^2u+f=-\ddot{u}_g \tag{1}$$

in which the circular frequency ω and the damping ratio f refer to the elastic frame, and f is the normalized to m resisting force of the infill, which is equal to $F_u/1.15m$ and to $-F_u/1.15m$ if both u and $\dot{u}$ are positive or negative respectively, or zero otherwise (factor 1.15 gives a constant strength equal to the mean of the cracking and the ultimate strength of the infill). The elastic natural period of the infill-frame system is zero in this case, while the equivalent damping ratio of the infill is equal to $1/\pi\approx0.32$ and exceeds slightly that of the model in Fig. 1(a) for the first large post-cracking excursion. As shown in Fig. 2(c), despite the very large apparent stiffening of the elastic system, peak response is drastically reduced throughout the spectrum. This reduction is the result of the higher hysteretic damping of this infill model: This is evidenced also by the results in Fig. 3, obtained for a real accelerogram with just two large half-cycles in each direction, instead of the many large ones of the synthetic accelerograms of Fig. 1. In this case the idealized infill model of Fig. 1(b) and (1) and the realistic one of Fig. 1(a) with $K_3=0.1K_1$, give almost identical results. In other words, the elastic stiffness of the infills is not an important parameter, while their ultimate strength is, especially when it does not exceed the peak ground acceleration times the system mass. The most important characteristic of the infills seems to be their high energy absorption in the first post-cracking excursion, a feature which influences most the response to impulsive ground motions with one or few large acceleration peaks.

PARAMETRIC ANALYSES ON INFILLED MULTISTORY RC STRUCTURES

The effect of strength/stiffness and of regularity in elevation of the infills in actual multistory buildings is studied in relation to a 4-story RC frame structure with 2 bays in each direction, pseudodynamically tested at the ELSA laboratory in Ispra to an input motion with intensity 1.5 times its design seismic action. The structure had been designed according to Eurocodes 2 and 8 for a ground acceleration of 0.3g and a behavior factor q of 5.0 (i.e. for a base shear coefficient of 0.15). It was first tested bare, then with its two exterior

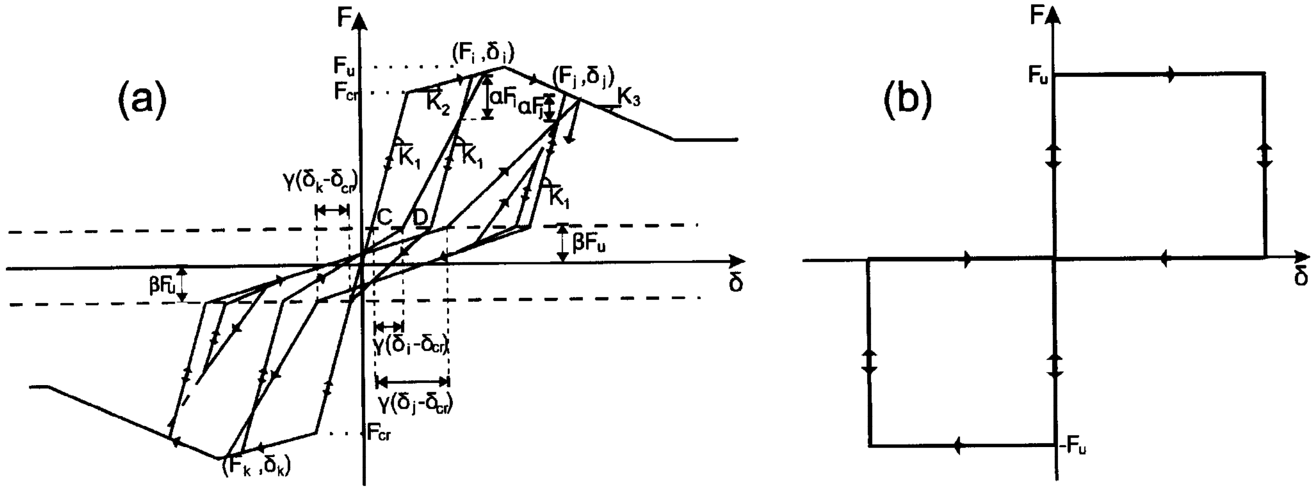

Fig. 1. Interstory shear-drift hysteretic models for infill panels: (a) realistic; (b) simplified for Fig. 3.

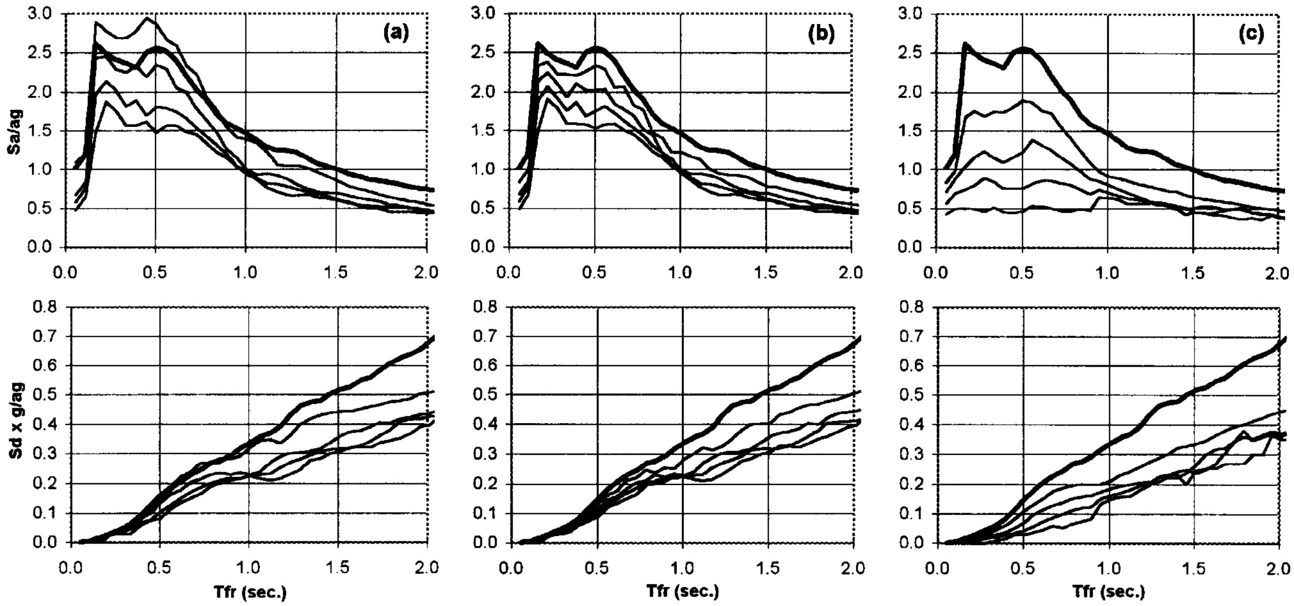

Fig. 2. Average (for 4 artif. motions) spectral acceleration S_a normalized to peak ground acceleration a_g, and peak displacement S_d(m) normalised to a_g/g, vs. elastic period T_{fr} of SDOF frame infilled accord. to model of Fig. 1(a) with $K_3=0.1K_1$ in (a), or with $K_3=0.01K_1$ in (b), or accord. to Fig. 1(b) in (c). Thick line: bare elastic frame. Other lines from top to bottom: infill ult. strength/ma_g, f_u = 0.5, 1.0, 1.5, 2.0.

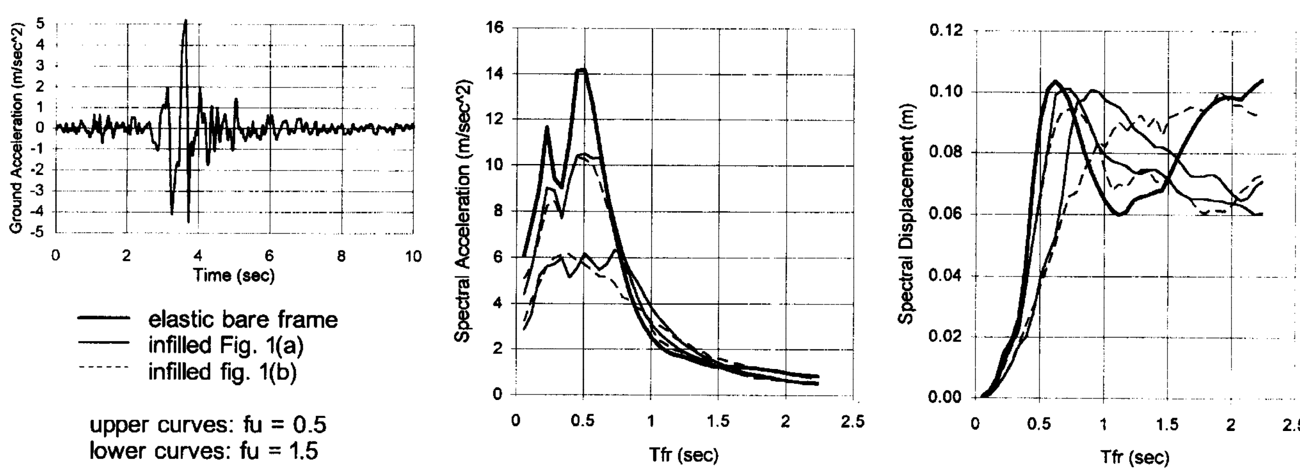

Fig. 3. Infilled SDOF frame of Fig. 2 subjected to Aegion 1995 ground motion, with infills according to Fig. 1(a) with $K_3=0.01K_1$, or according to Fig. 1(b).

frames fully infilled in all 4 stories and finally in a soft 1st story configuration, i.e. with only the 3 top stories infilled. (Donea et al 1995). In the fully infilled structure the ultimate strength of the infills corresponds to a base shear coefficient of 0.08, while the contribution of their elastic uncracked stiffness to the overall lateral stiffness of the structure is about 24 times the lateral stiffness of the fully cracked bare frame, with all its members considered with their secant stiffness at yield.

Table 1. Results of parametric studies of infilled 4-story ELSA structure (average of response to 4 motions)

Infills	a_g (g's)	T_{el} (s)	T_{ef} (s)	base shear coef.	$(E_{in}/M)^{1/2}$ intensity (m/s)	drift rat. % top	drift rat. % 1st	hyst. energy absorption tot.	hyst. energy absorption inf.	hyst. energy absorption beams	hyst. energy absorption columns tot	hyst. energy absorption columns 1st	damage index % story mean / max columns 1st	columns 2nd	beams 1st	beams 2nd
bare	0.30	1.16	1.30	0.32	0.73	1.4	1.5	43	-	30	13	5	4/7	3/5	3/5	3/4
	0.45		1.43	0.39	0.72	2.0	2.3	55	-	40	15	7	7/11	6/8	6/9	5/9
	0.60		1.66	0.43	0.70	2.8	4.1	58	-	40	18	9	9/17	8/12	9/16	7/12
	0.75		1.77	0.45	0.67	3.2	5.1	61	-	38	23	10	13/20	11/16	13/20	9/15
	0.90		1.86	0.47	0.66	3.8	5.7	63	-	35	28	16	15/26	13/20	17/27	12/20
full	0.30	0.34	1.10	0.22	0.71	0.4	0.7	34	23	1	10	8	1/2	1/1	0/1	0/0
	0.45		1.10	0.30	0.70	0.7	1.1	30	17	2	12	9	2/4	1/2	1/2	1/1
weak	0.60		1.12	0.36	0.69	1.1	1.5	29	14	3	12	9	4/6	3/4	3/4	1/2
	0.75		1.37	0.40	0.68	1.4	1.9	28	11	4	13	10	6/9	3/5	5/7	2/4
	0.90		1.38	0.43	0.67	1.7	2.5	29	10	5	14	11	8/11	5/7	6/10	4/6
full	0.30	0.26	0.91	0.26	0.65	0.2	0.4	40	28	0	12	10	1/1	0/0	0/0	0/0
	0.45		1.12	0.32	0.67	0.4	0.8	37	23	1	13	11	2/2	1/1	1/1	0/0
ref.	0.60		1.12	0.38	0.67	0.6	1.1	34	18	1	15	12	3/4	1/2	1/2	0/1
	0.75		1.12	0.43	0.67	0.8	1.4	33	15	2	16	13	4/6	2/3	2/3	1/1
	0.90		1.24	0.47	0.66	1.1	1.7	31	13	2	16	13	6/8	3/4	4/6	1/2
full	0.30	0.18	0.76	0.36	0.44	0.1	0.1	48	29	0	19	15	0/0	0/0	0/0	0/0
	0.45		0.92	0.40	0.52	0.2	0.3	44	26	1	17	14	0/1	0/1	0/0	0/0
str-	0.60		0.96	0.44	0.56	0.3	0.6	41	23	1	17	14	1/1	1/1	0/0	0/0
ong	0.75		1.12	0.48	0.58	0.4	0.8	39	21	1	17	15	2/3	1/2	1/1	0/0
	0.90		1.12	0.51	0.59	0.5	1.0	37	18	1	18	16	3/4	2/3	1/1	0/0
soft	0.30	0.77	1.02	0.29	0.77	0.7	1.3	29	13	3	13	10	4/7	1/2	2/2	0/1
1st	0.45		1.08	0.38	0.76	1.1	1.9	28	11	5	12	8	7/12	3/4	4/5	1/2
stor.	0.60		1.23	0.41	0.75	1.6	3.0	36	9	8	19	14	15/23	4/7	7/10	2/4
	0.75		1.56	0.44	0.74	2.1	4.1	37	7	6	24	20	29/47	5/9	10/13	3/4
weak	0.90		1.63	0.45	0.71	2.9	6.0	44	6	9	29	26	40/65	8/13	16/20	5/7
soft	0.30	0.76	0.96	0.37	0.82	0.6	1.5	28	12	2	14	12	7/11	2/4	2/2	0/0
1st	0.45		0.98	0.41	0.78	0.9	2.3	31	11	3	17	15	13/21	5/8	4/4	1/1
stor.	0.60		1.15	0.43	0.75	1.5	4.4	39	8	2	29	27	27/42	6/10	6/6	1/1
	0.75		1.38	0.45	0.72	2.2	6.6	43	6	2	35	33	43/76	8/13	8/10	1/1
ref.	0.90		1.46	0.47	0.73	2.7	8.4	45	5	2	38	37	60/103	10/17	12/16	2/2
soft	0.30	0.75	0.87	0.41	0.88	0.7	2.3	46	3	3	40	39	12/19	1/2	2/2	0/0
1st	0.45		0.92	0.43	0.81	0.9	2.9	53	3	2	48	47	19/31	2/3	3/4	0/0
stor.	0.60		1.00	0.44	0.76	1.4	4.8	56	3	1	52	51	28/44	3/5	3/5	0/0
str-	0.75		1.37	0.46	0.74	1.7	5.7	53	2	2	49	48	49/81	5/8	5/9	0/1
ong	0.90		1.58	0.48	0.74	2.4	8.1	60	2	1	57	56	61/97	7/10	6/10	1/2

For the purposes of the nonlinear dynamic analyses a bidiagonal equivalent strut model is used for the infill panels, with the hysteretic model of Fig. 1(a). Parameters α, β and γ of the hysteresis are taken equal to 0.15, 0.1 and 0.8 respectively, the post-ultimate softening ratio $p_1 = K_3/K_1$ of the monotonic curve is taken equal to 0.5%, the shear force and deformation at cracking are estimated from test results on wallettes in diagonal compression, while those at ultimate strength are obtained as 1.3 times the cracking force and from the secant stiffness of the panel estimated on the basis of the Mainstone (1971) formula for the equivalent strut width and of the masonry Elastic Modulus in the (weak) horizontal direction of the masonry. The corresponding value of the hardening ratio $p = K_2/K_1$ is between 1/7 and 1/10. This combination of infill parameters provides the best agreement with the available monotonic and cyclic test results on infill panels. A one-component point-hinge type model is used for the beams and columns of the frame. The post-yield chord-rotation vs. end moment relation of this model is based: a) on the assumption of member antisymmetric bending; b) on a bilinear skeleton curve, the parameters of which are determined from the moment and chord rotations of the shear span at yielding and at ultimate according to the Park and Ang (1985) and Park et al (1987) models, and c) on the modified Takeda model with 9 hysteresis rules according to Litton (1975). P-δ effects are also included. RC member damage is described in terms of the energy-based index proposed by Fardis (1994), which is an extension of the Park et al (1987) damage index. Such modeling provides very good agreement of the nonlinear dynamic analysis with the results of the 3 full-scale tests of the 4-story structure at 1.5 its design intensity as far as the response waveform and the damage are concerned, while peak story drifts and story shears are underestimated by 5% to 35% (Fardis and Panagiotakos, 1995).

In the parametric analyses the 3 configurations of the 4-story structure as tested are considered as the "reference" case and the sensitivity of the response to the infilling is studied by considering a "weak infill" and a "strong infill" case, in which the infill strength and stiffness of the reference case are halved or doubled respectively. The same 4 artificial motions compatible with the Eurocode 8 soil B elastic response spectrum, which were used for the SDOF studies of the first part of the paper, are used as input motions, scaled to effective peak accelerations ranging from 0.3g to 0.9g, i.e. up to 3 times the design acceleration of 0.3g. Analysis results, summarised in Table 1 as average values for the 4 input motions, include: The predominant period of the nonlinear response T_{ef}, as obtained from a Fourier analysis, which can be compared with the elastic period, T_{el}, corresponding to the secant stiffness of the RC members at yield and to the elastic shear stiffness, GLt/H, of the uncracked infills. The peak base shear coefficients, to be compared to the values of 0.23, 0.21, 0.24, 0.28 and 0.36, which correspond to first yielding in the frame of the bare, soft story and fully-infilled structure with "weak", "reference" and "story" infills, and to values of 0.42, 0.40, 0.40, 0.44 and 0.52, corresponding to formation of a sidesway mechanism for the same set of structures (as obtained from pushover static nonlinear analyses under triangularly distributed lateral loads). The normalised to motion intensity (with intensity 1.0 corresponding to the design acceleration of 0.3g) ratio $(E_{in}/M)^{1/2}$, where E_{in} is the absolute input energy of the structure, computed as the total work done by the story inertia forces on the story displacements. (This ratio has dimensions of velocity and its value should be compared with the constant pseudovelocity of 0.7m/s of the elastic input spectrum for T>0.6s.). The story drift values, to be compared to the values of 1% and 2.3% corresponding to first yielding and to formation of a sidesway mechanism in the frame. The story-average and the story-maximum damage index values in 1st and 2nd story columns and beams. (Damage index values are in the 3rd story slightly lower than in the 2nd in the bare frame, or negligibly small in all other cases).

Results in Table 1 show that: a) Despite the very high stiffness of the uncracked infills, the frequency content of the nonlinear response is controlled by the fully cracked frame, as infills crack and separate from the surrounding frame quite early, at motion intensities below that of the design motion of 0.3g. b) The higher lateral stiffness of the infilled structures, which significantly reduces top and interstory drifts (except in the soft story), does not lead to an increase in seismic force demands and of the base shear coefficients (except in the "strong infill" case). The simultaneous reduction of peak displacements and forces is due to the increased energy dissipation in the infills, esp. during their first major post-cracking excursion. c) The (normalised to motion intensity) pseudovelocity-type of input energy measure decreases with full infilling, as it depends also on the initial part of the response during which infills are not fully cracked and the predominant period of vibration is shorter than the value of T_{ef} in Table 1 and than 0.6s. d) Comparison of the peak base shear coefficients with those at first yielding of the frame and at formation of a mechanism (see above), shows that the stronger are the infills the higher is the motion intensity at which these phenomena take place in the fully infilled structures and the lower it is in the soft-story ones. e) Although in the bare frame most of the energy dissipation occurs in the beams (consistent with the weak-beam strong column philosophy of Eurocode 8), in the infilled structures the contribution of beams to the energy dissipation is negligible and most of the energy is dissipated in the infills and the 1st story columns (in that order in the fully infilled structures, or in the opposite in the soft-story ones). Because infills crack and start contributing heavily to the energy dissipation at low motion intensities, whereas frame elements do so only at high intensities, the contribution of infills to the energy dissipation decreases with motion intensity, whereas that of the frame increases. In soft-story structures most of the energy dissipation is concentrated in the 1st story columns. The higher is the motion intensity and/or the stronger are the infills, the more pronounced is this concentration. Indeed, due to this phenomenon and contrary to what happens in fully infilled structures, the stronger are the infills, the smaller is their participation in the energy dissipation of the soft-story structures. Finally, both in bare and in soft-story structures, the fraction of input energy which is dissipated by hysteresis increases with motion intensity, as energy dissipation in RC elements increases with the magnitude of inelastic deformations. In bare frames the gradual spreading of inelasticity throughout the structure increases further the fraction of energy dissipated by hysteresis. On the contrary, in fully infilled structures this fraction decreases with motion intensity, as it is the infills rather than the frame that dissipate the energy and the ceiling in their energy dissipation capacity is already reached at low excitation intensities. f) Structural damage decreases with the presence and the strength/stiffness of infills, everywhere except in the columns of the soft story. In sharp contrast with the very uniform distribution of deformations and damage throughout the bare frame, in soft-story structures drifts and structural damage are heavily localised in the 1st story. There is little difference in that respect between the "reference" and the "strong-infills" case, whereas in the structure with "weak infills" for low motion intensities, the soft story is not more critical than in the bare frame, as far as drift and damage is concerned.

A more extensive parametric study has also been performed, focusing on the effect of structural configuration and of the design of the frame for earthquake resistance. In this case 2 of the 6 configurations of RC buildings of the PREC8 project are considered, namely the 4-story, 3 by 5 bay building ("Configuration 1") and the 3-story industrial building ("Configuration 4") with two 12m span in one direction (Z) and eight 6m spans in the other (X) (Carvalho, 1995). Four alternative seismic designs according to Eurocode 8 were considered for each configuration: One at Ductility Class (DC) L (Low) and at design acceleration 0.15g, another at DCM (Medium) and 0.15g, one at DCM and 0.3g and another at DCH (High) and 0.3g. The bare frames with the same design ground acceleration are about equivalent in terms of total material quantities and seismic performance to motions up to twice the design intensity (Fardis and Panagiotakos, 1995). Herein all the bays of the exterior frames of these buildings are considered infilled, with the infill masonry of the ELSA test structure (reference case above). The ultimate strength of such infilling is equivalent to a base shear coefficient of about 0.17 and 0.135 in the X and Z directions of the "Configuration 1" building and to 0.11 and 0.06 for the X and Z directions of "Configuration 4". In addition to full infilling, two soft 1st story cases are considered, in the first of which this irregularity of infilling in elevation is not considered in the design of the structure, while in the second the 1st story beams and columns are designed for this irregularity according to Eurocode 8, i.e. by a percentage-wise increase of their design seismic forces by the ratio of the infill ultimate strength to the design base shear. For the nonlinear dynamic analyses the same infill and RC member modeling and the same 4 artificial input time histories, compatible with the design 5%-damped elastic spectrum, are used as for the 4-story ELSA structure. As ground motions with the design intensity of 0.15g or 0.3g effective peak acceleration are found to cause little inelastic action of the structure, the presentation here focuses on the response to motions with twice the design intensity. Results are summarized in Table 2, for both directions of the two building configurations, separately for the bare frame, the soft story buildings, the soft story buildings designed according to Eurocode 8 for the effect of infill irregularity and for the fully infilled buildings. For the last two classes of buildings, results are affected very little by the Ductility Class for which the frame was designed. Accordingly, only average results for the two DCs are presented.

All conclusions already drawn on the basis of Table 1 are verified by the results of Table 2. So this discussion focuses mainly on the effect of designing the 1st story elements of the soft-story buildings for the effects of the infills-irregularity. These structures develop by far the highest seismic force and input energy demands within their class of buildings, whereas fully infilled structures develop the lowest. Their 1st-story drifts are, in general, lower than the corresponding ones of the bare structures (which, in turn, are not significantly greater than those of the soft-story ones not designed for the infill irregularity, except when the infilling is heavy and the excitation acceleration is 0.6g). The percentage of input energy dissipated in soft-story structures which are designed for the infill irregularity is low. It is only higher than in the fully infilled ones and much lower than in the bare structures. Energy dissipation in beams is still very low. Although much lower than in the fully-infilled structures, the fraction of energy dissipated by the infills in the soft-story buildings designed for the infill irregularity is higher than in the non-designed ones. Indeed, for the 0.3g excitation of the 0.15g-designed structures, this fraction is comparable to that of energy absorption in the columns. Structural damage in beams is already very low in soft-story structures not designed for the infill irregularity and decreases further in those designed for this irregularity. Nevertheless, in view of the low beam damage in the former class of soft-story structures, the benefit from upgrading the resistance of the soft-story beams to account for the irregularity according to the Eurocode 8 provisions seems very small. Similar upgrading of the soft-story columns is, in general, quite effective in limiting the localisation of structural damage and energy dissipation to these columns and in reducing their damage to the levels of the bare structure. With one exception, though: If infills are heavy and the excitation is high (at 0.6g), upgrading the soft-story columns for this irregularity according to EC8 does not reduce their damage, although the 1st-story drift is reduced. The reason seems to be the reduction in ductility due to the heavier reinforcement of the strengthened columns, in connection with the higher seismic force demands to which the structures designed for the infill irregularity are subjected. It seems, therefore, that the relevant Eurocode 8 provisions may need some improvement, in the direction of increasing the deformation capacity and the ductility of the columns of the soft story columns, rather than their strength, and in reducing the concentration of inelastic deformations and energy dissipation in the soft columns. Indeed, by repeating the design of the soft-story structures, accounting this time for the infill irregularity according to Eurocode 8 only in the dimemsioning of the columns of the 1st story and not in that of the beams, and by repeating the nonlinear dynamic analyses, it was confirmed that not only structural damage of the 1st story beams is acceptable and below that in the bare frames, but also that energy dissipation and structural damage

Table 2. Results of parametric studies of various infilled structures designed to EC8 (average for 4 motions)

Infill-ing	DC	T_{el} (s)	T_{ef} (s)	base shear coef.	$(E_{in}/M)^{1/2}$ intensity (m/s)	drift rat. %		hyst. energy absorption					damage index % story mean / max			
											columns		columns		beams	
						top	1st	tot.	inf.	beams	tot	1st	1st	2nd	1st	2nd
Config.1 (4-story), direct. X. Des. acc. 0.15g, excitation acc. 0.3g (infill ult. strength: base shear coef.=0.17)																
bare	L	1.21	1.30	0.27	0.38	1.4	1.8	42	-	22	20	6	5/9	4/8	5/7	5/6
"	M	1.20	1.32	0.24	0.37	1.4	1.9	44	-	24	21	6	4/6	4/6	4/7	4/6
soft st.	L	0.74	0.93	0.35	0.40	0.7	2.4	42	13	6	23	19	12/24	0/1	3/4	0/1
"	M	0.71	0.93	0.34	0.40	0.7	2.1	43	13	7	23	19	10/15	0/1	2/3	0/1
soft/des.	LM	0.61	0.79	0.42	0.42	0.4	1.1	35	17	5	14	10	5/8	1/1	1/2	0/1
infilled	LM	0.26	0.83	0.24	0.32	0.2	0.4	41	32	4	4	1	1/1	0/1	0/1	0/0
Config.1 (4-story), direct. Z. Des. acc. 0.15g, excitation acc. 0.3g (infill ult. strength: base shear coef.=0.135)																
bare	L	1.33	1.52	0.24	0.37	1.4	1.9	45	-	27	18	7	4/7	3/6	6/7	5/6
"	M	1.34	1.58	0.21	0.36	1.4	2.0	49	-	30	19	8	3/4	2/4	5/6	4/5
soft st.	L	0.77	0.98	0.31	0.39	0.7	1.7	37	16	6	15	10	7/13	1/1	3/5	0/0
"	M	0.74	0.98	0.30	0.39	0.6	1.6	42	15	8	19	13	5/8	1/1	3/3	0/0
soft/des.	LM	0.66	0.86	0.36	0.40	0.5	1.0	34	18	4	12	8	3/4	1/1	1/2	0/0
infilled	LM	0.28	0.93	0.25	0.35	0.3	0.6	36	30	4	2	1	1/1	0/1	0/1	0/0
Config.1 (4-story), direct. X. Des. acc. 0.3g, excitation acc. 0.6g (infill ult. strength: base shear coef.=0.17)																
bare	M	1.08	1.35	0.44	0.36	2.5	3.4	54	-	26	28	12	7/11	6/13	8/14	8/12
"	H	1.13	1.55	0.39	0.36	2.4	3.9	57	-	22	35	13	6/11	7/13	7/11	6/9
soft st.	M	0.63	0.99	0.47	0.37	1.6	5.4	51	10	5	36	32	22/36	1/2	6/12	1/1
"	H	0.66	1.02	0.43	0.36	2.0	7.5	46	9	3	34	31	20/36	1/2	4/7	0/1
soft/des.	MH	0.61	1.02	0.57	0.38	1.6	5.5	40	11	2	27	25	23/46	1/3	2/4	1/1
infilled	MH	0.26	0.92	0.40	0.35	0.7	1.1	27	22	2	3	2	2/3	1/2	2/3	1/2
Config.1 (4-story), direct. Z. Des. acc. 0.3g, excitation acc. 0.6g (infill ult. strength: base shear coef.=0.135)																
bare	M	1.20	1.55	0.40	0.36	2.6	3.3	57	-	33	24	10	5/9	5/10	11/14	8/10
"	H	1.26	1.84	0.35	0.35	2.8	4.1	57	-	30	27	10	5/8	6/10	8/10	7/9
soft st.	M	0.65	0.98	0.45	0.38	1.4	3.7	35	11	4	20	16	16/30	2/4	6/9	1/2
"	H	0.68	1.05	0.40	0.36	1.7	5.3	40	10	5	25	21	17/31	1/3	5/7	1/1
soft/des.	MH	0.63	0.99	0.54	0.38	1.3	3.3	31	12	3	16	12	15/27	2/4	3/5	2/3
infilled	MH	0.29	1.03	0.39	0.35	0.8	1.3	25	18	3	3	2	2/3	1/2	3/3	1/1
Config.4 (3-story), direct. X. Des. acc. 0.15g, excitation acc. 0.3g (infill ult. strength: base shear coef.=0.11)																
bare	L	1.94	2.03	0.15	0.31	2.1	4.3	39	-	7	32	30	11/15	2/4	3/7	1/2
"	M	1.87	2.04	0.15	0.31	2.0	3.9	40	-	14	26	23	8/10	3/4	6/10	1/2
soft st.	L	1.50	2.42	0.15	0.33	1.7	4.6	49	1	1	47	47	14/18	0/0	1/2	0/0
"	M	1.50	2.37	0.15	0.33	1.5	4.2	50	1	1	48	47	10/13	0/0	1/2	0/0
soft/des.	LM	1.36	1.62	0.26	0.33	1.2	2.9	25	10	1	14	12	10/12	0/0	2/3	0/0
infilled	LM	0.39	1.23	0.14	0.34	0.3	0.8	26	24	0	2	1	1/1	0/0	0/0	0/0
Config.4 (3-story), direct. Z. Des. acc. 0.15g, excitation acc. 0.3g (infill ult. strength: base shear coef.=0.06)																
bare	L	2.14	2.15	0.29	0.33	1.5	2.8	45	-	7	38	36	11/14	3/4	2/2	0/1
"	M	2.09	2.10	0.22	0.33	1.5	2.7	51	-	10	41	35	8/11	2/3	2/2	0/1
soft st.	L	1.53	1.87	0.20	0.33	1.2	2.7	38	6	2	30	28	12/21	0/1	1/1	0/0
"	M	1.40	1.69	0.22	0.35	1.1	2.4	34	8	1	25	23	11/16	1/1	1/1	0/0
soft/des.	LM	1.32	1.27	0.27	0.37	1.0	1.8	25	10	3	12	8	6/9	1/2	1/2	0/0
infilled	LM	0.44	0.97	0.15	0.34	0.5	1.0	22	20	0	2	1	2/2	0/0	0/0	0/0
Config.4 (3-story), direct. X. Des. acc. 0.3g, excitation acc. 0.6g (infill ult. strength: base shear coef.=0.11)																
bare	M	1.51	1.82	0.32	0.33	2.7	5.4	62	-	16	46	42	15/22	4/5	13/19	4/6
"	H	1.57	2.27	0.29	0.33	2.5	4.9	50	-	16	34	31	9/13	2/3	14/18	3/5
soft st.	M	1.31	1.73	0.33	0.33	2.2	5.3	59	5	2	52	51	20/28	0/1	4/6	0/1
"	H	1.37	1.91	0.30	0.33	2.1	5.1	51	4	3	44	42	13/19	0/0	5/7	0/0
soft/des.	MH	1.15	1.49	0.44	0.36	1.9	4.0	39	7	4	28	25	13/19	2/2	7/15	1/1
infilled	MH	0.36	1.59	0.30	0.34	0.9	1.9	22	18	1	3	2	3/4	0/1	2/3	0/1
Config.4 (3-story), direct. Z. Des. acc. 0.3g, excitation acc. 0.6g (infill ult. strength: base shear coef.=0.06)																
bare	M	1.06	1.55	0.48	0.37	2.9	3.4	65	-	28	37	23	11/20	7/15	9/11	5/7
"	H	1.13	2.27	0.43	0.36	2.2	3.3	53	-	23	30	24	8/14	3/6	7/9	3/4
soft st.	M	0.90	1.18	0.49	0.37	1.6	3.0	39	5	11	23	20	12/25	3/5	7/9	1/2
"	H	0.97	1.32	0.42	0.36	1.7	3.3	41	5	9	27	24	11/19	2/3	6/7	1/1
soft/des.	MH	0.82	1.20	0.53	0.38	1.6	2.4	43	6	14	23	18	6/10	3/5	8/9	2/2
infilled	MH	0.40	1.14	0.41	0.36	1.1	1.9	24	11	6	7	6	4/7	2/3	4/4	1/1

in the 1st story columns is significantly reduced, relative to the case in which both beams and columns of the 1st story are designed for the infill irregurality according to Eurocode 8. The problem of the higher damage in the 1st story columns of the heavily-infilled buildings at 0.6g excitation, caused by upgrading their resistance for the infill irregularity is also ameliorated if beam resistance is not upgraded also, at least to the point that such damage is less than in the soft-story columns of the buildings not designed for the irregularity.

CONCLUSIONS

A systematic set of parametric analyses on idealized SDOF infilled frames, as well as on many multistory RC buildings with various degrees and configurations of infilling, shows that, with very few exceptions, the presence of infills is beneficial for the global seismic response and performance of the structure. This is more so for impulsive-type ground motions with one or a few large acceleration peaks, as for such motions the structure derives the most benefit from the energy dissipation capacity of the infills, which is much larger in a single large post-cracking or post-ultimate strength excursion than in subsequent large amplitude cycles. Infills are found to crack and separate from the frame at rather low ground motion intensities and hence their high stiffness affects very little the frequency content of the global dynamic response. The magnitude of this response is affected most by the ultimate strength and the post-ultimate behavior of infills, to a degree disproportional to the magnitude of the infill strength relative to that of the frame and to the design base shear. Very brittle infills, which shed all their load soon after reaching ultimate strength, and irregularities in elevation of heavy infills, are identified as the only conditions which may lead to a deterioration of the overall seismic performance due to the presence of infills. In the light of the present results, some of the provisions of Eurocode 8 related to seismic design of infilled RC structures seem too conservative and not fulfilling their purpose. In particular, it seems that a) there is no need to compute the lateral seismic forces and base shears of an infilled structure on the basis of the average of the period of the bare and the infilled configuration, and b) it is unnecessary and often counterproductive to upgrade the resistance of soft-story beams in proportion to the reduction of infill strength in the story relative to the design seismic shear, instead of improving the deformation capacity and the ductility of the most valuerable elements of soft stories, i.e. of the columns.

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