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Seismic Behaviour of Infilled Existing RC Buildings

E. Vintzileou[1], C. Zeris[1], C. Repapis[1]

Summary

The aim of this study is the evaluation of the actual capacity of existing reinforced concrete buildings taking into account the contribution of masonry infill walls. For this reason, typical existing buildings are selected, with various arrangements of masonry infills and masonry properties at the perimeter frames. A new finite element has been developed and included in Drain-2DX for modelling infill walls. The buildings are designed according to the earthquake resistant design codes valid for the examined period. Inelastic static analyses are performed for each building and its overstrength and global ductility are evaluated. Analytical predictions indicate that the presence of infill walls in the perimeter frames increases considerably the stiffness of the structures and their global resistance to lateral loads, while their global ductility is reduced. Fully or partially infilled frames can perform well, while structures with an open floor, particularly at the ground storey, usually exhibit the worse performance by creating a soft storey. The analyses further prove that lower strength masonry provides the building with lower overstrength but higher ductility. Finally, it is demonstrated that shear failure becomes more critical in the lower stories of structures with partial height infills.

Introduction

In Greece, as in other Mediterranean European countries, a large number of existing reinforced concrete framed structures dates back to the 60's and 70's whereby they have been designed with past generation of codes. Consequently, the assessment of the potential seismic performance of these buildings is very important, for social and economic reasons. These frames are typically infilled with clay brick infill walls, typically not assumed to be part of the lateral resisting system. In general, the presence of unreinforced masonry infills (particularly of good quality) has been proven to improve the seismic performance of these buildings in recent earthquakes in densely inhabited areas, and can be a main contributor to their lateral strength and stiffness. Discontinuities in the layout of the perimeter infill walls, on the other hand, (potentially creating a soft storey), can cause unintended irregularities with height and are examined in this study. Finally, partial height infills, which may force unexpected failure of the surrounding reinforced concrete members due to increased shear demands, are also studied.

This study is part of a comprehensive analytical research programme, funded by Earthquake Planning and Protection Organisation, Greece, ongoing at the National Technical University of Athens, aimed at quantifying the inelastic response of existing

[1] National Technical University of Athens, Dept. of Civil Engineering, Reinforced Concrete Lab., Athens, Greece

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structures. Of interest are the estimation of behaviour governing parameters such as the structural overstrength, the collapse mechanism, the expected local distribution of damage, the distribution of energy dissipation and the structure global ductility.

Selection of Building Models

All buildings are typically cast-in-place reinforced concrete structures with beams cast monolithically with slabs and supported by columns. Out of a larger set of structural forms considered, with various forms of vertical irregularity, only one regular building is presented in this study. Results for more buildings can be found elsewhere ([7], [8]). The building considered is four by three bays in plan. Building denoted as K, a typical regular building of the 60's, is five storeys high with storey height of 3.00 m and regular 3.50 m bay sizes (Figure 1). The structure has been designed according to the 1959 seismic design code [4] following allowable stress procedures and a seismic coefficient of 0.04, using DIN B160 concrete (mean cube strength of 16 MPa) and DIN St I (S220 smooth) longitudinal and transverse reinforcement. The cross-section dimensions of columns are small, reflecting the tendency of early designs to be fairly economic in concrete usage. Structural elements and the building itself possess no critical region reinforcement for confinement. No capacity design provisions were used in the design of the members.

As it is mentioned above, masonry infills usually exhibit strong influence on the seismic response of frame structures, as it appears from earthquakes and test results. Despite this fact, in conventional structural design of the buildings, the infills are usually neglected or taken into account indirectly in the current codes. In order to examine the influence of the perimeter frame masonry infill panels to the structure, fully and partially unreinforced masonry frames are also considered herein. Five different arrangements of unreinforced masonry infilled frames (with 0.25 m wide infills) are studied (denoted as T1–T8), as shown in Figure 1. For frames T6–T8, the height of the infills in the first storey, is taken as 67%, 50% or 33% the storey height.

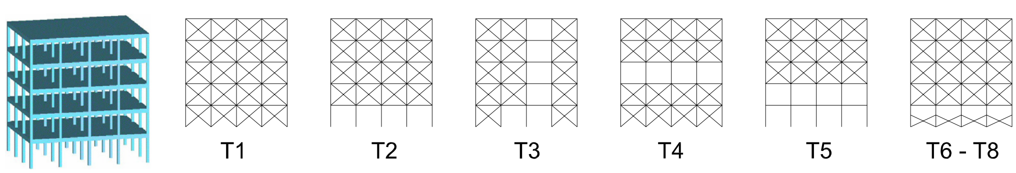

Figure 1. Bare building and types of masonry infilled perimeter frames

Analytical Modelling

All analyses are performed using an extended version of the computer program Drain-2DX [1]. All the beams and columns of the structures are modelled using the two component lumped plasticity beam column element (type 02). The inelastic moment-curvature characteristics are developed for all the end critical regions of beams and columns, using mean material properties. The infill walls are modelled by equivalent diagonal struts, which carry loads only in compression. A simple element (Compression-

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tension link element – Type 09) provided by Drain-2DX was modified and used for modelling the infills [6]. The new element has trilinear behaviour with softening and remaining strength (Figure 2). The trilinear envelope consists of an elastic part, a post-yield part with positive stiffness and a softening part with negative stiffness. The unloading stiffness is controlled by a parameter a between 0 and 1. For the analyses, a parameter a equal to 0 is used, assuming the unloading stiffness equal to the elastic.

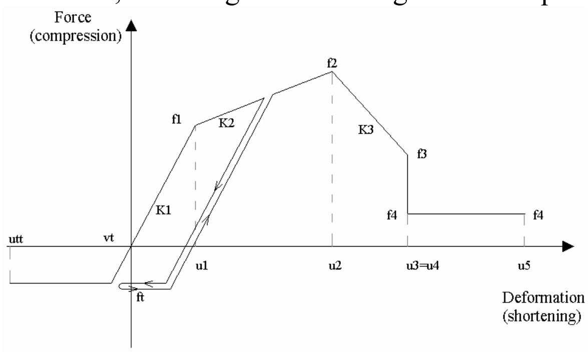

Figure 2. Hysteretic behaviour of infill walls

The properties of the masonry materials are subjected to large uncertainties and vary significantly. Therefore a combination of material strengths is considered to represent weak and soft, and strong and stiff masonry. Mainstone's approach is used to determine the initial stiffness and the effective width of the diagonal strut [10]. An expression by Dolsek and Fajfar [9], is used for the estimation of the maximum strength of infills, which takes place at an interstorey drift of 0.5%. The compression strength f_m of the masonry infill varies from 0.5 to 2.5 MPa and the Young's modulus of elasticity is $E_w = 750 \cdot f_m$ [5]. The thickness of the masonry is 0.25 m. The properties of the envelopes for the equivalent struts used in analyses, depending on the bay size, the panel height and the various values for compression strength of the masonry are summarised in Table 1.

Table 1. Properties of the envelope of the equivalent diagonal strut in compression.

$f_{masonry}$ [MPa]	Width [m]	Height [m]	Stiffness k_1 [KN/m]	$f_y = f_1$ [KN]	$f_{max} = f_2$ [KN]	u_2 [m]	k_3/k_1	u_3 [m]	$f_3 = f_4$ [KN]
2.5	3.5	3.0	27859.5	121.5	243.0	0.015	-0.10	0.089	36.5
2.5	3.5	2.0	42479.9	112.6	225.1	0.010	-0.10	0.055	33.8
2.5	3.5	1.5	52807.5	104.1	208.2	0.0075	-0.10	0.041	31.2
2.5	3.5	1.0	67354.9	96.2	192.3	0.005	-0.10	0.029	28.9
1.5	3.5	3.0	17591.8	72.9	145.8	0.015	-0.10	0.085	21.9
0.5	3.5	3.0	6544.9	24.3	48.6	0.015	-0.10	0.078	7.29
0.5	3.5	1.5	12405.7	20.8	41.6	0.0075	-0.10	0.036	6.25

Local or global failure definition criteria are adopted for the infilled RC structures (see also [7], [8]): (a) local inelastic rotation capacities at the end critical regions of beams and columns, (b) local shear force capacity of the individual members, (c) 1.25%

global relative interstorey drifts, (d) 15% reduction of the base shear resistance, for the bare frames only, and (e) any infill reaching its maximum strength f_{max}. Inelastic rotation capacities are based on inelastic curvatures times an average plastic hinge following [5].

Results

The maximum global roof deformability of each building expressed as the minimum roof deformation satisfying all of the above criteria is estimated in each analysis. Ductility is derived dividing this value with the equivalent yield deformation, obtained using an equal area bilinear approximation of the response. Thus, the overstrength ratio Ω is the ratio of the maximum base shear resistance to the ultimate limit state reference shear. Both the Capacity Spectrum Method in ATC-40 [2] and the N2 Method [3] are used to evaluate the performance of all structures. The corresponding base shear resistance V, overstrength Ω, global ductility μ and maximum roof displacement δ_u are given in Table 2 for the frames considered, assuming a range of masonry infill quality f_m.

Table 2. Results from Pushover analyses.

	f_m [MPa]	T [sec]	V [KN]	Ω	μ	δ_u [m]		f_m [MPa]	T [sec]	V [KN]	Ω	μ	δ_u [m]
K	-	0,84	876.6	1.32	1.63	0.053	T1	1.5	0.51	1930.7	2.91	2.28	0.069
T1	2.5	0.44	2207.9	3.32	1.69	0.044	T2	1.5	0.56	1256.1	1.89	1.70	0.036
T2	2.5	0.51	1315.2	1.98	1.67	0.028	T3	1.5	0.58	1487.4	2.24	1.98	0.057
T3	2.5	0.52	1673.2	2.52	1.67	0.043	T4	1.5	0.63	980.3	1.47	1.55	0.032
T4	2.5	0.59	980.5	1.47	1.62	0.028	T5	1.5	0.67	987.9	1.49	1.91	0.041
T5	2.5	0.65	988.3	1.49	1.99	0.038	T1	0.5	0.65	1242.7	1.87	2.04	0.063
T6	2.5	0.45	971.6	1.47	1.27	0.012	T2	0.5	0.67	1105.3	1.66	1.91	0.055
T7	2.5	0.47	1003.2	1.51	1.28	0.013	T3	0.5	0.69	1131.5	1.71	2.06	0.065
T8	2.5	0.49	1067.8	1.61	1.28	0.015	T4	0.5	0.72	974.2	1.47	1.51	0.041
							T5	0.5	0.73	975.3	1.47	1.89	0.052
							T7	0.5	0.66	1166.8	1.76	1.85	0.055

In Figure 3 the inelastic characteristics, for both the bare and infilled structures are compared. The failure displacement is reduced up to 45% for the full height infilled structures, compared to the bare one. The presence of the infills induces a significant initial stiffness increase. However, the shear capacity of columns is exceeded earlier than in bare frames, but this failure is not critical because plastic rotation capacity is exceeded first. In all structures with full height infills the critical limit state for maximum deformability is the plastic rotation capacity of columns.

Shear failure of columns becomes more critical in the lower stories of structures with partial height infills. For these buildings, short columns fail in shear even before the development of plastic hinges and a brittle failure occurs. Reducing the ground infill height from 67% to 33% of the ground storey height, increases overstrength and ductility, since the free column height increases thereby reducing the shear taken by these members at comparable roof drifts (Table 2). For better masonry quality, overstrength increases by

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10% but ductility remains practically the same. Failure in all cases occurs at very small drifts, therefore the seismic behaviour of these structures is poor.

In the same figure, the plastic hinge distribution is shown for three typical frames considered. Infills that have cracked are also plotted with a dashed line. Only perimeter frames are shown. In structures with an open storey, infills do not reach the maximum strength, since inelastic energy absorption concentrates to the columns of the open storey. On the contrary, for the fully or partially infilled frames, infills in the lower part of the frame reach their maximum strength, but at a higher drift than the limiting drift due to inelastic action in the RC frames. Ductility supply is lower for the infilled structures, but performance point demand is also lower due to their increased resistance. After the failure of the infills the lateral resistance approaches the bare frame level, but the performance demand is expected earlier. It can be seen that partially infilled frames can behave in a satisfactory manner, although even for this case, inelastic energy absorption of beams and columns is mainly concentrated in the ground floor. Nevertheless, for weaker infills the inelastic energy absorption is better distributed with height.

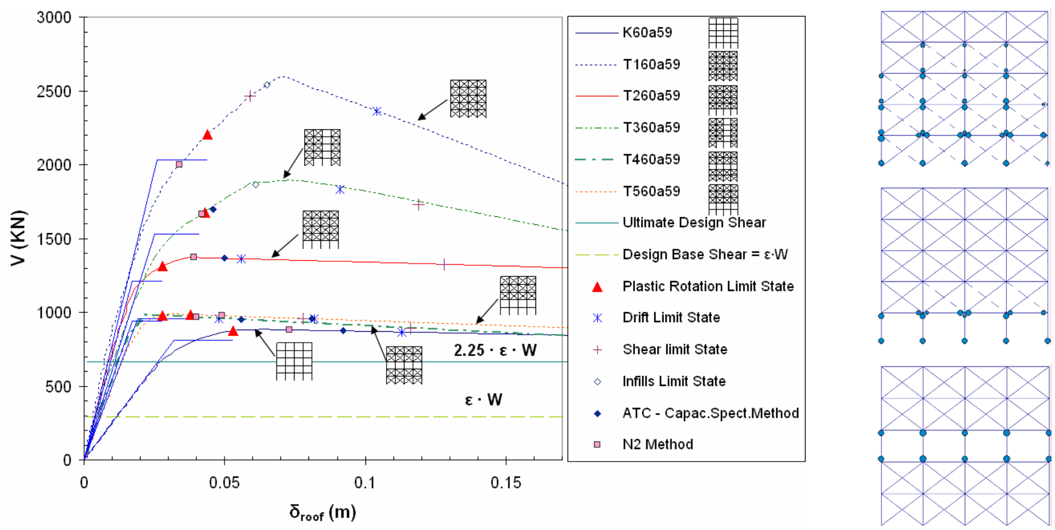

Figure 3. (a) Inelastic characteristics of infilled frames and (b) plastic hinge distribution

In general, structures with weaker and softer infills exhibit smaller overstrength, but their global ductility is increased, as the interstorey stiffness ratio is reduced. The failure deformation of infilled structures increases significantly with the reduction of masonry's strength. Moreover, the effect of the short columns is reduced when weaker infills are used. Column shear failure still remains to be critical, however some plastic hinges have already been developed and energy is absorbed by beams and columns before this form of brittle failure. A reduction of masonry's strength from 2.5 to 0.5 MPa, causes a 35% increase in ductility for building with 50% partial infill height. The overstrength is also increased by 10%, since failure occurs at a higher drift.

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Conclusions

The results of analyses confirm that the influence of the infills is important and that they should be included in modelling for the performance evaluation of existing RC frames. In general, infills increase the stiffness and overstrength of the structure, but reduce its global ductility. A non-uniform distribution of infills, like an open first storey, results in a concentration of the damage at this storey, creating a soft-storey response mechanism, whether at the ground or at intermediate levels. Regularly distributed infills significantly reduce the deformation and ductility demand in structural elements: fully or partially infilled frames with vertical stiffness regularity behave adequately. Lower strength masonry provides the building with lower overstrength but higher ductility. Shear failure becomes more critical in the lower stories of structures with partial height infills. These effects are less intense as the masonry strength reduces.

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