Inelastic static analysis of infilled R/C buildings

A.J. Kappos[1] , C.G. Panagiotopoulos[1]

Summary

An extensive analysis of typical R/C building configurations, including brick masonry infill walls arranged either regularly or irregularly (creating soft-storeys) is presented. A rather sophisticated nonlinear constitutive law is used for describing the contribution of infills, along with a diagonal strut model, introduced into SAP2000 and tested for stability. Significant overstrength is found for the infilled buildings, particularly the low-rise ones.

Introduction

Significant efforts have been made recently towards developing reliable as well as feasible methods for assessing the seismic behaviour of structures. The approach that appears to be favoured by many engineers is that based on inelastic static (pushover) analysis, since it combines some key advantages of the inelastic dynamic (time-history) analysis with the simplicity of using equivalent static loads. Within the same basic approach several different methods have been developed, the main difference among them being the way the displacement demand is defined, in other words the estimation of the target displacement for the pushover analysis.

The vast majority of assessment studies based on pushover analysis focused on structures in which 'non-structural' elements did not contribute to the lateral resistance. However, reinforced concrete (R/C) buildings in many places around the world typically include brick masonry infills that increase both their strength and stiffness [1,2]. Ignoring this contribution of infill walls obscures the assessment of the lateral load capacity of the building and may lead to erroneous conclusions, usually (but not necessarily) underpredicting this capacity.

In the following, a large number of R/C building structural systems including clay brick masonry walls are analysed using pushover analysis wherein the contribution of infills is explicitly accounted for by including appropriate strut elements in the structural model.

Modelling of infill panels

The model used herein for masonry infills is the one developed in [1] and is based on the well-known diagonal strut concept. The relationship between the stiffness of the strut and that of a shear panel can be derived using the condition that the lateral displacement of the two models be equal. Another assumption is that the panel sustains negligible vertical deformations. The axial stiffness coefficient $E_s A_s$ of the strut can be expressed in terms of the shear stiffness $G_w A_w$ of the panel and the inclination (α) of the strut from

$$E_S \cdot A_S = \frac{G_W \cdot A_W}{\cos^2 a \cdot \sin a} \tag{1}$$

---

[1] Dept of Civil Engineering, Aristotle University of Thessaloniki, 54124 Greece.

Based on the assumption of equal areas (absorbed energies) under the envelope curve, the exponential descending branch of the monotonic τ–γ curve suggested in [1] can be substituted by an equivalent bilinear one (Fig. 1). Using the relation between the axial stiffness of the strut and the shear stiffness of the panel (defined by equation 1) it is possible to construct the axial force-displacement diagram of the strut model, which can be directly introduced in the program used (SAP2000 [3] in the present study).

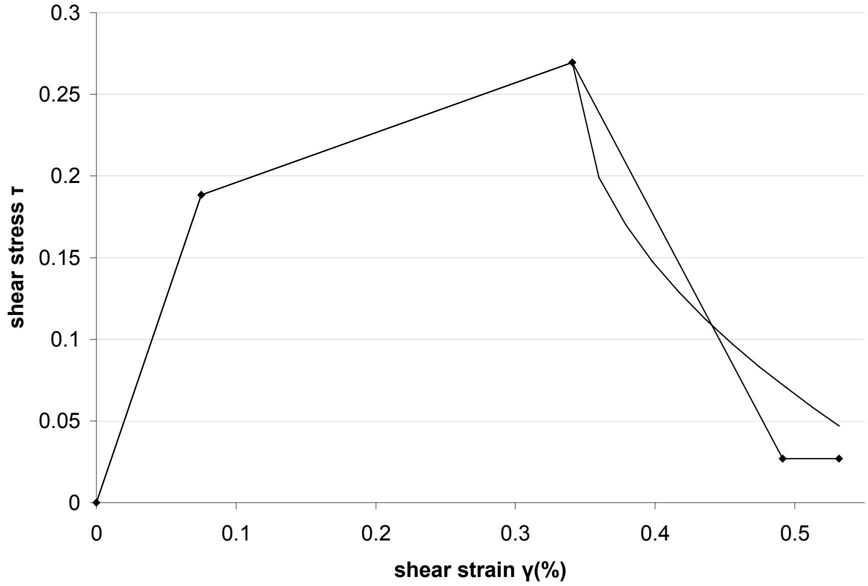

Fig. 1 Envelope shear stress vs. shear strain curves for infill panel

To verify the ability of the program to treat this softening behaviour of the strut element, some simple cases were first studied. Initially, a simple truss with a concentrated plastic hinge at its end was analysed, having the constitutive relation shown as Truss 1 in Fig. 2. It was found out that instead of using the input value of the slope of the descending branch of the curve, SAP2000 reduces this value by the amount corresponding to the slope of the initial (elastic) branch; this is apparently done to avoid having a zero stiffness when the strain at peak and the strain at the beginning of the residual strength branch are given the same (which is commonly done by several users). Hence, to overcome this problem, instead of the actual slope of the descending branch, an increased one is given ("Truss 1 (input)" in Fig. 2) which is the sum of the elastic and the actual slope of the descending branch.

The second example analysed was a system of two trusses connected at the end with a rigid member (Truss 2 in Fig.2 is added to Truss 1 of the first example). Providing as input the aforementioned increased slopes of the descending branch of each element, the desired behaviour is adequately modelled as shown from the results plotted in Fig. 2. A problem that may arise in the procedures described above is that when the absolute value of the descending branch slope is equal to the elastic one, hence after summation a zero value results, in the presence of a second hardening branch of noticeable slope overshooting phenomena may occur. Another problem is that in some cases when one of the elements exceeds its final displacement (terminal value of residual strength branch) so it has to assume a zero value of strength, the solution may become unstable, depending on the condition of the remaining elements. Clearly, both problems can be easily avoided by providing appropriate input values, depending on the type of structure analysed.

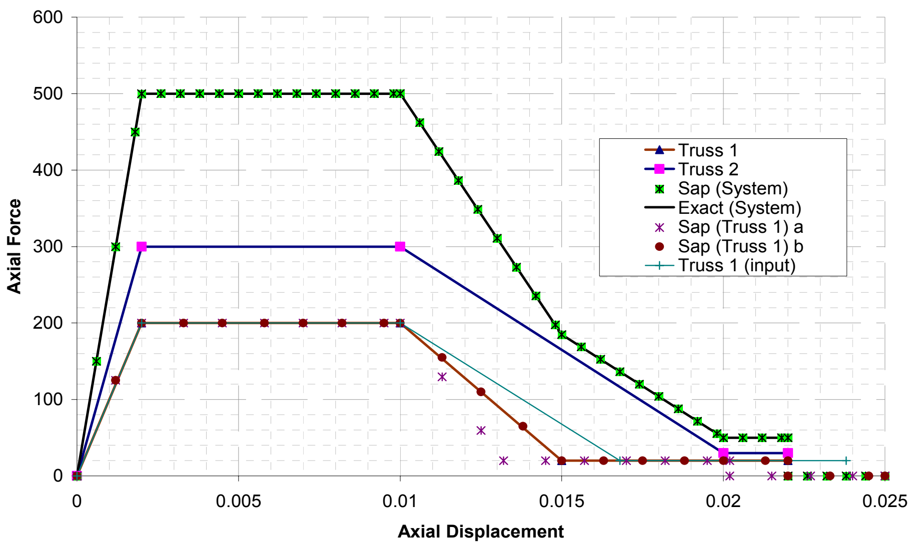

Fig. 2 Input and output curves for simple structures analysed.

As a last pilot case, a simple single-storey R/C frame was considered with a masonry infill modelled as a diagonal strut; the standard member-by-member modelling, with concentrated plastic hinges at the ends was adopted for the R/C members. Shown in Fig. 3 are the pushover curves (top displacement vs. base shear) for the infilled frame and the bare frame, as well as the difference between them, which ideally should coincides with the curve for the diagonal strut ("Strut(exact)" in Fig. 3). As can be seen from Figure 4, the two curves are indeed in very good agreement with each other.

Building types analysed

Using the procedures described previously, analysis of several different R/C building configurations has been performed. Referring to the height of the buildings, 2-storey, 4-storey, and 9-storey R/C buildings were analysed. Regarding the structural system, both frames and dual (frame+shear wall) systems were addressed. Two seismic code levels were considered: low (early seismic codes) and high (modern seismic codes). To keep the cost of analysis within reasonable limits, all buildings were analysed as 2D structures. Some typical configurations of infilled structures studied are shown in Fig. 4 (referring to dual systems). For the frame structures, in order to approximate the distribution of the masonry infills two identical R/C were assumed to resist the seismic loading, one bare and one with masonry infills. The abbreviations used for the buildings consist of four letters, the first letter refers to the structural system, i.e. D(ual) or F(rame), the second letter refers to the distribution of infills, R(egular) and I(rregular), the third letter refers to the seismic code level H(igh) or L(ow), and finally the fourth letter refers to the height of the building, L(ow) for 2 storeys, M(edium) for 4 storeys and H(igh) for 9-storey buildings. Hence, as an example, DRLH is a building with dual system, regularly infilled, designed to low seismic code, and high-rise (9 storey).

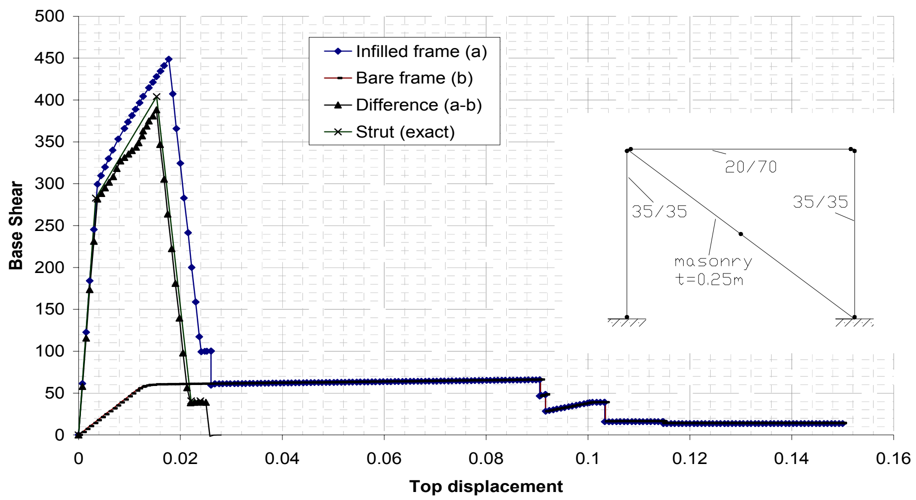

Fig. 3 Pushover curves for bare and infilled R/C single-storey frame

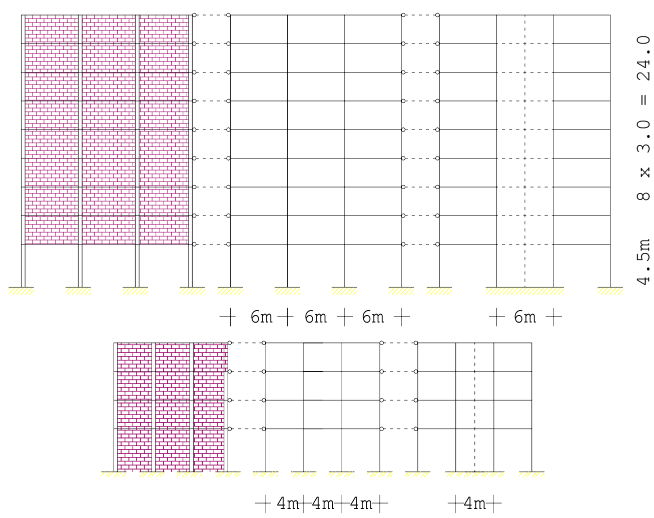

Fig. 4 Dual R/C buildings analysed: 9-storey irregularly infilled (top); 4-storey regularly in-filled (bottom)

Results of analysis

Some selected pushover curves in normalised form (V/W vs. D/H_{tot}) for the buildings analysed are given in Fig.5; they refer to dual regularly infilled buildings, designed to a “low” seismic code (in this case the 1959 Greek Code). It is worth noting the significant overstrength of the low-rise building (DRLL), mainly attributed to the large influence of the brick masonry infills. On the other hand, R/C members in the high-rise building (DRLH) are stronger, hence the contribution of infills is less pronounced and so is the resulting overstrength. Notably, all buildings to which Fig. 5 were designed for a base shear less than 10% of W, without any special provisions for ductility.

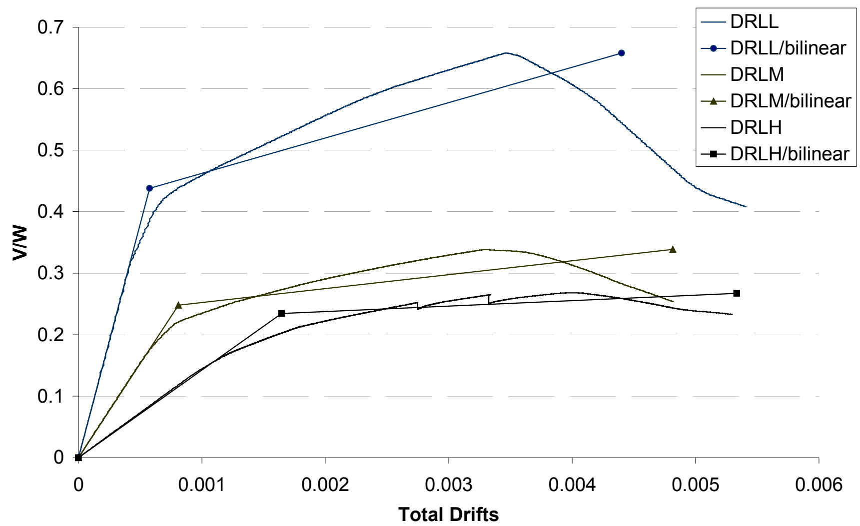

Fig. 5 Pushover curves for infilled dual structures

In addition to the actual curves calculated, bilinear versions are also shown in Fig. 5, based on the assumption of equal areas under the pushover curves; as a terminal point the one corresponding to the drift of the actual curve at the time the building has lost 30% of its maximum strength was taken. Table 1 summarises the parameters of these bilinear pushover curves (in terms of V vs. D) for all structures studied. Such curves are particularly useful in assessing the seismic vulnerability of buildings using analysis-based methods [4].

Conclusions

An extensive analysis of typical R/C building configurations, including brick masonry infill walls arranged either regularly or irregularly (creating soft-storeys) has been carried out. A rather sophisticated nonlinear constitutive law was used for describing the contribution of infills, together with a diagonal strut model. The proposed model was introduced into SAP2000 and was tested for stability through various pilot analyses of simple structures.

Table 1. Parameters for bilinear pushover curves

Building Type	Yield Capacity Point		Ultimate Capacity Point	
	D,y (m)	V (kN)	D,u (m)	V (kN)
FRLL	0.0062	632	0.023	896
FRLM	0.0113	654	0.035	983
FRLH	0.0388	875	0.097	1240
FILL	0.0239	151	0.113	168
FILM	0.0266	315	0.101	356
FILH	0.0488	760	0.112	916
DRLL	0.0043	1175	0.033	1765
DRLM	0.0109	1451	0.065	1980
DRLH	0.0469	2800	0.152	3192
DILL	0.0052	950	0.043	1254
DILM	0.0118	1300	0.064	1640
DILH	0.0417	2400	0.125	2875
DRHM	0.0156	1895	0.063	2267
DIHM	0.0151	1550	0.065	1930

The pushover curves derived for the various building configurations are very different from those describing the behaviour of bare R/C frames, in terms of strength, stiffness, and also displacement ductility. Significant overstrength of the low-rise building was found, mainly attributed to the large influence of the brick masonry infills. On the other hand, R/C members in the high-rise building (DRLH) are stronger, hence the contribution of infills is less pronounced and so is the resulting overstrength.

References

1 Kappos, A.J., Stylianidis, K.C., and Michailidis, C.N. (1998) "Analytical models for brick masonry infilled R/C frames under lateral loading", *Jnl. of Earthquake Engineering*, Vol. 2, pp. 59-88.

2 Dymiotis, C., Kappos A.J., and Chryssanthopoulos, M.C. (2001) "Seismic reliability of masonry infilled R/C frames", *Jnl. of Struct. Engng., ASCE*, Vol. 127, pp. 296-305.

3 Computers and Structures Inc. (2002) "SAP2000 – Version 8: Integrated software for structural analysis and design", Berkeley, California.

4 FEMA-NIBS 1999. Earthquake loss estimation methodology - HAZUS99 Technical Manual, Volumes 1-3, Washington DC.