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Analytical modeling of masonry infills with openings

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Abstract. In order to perform a step-by-step force-displacement response analysis or dynamic time-history analysis of large buildings with masonry infilled R/C frames, a continuous force-deformation model based on an equivalent strut approach is proposed for masonry infill panels containing openings. The model, which is applicable for degrading elements, can be implemented to replicate a wide range of monotonic force-displacement behaviour, resulting from different design and geometry, by varying the control parameters of the model. The control parameters of the proposed continuous model are determined using experimental data. The experimental program includes fifteen 1/3-scale, single-story, single-bay reinforced concrete frame specimens subjected to lateral cyclic loading. The parameters investigated include the shape, the size, the location of the opening and the infill compressive strength. The actual properties of the infill and henceforth the characteristics needed for the diagonal strut model are based on the assessment of its lateral resistance by the subtraction of the response of the bare frame from the response of the infilled frame.

Keywords: infilled R/C frames; masonry infills; openings; experimental results; analytical modeling.

1. Introduction

A large number of buildings are constructed with masonry infills. For the influence of infill panels on structural performance controversial results and conclusions have been reported, and henceforth no code provisions or rational guidelines are still available for the design and safety assessment of such structures. The contribution of infills to lateral stiffness and strength of frames is usually neglected during the design of new buildings. On the other hand, retrofit of older buildings for seismic resistance requires an accurate evaluation of the building response including the contribution of the existing infills (Ellul and D'Ayala 2004, Dritsos 2005). Therefore, appropriate analytical tools for elastic and inelastic analysis of reinforced concrete frames with masonry infills need to be developed and verified through laboratory tests (Abrams 1994). The lateral load behavior of frames with masonry infills is usually studied taking into account the influence of the masonry using diagonal struts which can transfer only the compressive force between the diagonally opposite joints (FEMA 356 2000). A key point of this approach is the determination of the actual hysteretic rule parameters of the equivalent diagonal compression strut. The conditions required for a compression strut to develop must be present too. Openings, interface gaps and other discontinuities may affect development of a compression diagonal (Moghaddam and Dowling 1987). A coordinated

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experimental and analytical research program has been under way. One of the purposes for this study was to experimentally investigate the inelastic behavior of brick masonry infilled frames so that improved modeling can be developed for the design of new structures with infilled frames. This paper presents the initial results of this effort.

The numerical simulation of infilled frames is difficult and generally unreliable, essentially because of the very large number of phenomena to be taken into account and of the tremendous uncertainties associated with most of them (CEB 1996). The models proposed and implemented reflect this situation, being limited in number and in power of simulation. From the point of view of the simulation technique the models may be divided into fundamental (or micro-) models and simplified (or macro-) models. The first class includes models based on a finite element representation of each infill panel, in which case appropriate constitutive relations of the materials used for the construction of the infills are required (Shing *et al.* 1994, Mosalam *et al.* 1994, Kariotis *et al.* 1994). The second class comprises models based on a physical understanding of the behaviour of an infill panel as a whole: in some cases a single (or few) element simulates each infill panel, identified as a structural member with its own behavior (Mainstone 1971).

The idea of modeling an infill panel with a single element able to simulate the global effect of the panel on the response of the structure has always been attractive because of the obvious advantages in terms of computation simplicity and efficiency. Since the first attempts to produce simplified models, a few experimental and conceptual observations indicated that a diagonal strut with appropriate mechanical characteristics could possibly provide a solution to the problem (FEMA 306 1999). The higher shear stiffness of the infill panel relative to the frame, the usually low tensile and shear strength at the interface between frame and infill, the probable micro-cracking in the corner of the infill where tensile stresses are dominating, all contributed to the suggestion that a diagonal strut could be considered a realistic simplification of the actual situation. More recently, it became clear that one single strut element is unable to condense complex phenomena such as strength and stiffness degradation under alternate cyclic loading, out-of-plane expulsion after diagonal cracking, or possible shear sliding along bed joints at approximately mid-height of the panel. More complex simplified models were then proposed, usually still based on a number of diagonal struts (Chrysostomou and Gergely 1992, Mander *et al.* 1994, Gergely *et al.* 1994). The earliest model that simulates the infill behavior with non-linear diagonal struts was proposed by Klingner and Bertero (1976); it is the first example of a stiffness degrading model, in which one of the two diagonal struts alternately reacts when the loading reverses its sign. In spite of the fact that the numerical results did not match correctly those obtained experimentally, the abovementioned model served as an important reference for the following works. Essentially, progress consisted of the introduction into the strut model of an increasing number of features characterizing the actual behavior. Presently available models account, for example, for the effects of the diagonal tensile stress, for the crushing near the compressed corners, etc. (Saneinejat and Hobbs 1995).

Macro-models are generally more appropriate for the overall simulation of infilled frame structures (Combescure and Pegon 2000). It has been proven in the past that the non-linear response of bare frames can be represented adequately using member type models, and a great effort is presently being made around the world to extend the ability of such models to represent specific phenomena related to seismic response, such as the dependence of shear strength and deformability on flexural ductility (Mosalam 1997, Papia *et al.* 2002). The further development of member type models for infill panels, to be used in conjunction with refined R/C elements, is probably the most promising future advancement for the simulation of the global behavior of infilled frames (Reinhorn *et al.* 1995, Dolsek and Fajfar 2002, Karayannis *et al.* 2005). An important possible application of such models consists in the verification and validation of more simplified model. None of the computer codes commonly used around the world is endowed with rational and specific elements to simulate accurately the presence of infills.

In the present context, considering that many aspects have not been clarified, an experimental investigation has been carried out, as will be shown in the following sections, and an analytical model for masonry infill with openings has been developed reproducing the behavior that has been observed. The objective of the experimental program presented herein is two-fold. First it is intended as a parametric study for evaluation the performance of masonry-infilled R/C frames with openings, that are representative of current construction practice, under in-plane lateral cyclic loads. Secondly, it is intended to identify the control parameters of the proposed continuous model for non-linear analysis of large buildings.

2. Experimental data

2.1 Experimental program

The experimental program as shown in Table 1 and Fig. 1 consisted of fifteen tests of single - story one - bay 1/3 - scale specimens of reinforced concrete frames with infills of “weak” clay brick and “strong” vitrified ceramic brick. The program results provide data for the evaluation of the influence of different opening shapes, different opening sizes, different opening locations and different infill compressive strengths on the surrounding frames. The program included the test of: reference frame specimens (bare frame and frame specimens with solid weak and solid strong

Table 1 Test specimens

Specimen notation	Opening shape		Opening size l_a/l				Opening location x/l			Masonry type	
	Window	Door	0	0.25	0.38	0.50	0.17	0.33	0.50	Weak	Strong
B	Bare	Bare									
S	Solid	Solid	•							•	
WO2	•			•					•	•	
WO3	•				•				•	•	
WO4	•					•			•	•	
DO2		•		•					•	•	
DO3		•			•				•	•	
DO4		•				•			•	•	
WX1	•			•			•			•	
WX2	•			•				•		•	
DX1		•		•			•			•	
DX2		•		•				•		•	
IS	Solid	Solid	•								•
IWO2	•			•					•		•
IDO2		•		•					•		•

l = length of masonry infill, l_a = width of opening, x = distance between opening center-edge of infill.

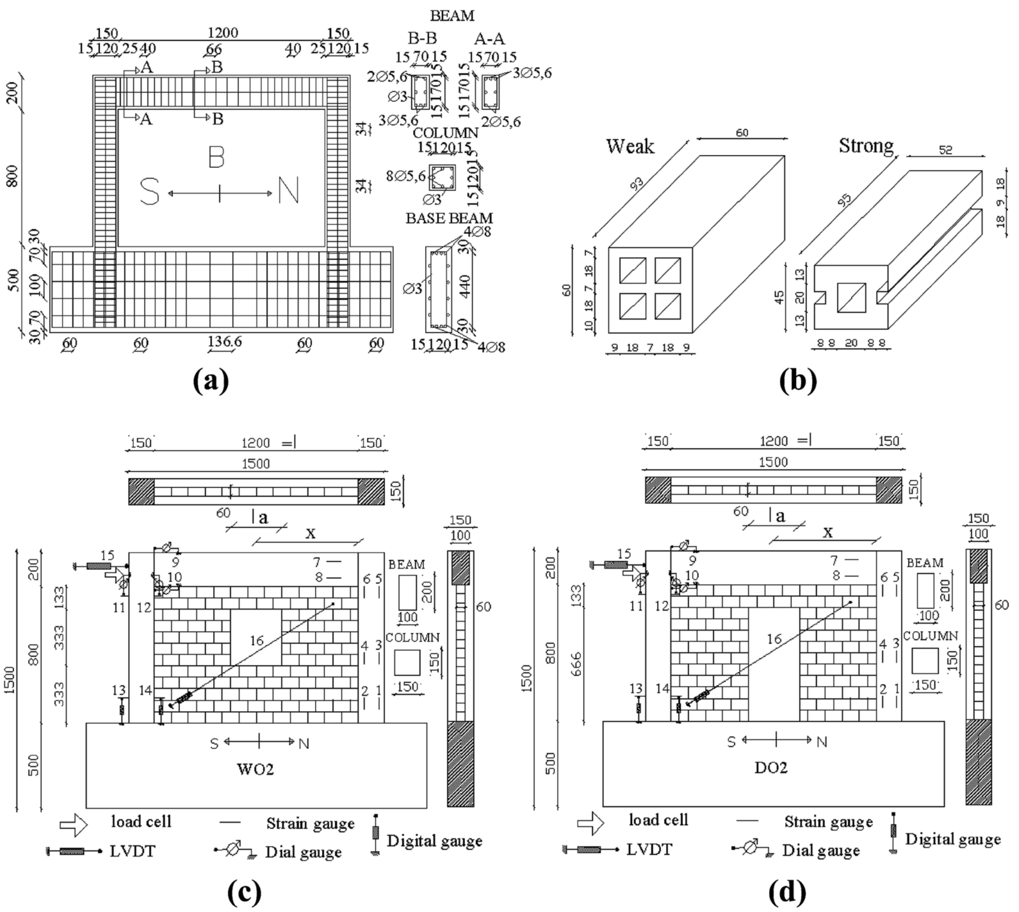


Fig. 1 Description of infilled frame specimens and instrumentation (mm): (a) reinforcement detailing of the R/C frame model, (b) weak and strong brick units, (c) specimen with window opening and instrumentation, (d) specimen with door opening and instrumentation

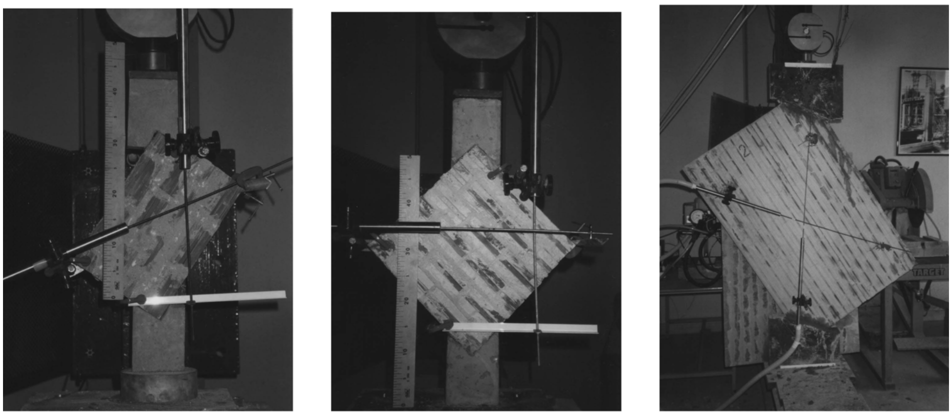
infills), frame specimens with concentric window and door opening with three sizes, frame specimens with eccentric window and door opening in infills with two eccentricities, frame specimens with concentric window and door opening in weak and strong infills.

The geometric characteristics of the R/C 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 Fig. 1(a). 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, as shown in Fig. 1(b).

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. The diagonal compression tests of masonry panels with various length L_i to height H_i ratios and full size panels as well are presented in Fig. 2. The latter

Table 2 Mechanical properties of the used material (MPa)

Mechanical properties		Weak masonry t = 6 cm	Strong masonry 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 voids	f_c	2.63	15.18
Elastic Modulus ⊥ to voids	E	660.66	2837.14
Compressive strength // to voids	f_{c90}	5.11	17.68
Elastic Modulus // to voids	E_{90}	670.3	540.19
Shear Modulus	G	259.90	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 masonry panels of length* L_i *and height*		0.33/0.22	0.26/0.17
H_i, $f_v/f_n=L_i/H_i$		0.30/0.30	0.60/0.61
* O*n full size infills L/H=120 cm/80 cm*		0.21/0.37	0.39/0.72
		0.20/0.73	0.41/1.55



(a) **(b)** **(c)**

Fig. 2 The diagonal compression tests: (a), (b) masonry panels with various length L_i to height H_i ratios, (c) full size masonry panels

tests determine the shear strength of the bed joints f_v subjected to normal stress f_n ($f_v/f_n = L_i/H_i$).

The test setup of the infilled frames is shown in Figs. 1(c), (d). The lateral load was applied by means of a double action hydraulic actuator. The vertical loads applied at the top of the columns were equal to 50 kN (0.1 of the ultimate load). One LVDT measured the lateral drift of the frame and one load cell measured the lateral force of the hydraulic actuator. The loading program included full reversals of gradually increasing displacements. Two full loading cycles were applied for each displacement level. The cycles started from a ductility level equal to 0.8 corresponding to an amplitude of about ±2 mm (yield initiation displacement is considered as ductility level μ = 1). The

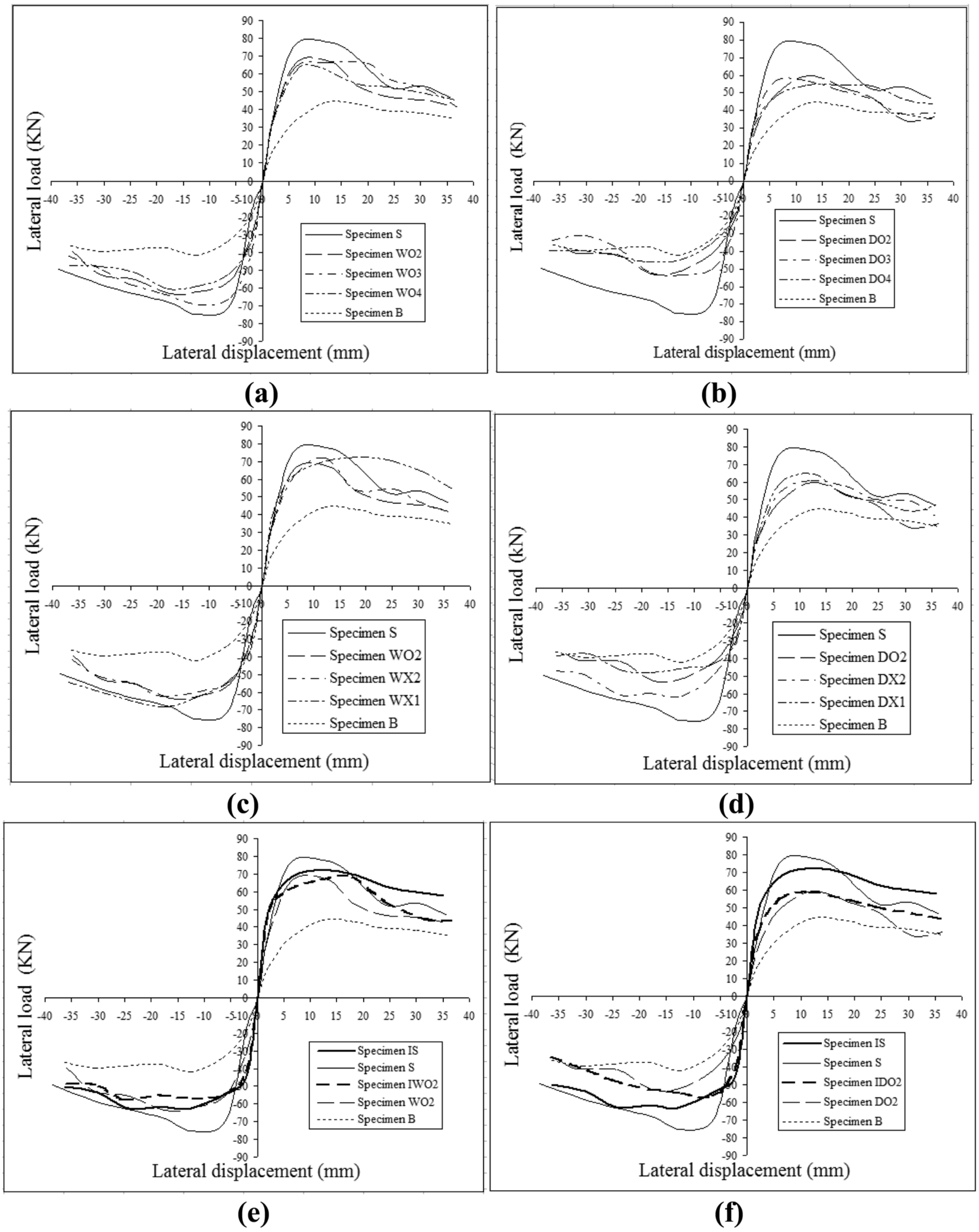


Fig. 3 Lateral Load against displacement envelops: (a) Window openings of various seizes, (b) Door openings of various seizes, (c) Window openings of various locations, (d) Door openings of various locations, (e) Weak and strong infill with window, (f) Weak and strong infill with door

main output of the experimental investigation was a load against displacement hysteretic curve for each frame. The complete information and detailed results of the aforementioned experimental study have been reported by Karayannis and Kakaletsis (2006), Kakaletsis and Karayannis (2007), and Kakaletsis and Karayannis (2008). The hysteretic response envelopes are shown in Fig. 3. It must be pointed out that the hysteretic characteristic values of the weak masonry infill are in some cases higher than the corresponding ones of the strong masonry infill. It may be attributed to the larger units of the weak masonry infill.

2.2 Net infill contribution to the frame resistance

In order to perform a step-by-step force-displacement response analysis or dynamic time-history analysis of large buildings with masonry infilled frames, a continuous force-deformation model for masonry infill panels is required. Such a model is suggested herein.

When the infill is present a diagonal strut action is formed and the action of the system as a whole is mobilized. Therefore, the net response of the infill, V_{INFILL}, is thus obtained by subtracting the bare frame load for a given drift from the infilled frame response. It is therefore assumed that

$$V_{INFILL} = V_{TOTAL} - V_{FRAME}$$

where V_{TOTAL} is the force resisted by the infilled frame and V_{FRAME} is the force resisted by the bare R/C frame after the bricks had been removed.

So, from the hysteretic response envelopes of the infilled frames presented in Fig. 3, the net response of the infills was obtained by subtracting the bare frame load for a given drift from the gross infill frames response. These differences represent the contribution of the wall to the strength of the infilled frame, include the influences of the interaction between the infill with opening and the frame and consequently are strongly dependent on the geometric and the mechanical characteristics of both the R/C frame and the infill. Fig. 4 respectively, shows the net performance of the infills.

3. Proposed model

3.1 Idealization of force-deformation curve

From Fig. 4 it is concluded that the monotonic force-deformation curve of the panel in shear can be approximated by a four-branch curve having two ascending and one descending linear branches with a horizontal residual strength branch for very large values of the panel deformation. The corner between the first two branches corresponds to cracking and that between the second and third branch to ultimate strength of the panel. These points are defined as the intersections of straight trend lines of the experimental points. A small overestimation of the cracking and ultimate strength is observed but it is of an acceptable order of magnitude. The curve can be easily defined with the aid of the following control parameters:

1. The slope of the elastic branch representing the initial stiffness K_1 normalized to the initial stiffness of the solid infill K_{1S}, (K_1/K_{1S}).
2. The ultimate strength V_u normalized to the ultimate strength of the solid infill V_{uS}, (V_u/V_{uS}).
3. The hardening ratio of the post-cracking branch, $\rho_1 = K_2/K_1$.
4. The cracking force V_{cr} to ultimate strength V_u ratio, (v_1).

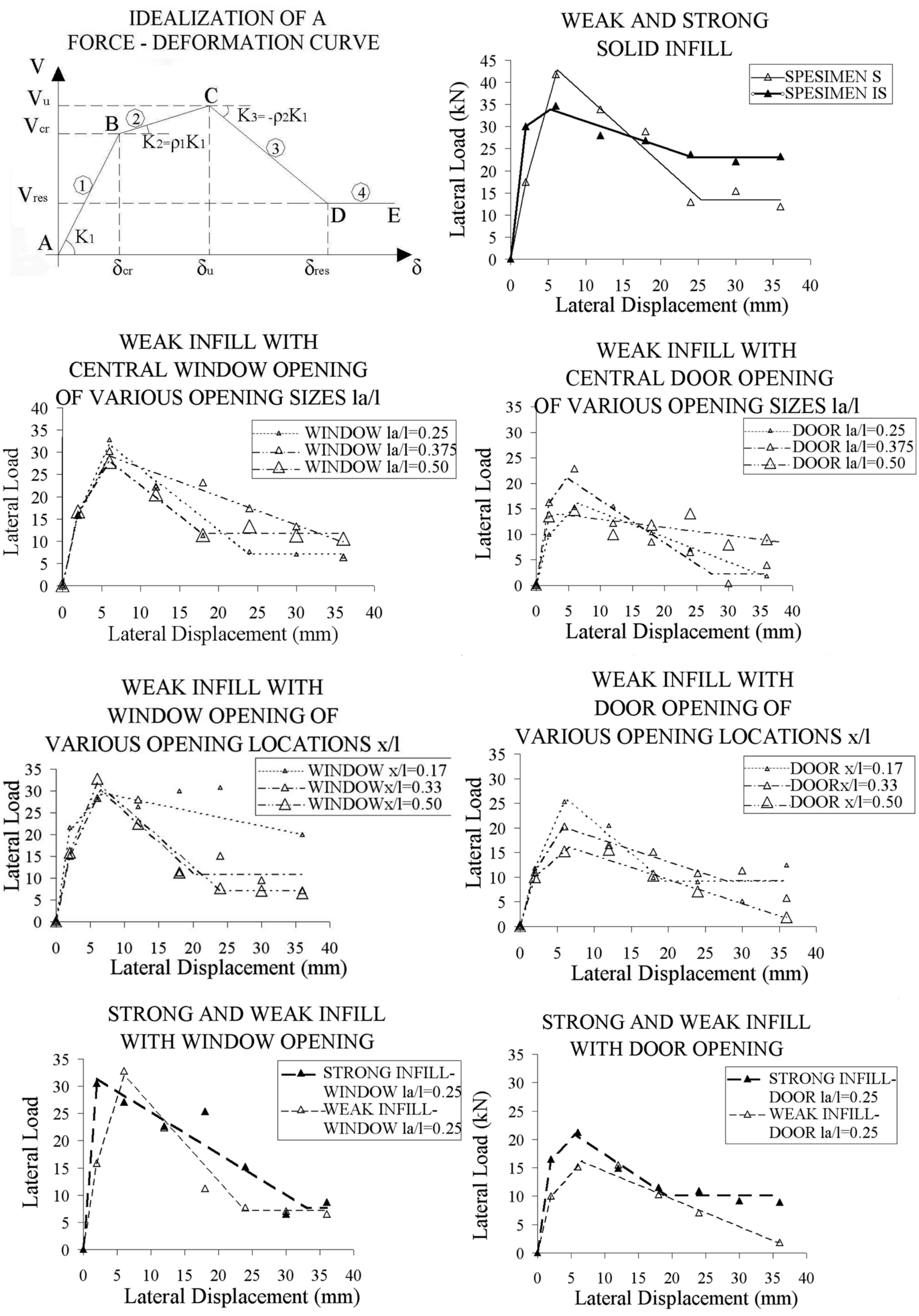
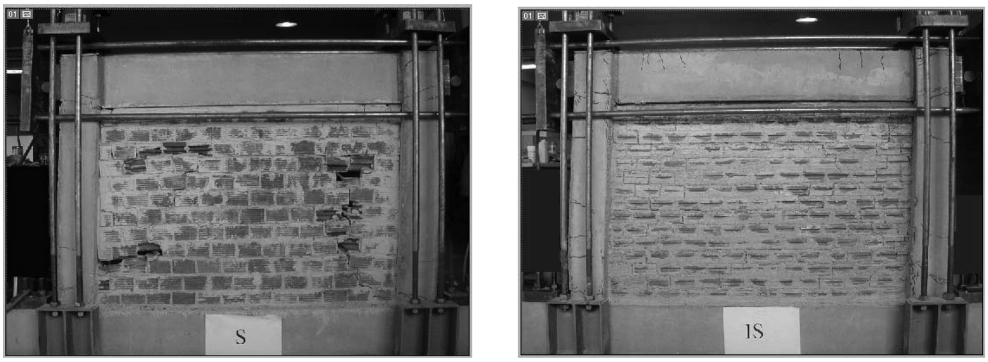


Fig. 4 Four-branch approximation of the monotonic force-deformation curve of the infill



(a) **(b)**

Fig. 5 Failure mechanisms of the solid infill: (a) compression failure of the weak solid infill, (b) shear-sliding failure of the strong solid infill

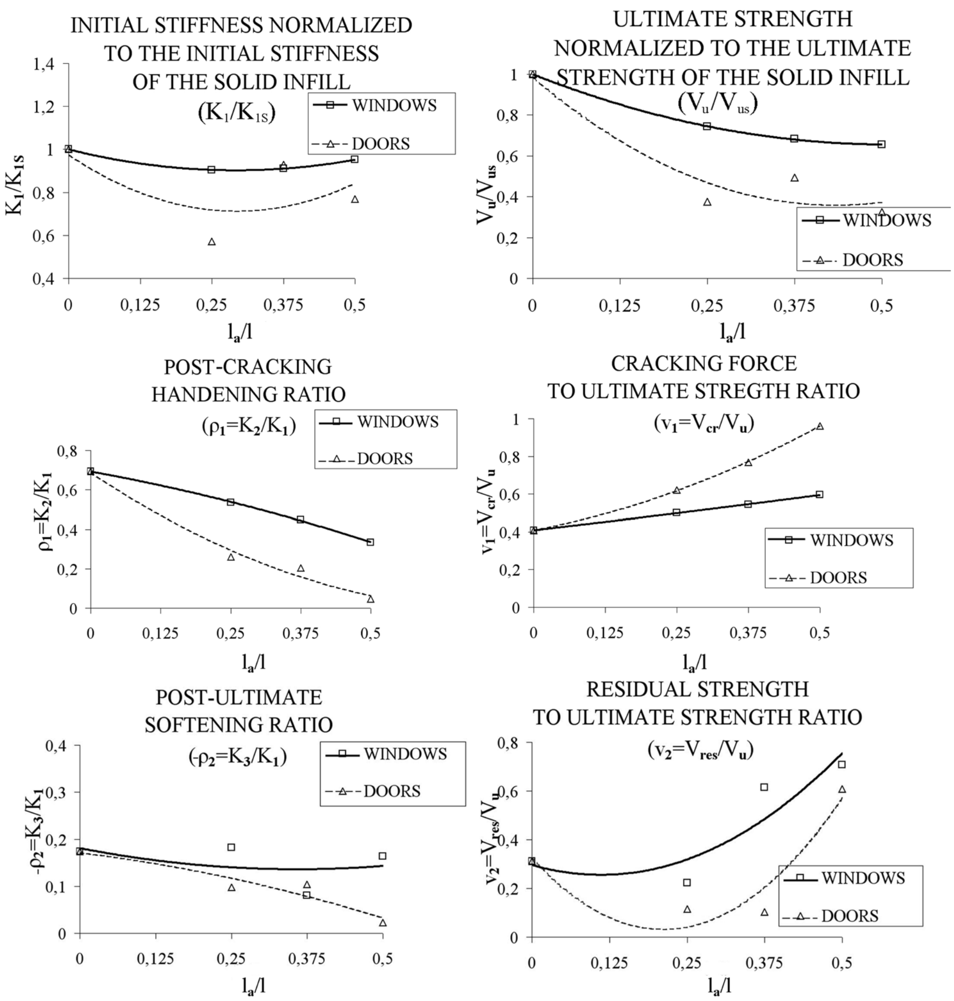


Fig. 6 Control parameters of the proposed model against window and door central opening sizes

5. The softening ratio of the post-ultimate branch, $-\rho_2 = K_3/K_1$.

6. The residual strength V_{res} to ultimate strength V_u ratio, (v_2).

The model can be implemented to replicate a wide range of monotonic force-displacement behavior resulting from different design and geometry by varying the control parameters of the model. The control parameters of the proposed continuous model for infill panels containing openings can be determined from the values of V_{uS} and K_{1S} provided by the failure mechanism of the solid infill according to FEMA 306 (1999). Herein, as shown in Fig. 5, the ultimate load for strong solid infill is due to shear-sliding failure and the ultimate load for weak solid infill is due to compression failure.

The values of the control parameters of the proposed model vs the window and door opening

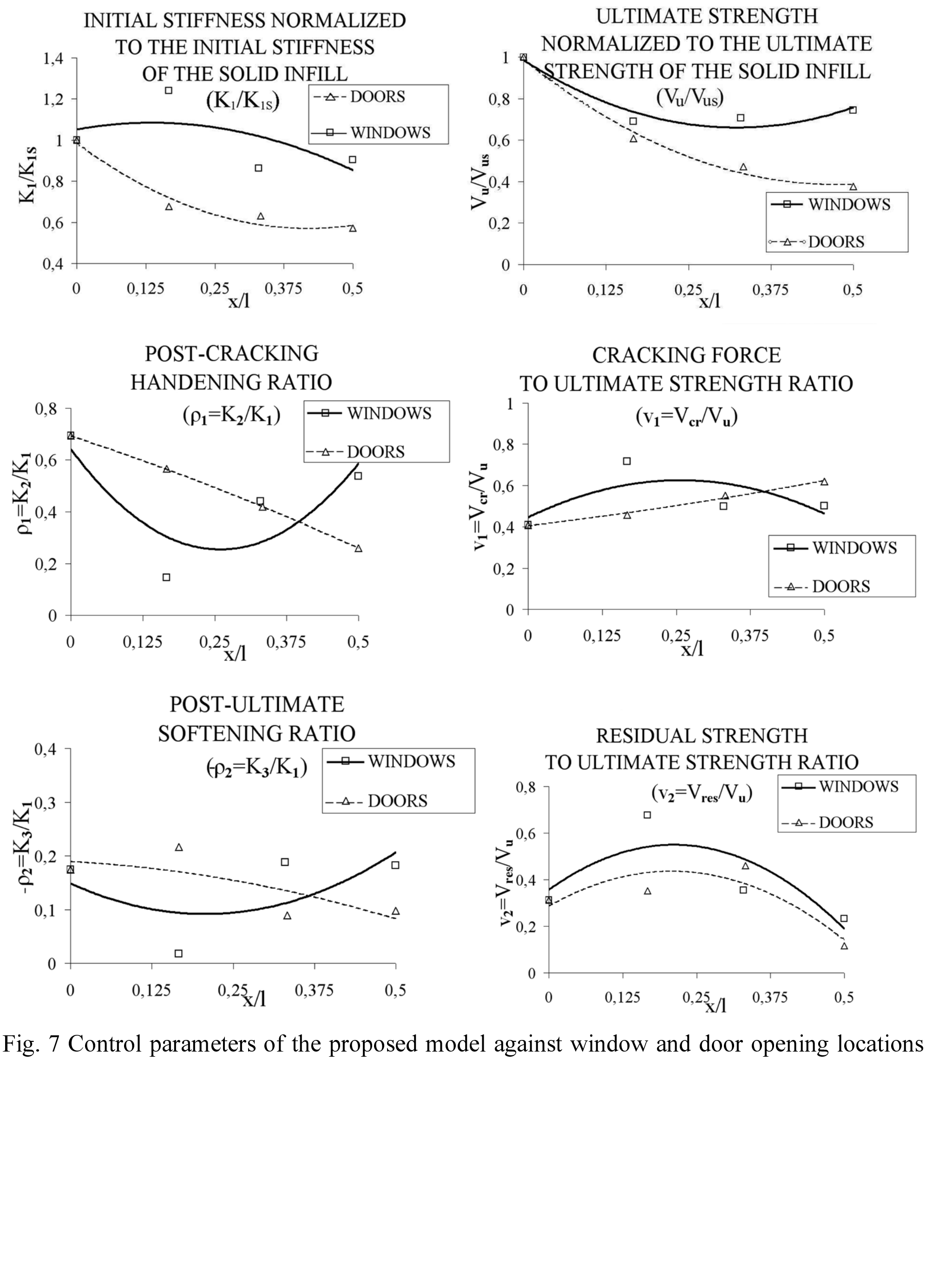


Fig. 7 Control parameters of the proposed model against window and door opening locations

width, the window and door opening location and the masonry strength, provided by various parametric combinations of the experimental specimens, are shown in Figs. 6, 7, 8 respectively.

The hysteretic response of an infilled frame can be calculated using existing inelastic analysis computer programs capable of analyzing R/C structures, such as DRAIN-2DX by Prakash *et al.* 1993, in which a model representing the behavior of the infills with openings, as it is established in Fig. 4 has been incorporated. Infill panels are modeled through diagonal struts, which are effective only in compression and follow the interstorey shear-drift relation of Fig. 4. The approach used is not dependent on the infill to R/C frame relative strength, has a general validity and introduces a new way of examining the behavior of the infills with openings. Simulations of experimental force-deformation behavior of prototype infill frame subassemblages have been performed to validate the

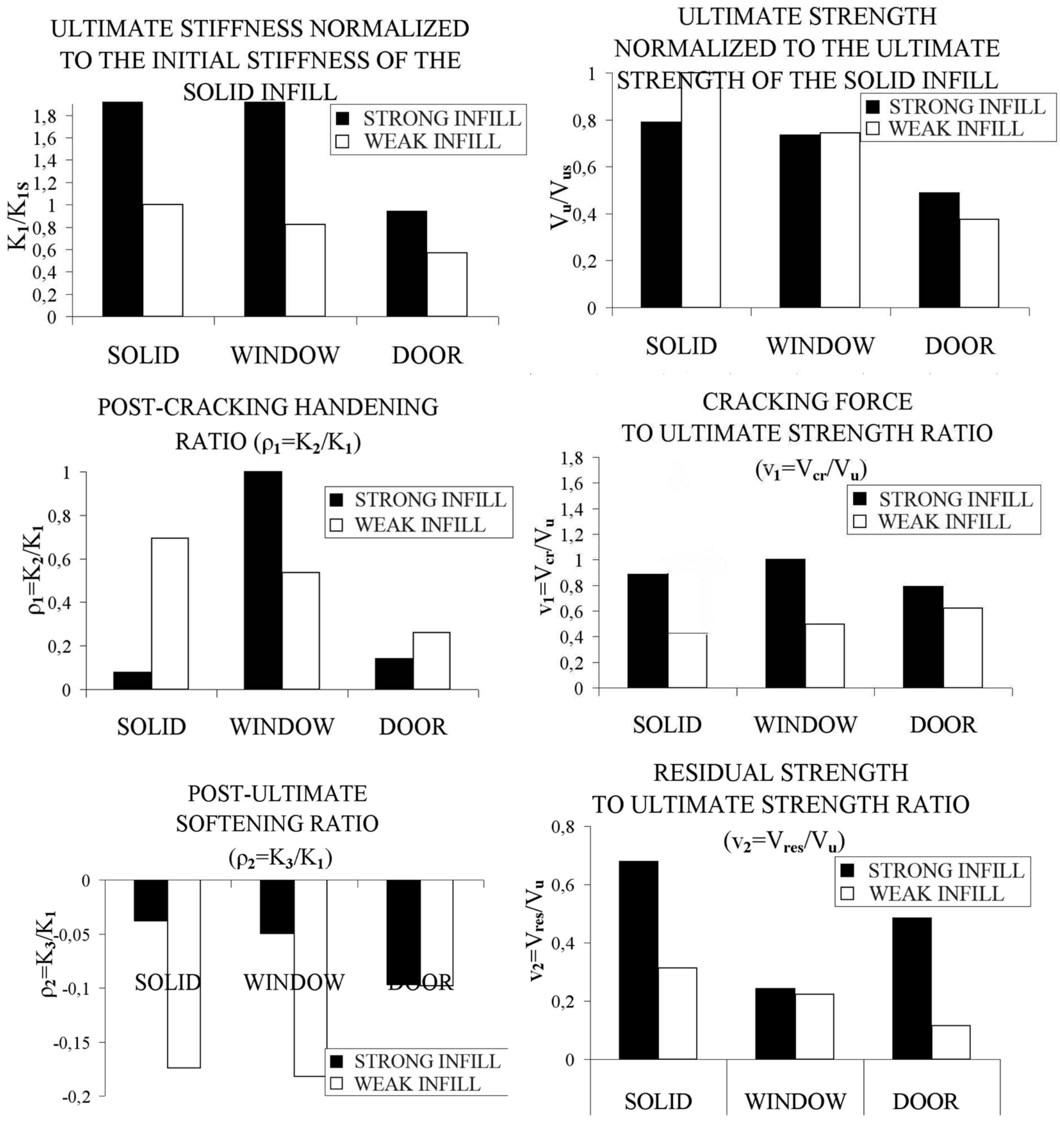


Fig. 8 Control parameters of the proposed model against infill strength

proposed model for the solid infill and have been presented by Karayannis *et al.* (2005). The use of the proposed model in non-linear analysis for strong ground motions of building structures, to evaluate the influence of masonry infill panels with openings on the response, is outside the scope of this experimental study, and is left for a future investigation.

3.2 Comparison of the proposed model

Herein, the ultimate load, V_{uS} and the initial stiffness, K_{1S} for the solid infill are taken according to Fardis and Panagiotakos (1997) model of the solid infill. According to this model the monotonic curve is trilinear with a horizontal residual strength branch for very large values of the panel deformation. The corner between the first two branches corresponds to cracking and that between the second and third branch to ultimate strength of the panel. The parameters in this model of the monotonic force-deformation curve of the solid panel in shear up to ultimate strength are determined as follows:

The slope of the elastic branch, K_{1S}, is taken equal to GA/h, in which G is the Shear Modulus of the panel as measured in diagonal compression tests of wallettes at 45° to the bed joints (Fig. 2 and Table 2), A the horizontal cross-sectional area of the panel and h its clear height. The cracking force V_{cr} is taken equal to $f_v \cdot A$, with f_v denoting the shear stress on bed joints at failure of the wallette specimens in diagonal compression (Fig. 2 and Table 2). The ultimate strength V_{uS} is taken equal to $1.3V_{cr}$ and the deformation at ultimate is determined from the corresponding secant stiffness of the panel equal to the product of the Elastic Modulus in the weak (horizontal) direction of the masonry, E_{90}, times the thickness, t, times the equivalent strut width, a, according to the Mainstone (1971)

Table 3 Comparison of the control parameters of the proposed model and the Fardis and Panagiotakos (1997), model

Infill wall description		K_{1S} (kN/mm)	V_{uS} (kN)	K_1/K_{1S}	V_u/V_{uS}	$\rho_1 = K_2/K_1$	$v_1 = V_{cr}/V_u$	$-\rho_2 = K_3/K_1$	$v_2 = V_{res}/V_u$
				Control parameters of the proposed model for infill walls with opening					
Door	l_a/l = 0-0.5 Weak infill	8.75	42.82	1-0.57	1-0.33	0.69-0.05	0.41-0.96	0.17-0.02	0.31-0.61
Wind.				1-0.90	1-0.65	0.69-0.33	0.41-0.60	0.17-0.08	0.31-0.71
Door	x/l = 0-0.5 Weak infill			1-0.57	1-0.38	0.69-0.26	0.41-0.62	0.17-0.09	0.31-0.12
Wind.				1-0.86	1-0.69	0.69-0.54	0.41-0.72	0.17-0.02	0.31-0.23
Door	l_a/l = 0-0.25 Strong infill	15	33.86	1.71-0.95	0.79-0.73	0.08-0.14	0.89-0.79	0.04-0.10	0.68-0.48
Wind.				1.71-1.74	0.79-0.49	0.08-1	0.89-1	0.04-0.05	0.68-0.24
				Control parameters of the Fardis and Panagiotakos (1997) model for solid infill walls					
Solid infill	Weak	23.35	35.57	1	1	0.20-0.10	0.77	0.005	-
	Strong	27.41	33.26	1.17	0.94				

l = length of masonry infill, l_a = width of opening, x = distance between opening center-edge of infill, K_{1S} (kN/mm) = initial stiffness for the solid weak infill, V_{uS} (kN) = ultimate strength for the solid weak infill, K_1/K_{1S} = normalized initial stiffness, V_u/V_{uS} = normalized ultimate strength, ρ_1 = hardening ratio of the post-cracking branch, v_1 = cracking force V_{cr} to ultimate strength V_u ratio, $-\rho_2$ = softening ratio of the post-ultimate branch, v_2 = residual strength V_{res} to ultimate strength V_u ratio expression, times the square of cosθ, over the frame diagonal length, where θ is the angle whose tangent is the infill height-to-length aspect ratio. With so determined cracking and ultimate points, the post-cracking hardening ratio $\rho_1 = K_2/K_1$ typically takes values between 1/5 and 1/10. This selection of panel parameters was found to provide the best (among various other simple alternatives) agreement with the few available tests on infill panels, in which measurements of masonry properties on wallettes are also available. The post-ultimate softening ratio, $\rho_2 = K_3/K_1$ is taken equal to 0.5%.

Using the dimensions shown in Fig. 1 and Table 1 and the material properties for the full size panels listed in Table 2, the control parameters based on the Fardis and Panagiotakos (1997) model are calculated and are summarized, with the control parameters of the proposed model, in Table 3.

The comparison shows that the values of the proposed model for the ultimate strength, V_{uS}, and initial stiffness, K_{1S}, for the solid infill are in good compliance with the values of the Fardis and Panagiotakos (1997) model. However, it should be noted that different failure mechanisms of the solid infill on which the behavior characteristics are dependent, contribute to the discrepancy of the quantitative results.

Comparing the proposed control parameters with the parameters of the similar work from Fardis and Panagiotakos (1997) model, one observes the reasonable correlation between the values obtained in the present study and those from that research.

4. Conclusions

1. The paper presents an alternative non-linear continuous model for masonry infill walls with opening. The model is based on the commonly used equivalent tie and strut approach in which the envelope properties of the strut are determined based on test data to define idealized multi linear load-deformation relations of infill panel with opening. The envelope model constitute a more efficient analytical alternative to the micro-models (i.e. finite element based) for analysis of complex structures in which the infill is just one component.

2. The envelope model determines the equivalent properties of the strut i.e. the stiffness and control force-deformation points based on behavior of infill panel and its interaction with the enclosing frame. The deterioration parameters are determined from the analysis of experimental data and are based on the assessment of infill's lateral resistance by the subtraction of the response of the bare frame from the response of the infilled frame. The values of the parameters are given vs the window and door opening width, the window and door opening location and the masonry strength.

3. The generalized load-deformation relation, appropriate for most infill panels with openings, is described by linear response to an effective yield point, followed by linear response at reduced stiffness with strain hardening, followed by strength degradation, followed by response at reduced resistance thereafter. The resulting hysteretic strut model is suitable for use in non-linear analysis - monotonic static "push-over" or time-history analysis of complex frame systems and provides a convenient and versatile analytical tool for simulating and predicting the response of framed structures with masonry infill panels with opening.

4. The macro-modeling approach presented herein considers the entire infill panel as a single unit and takes into account only the equivalent global behavior of the infill in the analysis. As a result, the approach does not permit study of local effects such as frame-infill interaction within the individual infilled frame subassemblies. More detailed micro-modeling approaches such as the finite

element models need to be used to capture the spatial and temporal variations of local conditions within the infilled frames by multiplicity of small elements each satisfying equilibrium and compatibility. However, the approach allows for adequate evaluation of the non-linear force-deformation response of the structure and individual components under seismic loading.

5. The experimental results indicate that the presence, behavior and failure of the infills even in the cases with openings can significantly improve the performance of R/C frames. However, the author's choice of reversed cyclic, pseudo-static testing of one-bay, one-story frames has inherent limitations for evaluation the performance of masonry-infilled R/C frames with openings that must be acknowledged. One of the most serious potential problems with infilled frames is that failure of all the infills on a particular level leads to the formation of a single-story mechanism at that level, greatly increasing the nonlinear deformation demand in column elements at that level. Tests on single-story models cannot provide information on this. It would be necessary to be developed an analytical element reproducing the behavior that has been observed, and then to be used that element in a multi-story frame subjected to a range of realistic earthquake motions, in the time-history analysis. That would enable one to observe the conditions under which infills might be beneficial, and the conditions under which they might be harmful. That would in turn permit one to make recommendations for design.

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