Structural Engineering and Mechanics, Vol. 21, No. 4 (2005) 469-494
DOI: http://dx.doi.org/10.12989/sem.2005.21.4.469

Infilled frames: developments in the evaluation of cyclic behaviour under lateral loads

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(Received December 8, 2004, Accepted August 25, 2005)

Abstract. In order to consider the modified seismic response of framed structures in the presence of masonry infills, proper models have to be formulated. Because of the complexity of the problem, a careful definition of an equivalent diagonal pin-jointed strut, able to represent the horizontal force-interstorey displacement cyclic law of the actual infill, may be a solution. In this connection the present paper, continuing a previous work in which a generalised criterion for the determination of the ideal cross-section of the equivalent strut was formulated, analizes some models known in literature for the prediction of the lateral cyclic behaviour discussing their field of validity. As a support of the discussion, the results of an experimental investigation involving single story-single bay infilled reinforced concrete. Frames under vertical and lateral loads with different kind of infill (actually not yet so much investigated) are presented. Finally, an improvement of a model known in the literature is proposed, taking the results of the experimental tests before mentioned into account.

Key words: infilled frames; masonry infill; stiffening effect; hysteretic behaviour; simplified model; equivalent strut.

1. Introduction

Though infills are considered non-structural, they radically modify the frame response under lateral loads. Commonly, infill panel may stiffen its bounding frame laterally by one order of magnitude and it may increase its ultimate strength up to four times. Many parameters influence these variations in strength and in stiffness: the system geometry, the mechanical characteristics of the materials used for infill, etc.

The interaction between infill and frame may or may not be beneficial to the performance of the structure under seismic loads as experienced in recent earthquakes. For this reason the evaluation of the effect of infills on frames is basic.

Historically, the attempts to evaluate the stiffening and the strengthening offered by infills or to define simplified mechanical response laws have been preceded by experimental tests leading to different solution criteria. Holmes (1961) was interested in infilled (steel) frames and, on the basis

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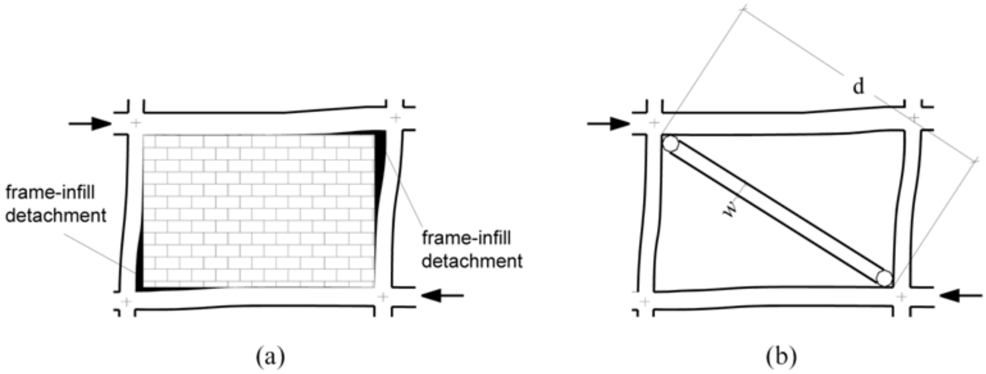


Fig. 1 Infilled mesh (a) state of frame-infill joint under horizontal loads, (b) simplified scheme based on an equivalent pin-jointed diagonal strut

of the experimental evidence (the detachment of the frame from the infill as shown in Fig. 1a), proposed replacing the infill panel with an equivalent strut made of the same material, having a width w equal to 1/3 of the infill diagonal length d (Fig. 1b). The lateral strength of the system was obtained by computing the horizontal component of the axial strength of the strut.

The idea of strut proposed by Holmes has been a long used later (e.g., Stafford Smith 1966, Stafford Smith and Carter 1969, Mainstone 1974, Klingner and Bertero 1978, Durrani and Luo 1994, Saneinejad and Hobbs 1995). Nevertheless, the approach based on a finite element representation (micro model approach) of the infill has been also followed. Surely, this approach requires much more computational effort in comparison to the use of the strut, but it gives the advantage to predict the local effects produced by the interaction frame-infill. Among the first researchers interested in micro model approach, Mallick and Severn (1967) have to be remembered, addressing the problem to an appropriate representation of the interface conditions between frame and infill. Further researchers, developing the idea of Mallick and Severn, interested in frame-infill interaction later (e.g., Rivero and Walker 1984, Papia 1988, Mehrabi and Benson Shing 1997).

Although many researchers have worked on infilled frames, analytical investigations available in the literature show that the results obtained are strongly influenced by the approach used. Similarly, the results of experimental investigations are influenced by the types of infill and the types of test. One arrives to this conclusion also by examining and by comparing results of further researchers, different from the ones mentioned before (e.g., Bertero and Brokken 1983, Valiasis *et al.* 1993, Panagiotakos and Fardis 1996, Madan *et al.* 1997), here not commented on in detail for brevity's sake.

On the whole, from the literature it is possible to have qualitative rather than quantitative information, without the possibility of generalising the different empirical expressions proposed for the evaluation of the lateral stiffness, for the evaluation of the lateral collapse load and for modelling the hysteretic behaviour to be used for practical applications.

As a consequence of what above, the work presented in this paper would be an attempt to give a contribution to the definition of a general procedure for modelling the behaviour of infilled frames to be adapted to any particular situation.

In a previous work (Papia *et al.* 2003) the elastic behaviour of infilled frames was studied in order to find the relationship between the characteristics of the infill and the dimensions of the equivalent strut, that is the first step for the definition of a complete law for the prediction of the response under cyclic loads as will be discussed later. Papia *et al.* (2003), in contrast with the available methods for the determination of the width of the strut and the definition of the lateral stiffness of the system, showed that the cross-section of the strut depends also on the axial stiffness of the elements constituting the frame, especially the columns. Beginning from that work, in this paper, the behaviour after the elastic stage is studied: first, the results of an experimental investigation are described, being this investigation required by few data available in the literature, also considering that many aspects of the problem have not been completely clarified yet (for example the role of the vertical loads for the lateral response of infilled frames (Cavaleri *et al.* 2003); subsequently, considering that the available modelling criteria are not totally suitable for describing the results of the experimentation, a development of a known model, given in the literature, is proposed. During the experimental study, the attention was focused on frames that, as many existing ones, do not respect the code provisions for seismic areas (because they were made before the code provisions themselves). In the opinion of the authors, for this kind of frames the study of the effect of infills is relevant both for the positive and negative influences that infills may have: in the positive case the strength of infills may make up for the deficiencies of the frames while in the negative case infills may anticipate the collapse more than in the case of seismic frames.

2. Experimental investigation

2.1 Prototype structure and test specimens

A single story-single bay reinforced concrete moment-resisting frame was selected as a prototype structure under vertical and horizontal loads. The ratio between the lengths of the bay and the column was 1. A weak frame was considered representing existing reinforced concrete frames that do not meet the detailing requirements of the current system design provisions. The specimens were chosen to be approximately ½-scale models. The details of the specimens are shown in Fig. 2. Close to the nodes column-beam, an increase of the section of the beams and the columns can be observed, which is constituted by non reinforced concrete having the function to locate two diagonal struts and to observe the difference between the behaviour of the frame with infill and the behaviour of the frame with diagonal struts in the prosecution of the research.

The masonry infill was made by a professional mason after the frame was completed. The bed joints and the vertical ones were made as in building practice. The joint between the frame and the infill masonry was made by mortar. The specimens were tested at least 28 days after the construction of the infill.

Eight infilled specimens (labelled from I_1 to I_8) and two further bare ones (respectively labelled B_1 and B_2) were investigated.

Previously, the bare frames were tested in order to observe their elastic characteristics and their lateral strength. Then, the infilled frames were tested. Two types of masonry were used for the infills, therefore two different groups constituted by four infilled frames were studied. The first type of infill was made by using calcarenite blocks, having nominal dimensions $21 \times 36 \times 16$ cm, assembled following the scheme in Fig. 3(a) and characterised by approximately 10 mm bed and vertical mortar joints. The second one was constructed with nominal $30 \times 24 \times 14$ cm clay tile units assembled following the scheme in Fig. 3(b), featured by the same thick for the bed and vertical joints.

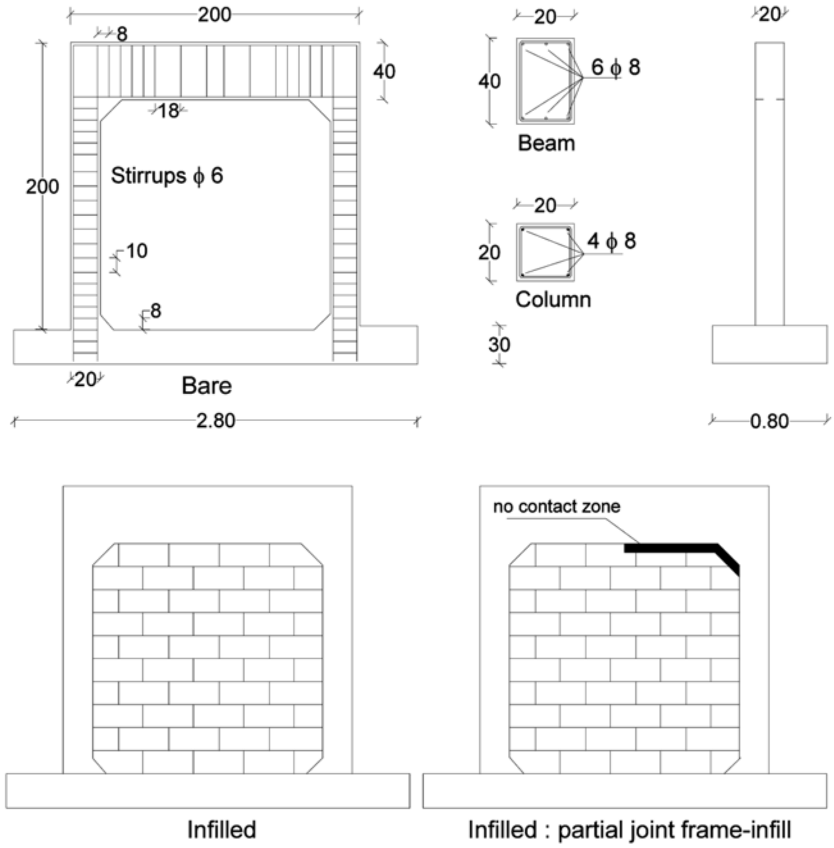


Fig. 2 Details of the specimens

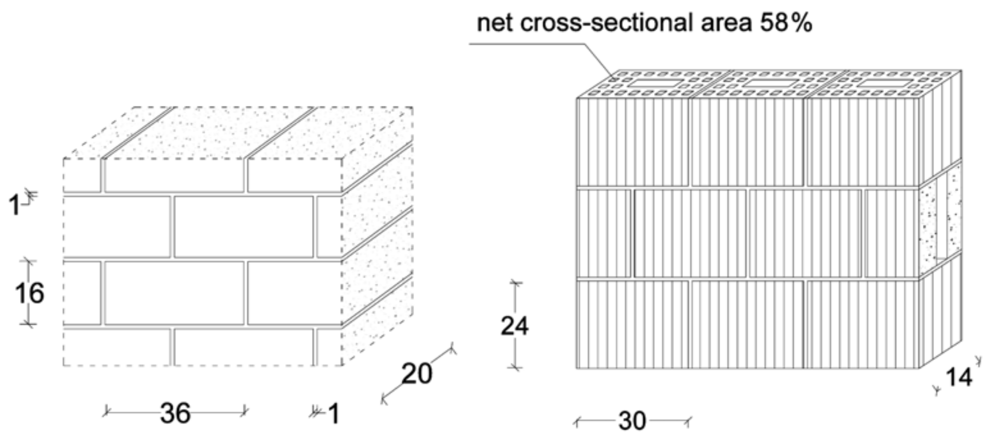


Fig. 3 Masonry used for the infills (a) calcarenite block masonry, (b) hollow clay tile masonry

The mortar used for the calcarenite masonry had the following composition in volume: 1 part of cement, 1 part of hydrated lime, 5 parts of sand, 0.5 water-cement ratio. While the mortar used for the clay tile masonry was composed by 1.5 parts of cement, 1 part of hydrated lime, 5 parts of sand, 0.5 water-cement ratio as usual in the practice.

The classification of the masonry was made by means of tests on the clay tile units, on the calcarenite stones and on the mortar as will be explained in the next paragraph.

The infilled frames were tested also before the construction of the infill with low levels of the loads in order to avoid the damage of the specimens. In this stage the elastic characteristics of the frames were observed.

Two frames in each of the two studied groups, were infilled in such a way the infill was partially in contact with the frame (see Fig. 2): in detail, a partial joint between the upper beam and the infill was provided in order to test the effect of a partial contact frame-infill as will be better explained through the paper.

2.2 Test setup and instrumentation

The test setup is shown in Fig. 4. The vertical loads were applied by four manual controlled hollow hydraulic jacks, each of those having 1968.1 kN as maximum nominal load. The resulting force applied was monitored by measuring the oil pressure in the jacks. The lateral loads were applied by a horizontal double-acting jack having 1393,5 kN as maximum nominal load in compression and 672.2 kN as maximum nominal load in tension. The level of the forces was

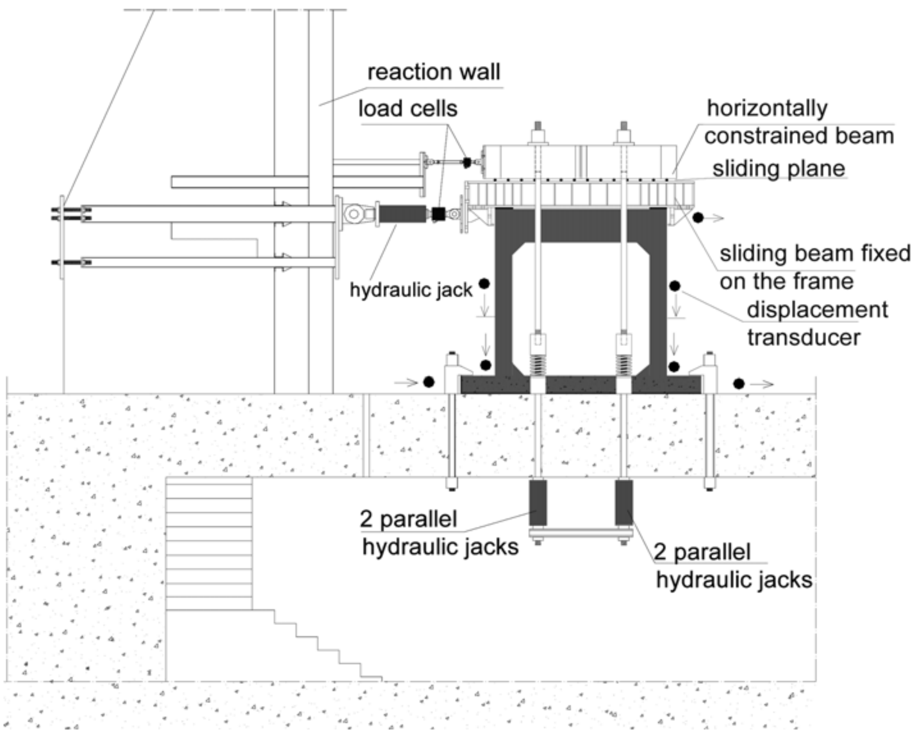


Fig. 4 Test setup

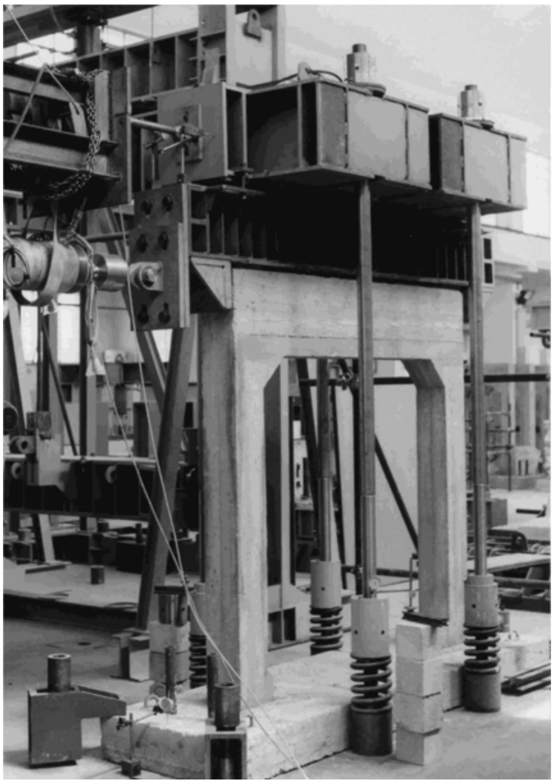


Fig. 5 A bare frame in the test apparatus

monitored by a load cell having 200 kN as nominal load. The device for the application of the vertical loads was constrained with respect to the horizontal displacement in order to maintain the vertical loads and to permit free sliding of the head of the frame.

The friction force transmitted by the vertical loading device was measured by a load cell having 50 kN as a nominal load. The displacements of the specimen were measured by transducers located as in Fig. 4. In addition to the lateral displacement of the frame head, the horizontal displacement and the rotation (in the plane of the frame) of the base were monitored. Further, the axial deformations of the columns were monitored.

In Fig. 5 a real view of a specimen in the test apparatus is shown.

2.3 Loading patterns and histories

The specimens were loaded with different combinations of vertical and lateral forces. The vertical forces (simulating dead and live loads) were applied on the columns after the infill was made, and were maintained constant during each test. The bare frames B_1 and B_2 were subjected to a total vertical force of 400 kN (200 kN on each column) and a monotonically increasing horizontal force up to the collapse. The same vertical force was applied on the infilled frames in combination with lateral loads (monotonically increasing and cyclic with an increasing value of the maximum load in each cycle). In details, the frames labelled I_1, I_2, I_5, I_6 were tested with a cyclic lateral load having

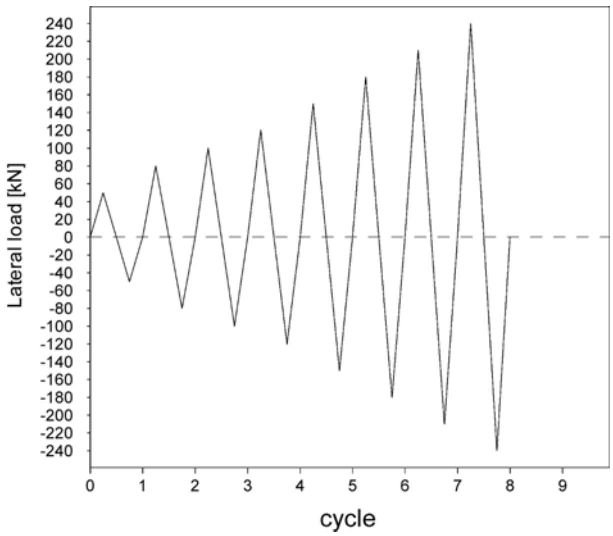


Fig. 6 Lateral load history for cyclic tests

Table 1 Specimens and types of test

Specimens	Description	Vertical load		Lateral load	
		Type	Value	Type	Value
B_1/B_2	bare	constant	40 kN	monotonically increasing	up to the collapse
I_1/I_2	infilled with calcarenite masonry - full contact frame-infill	constant	40 kN	cyclic with increasing amplitude	up to the collapse
I_3/I_4	infilled with calcarenite masonry - partial contact frame-infill	constant	40 kN	cyclic with increasing amplitude	up to the collapse
I_5/I_6	infilled with clay tile masonry - full contact frame-infill	constant	40 kN	cyclic with increasing amplitude	up to the collapse
I_7/I_8	infilled with clay tile masonry - partial contact frame-infill	constant	40 kN	cyclic with increasing amplitude	up to the collapse

the path shown in Fig. 6 while the frames labelled I_3, I_4, I_7 and I_8, featured by a partial contact between frame and infill, were monotonically loaded up to the collapse. Each test was stopped when severe damage was observed in the specimen.

Before the tests under lateral loads were carried out, the infilled frames were subjected to a vertical loading and the vertical strains in the infill were measured in order to verify the effectiveness of the horizontal frame-infill joint (effective contact between frame and infill).

In Table 1 the typology of the specimens and the loading types are summarised.

Table 2 Mechanic characteristics of the masonry and its components

Mean compressive strength/mean elastic modulus [N/mm^2]						
Mortar		Calcarenite	Clay tile block		Calcarenite masonry	Clay tile masonry (***)
Used for calcarenite masonry (*)	Used for clay tile masonry (**)		Along the direction of the holes	Orthogonal to the direction of the holes	4.1/6100	6.1/3810
6.5/3600	7.5/3750	4/9000	19.5/3870	3.1/1310		

(*) Composition: hydrated lime (1 volume); cement (1 volume); calcareous sand (5 volumes)
(**) Composition: hydrated lime (1 volume); cement (1.5 volumes); calcareous sand (5 volumes)
(***) Tests along the direction of the clay tile holes

2.4 Material properties

Tests were carried out on the reinforcing steel (tension tests) and on the concrete (compression tests) for their classification. These tests included evaluation of the Young modulus and the strength of the concrete used for the frames (respectively higher than 23000 N/mm^2 and 22 N/mm^2), and the evaluation of the tensile strength of the reinforcement bars (higher than 450 N/mm^2). Further, the classification of the masonry was performed by compression tests on the clay tile units (load applied along the direction of the holes and along the orthogonal direction), on samples of calcarenite, on the mortar and on samples of masonry made by means of the components mentioned before. The tests on the components of the masonry and on the masonry itself provided the mechanical characteristics inserted in Table 2.

2.5 Preliminary FEM analysis and remarks

In the behaviour of infilled frames a fundamental role is played by the mechanics of the stresses transferred between frame and infill. Infact, if the frame-infill joint has a low (or has not) tensile strength, under lateral loads, partial detachment of the frame from the infill may occur (Fig. 1a), then the stresses are transferred along the infill diagonal from the upper beam to the lower beam along a hypothetical diagonal strut.

The stiffness of the system is higher when the contact surface is wider (that is, when the section of the hypothetical diagonal strut is wider). Hence the lateral response of a generic infilled mesh is influenced by the features of the frame-infill joint as well as all the mechanical factors that modify the behaviour of the joint with consequent variation in the extension of the frame-infill detachment zone. One of these factors is vertical load.

In order to clarify the influence of vertical load a FEM analysis was carried out in which the masonry infill and the frame were modelled as equivalent continuum materials by means of bi-dimensional elements (the mechanical features were fixed by referring to the experimental tests mentioned in the previous section) while the interface was modelled by means of gap elements with no tensile strength. During the analysis different values of the vertical loads were considered. In Fig. 7 the results of the analyses in the two cases of an absent vertical load and a vertical load of 400 kN are summarised: the different contact extension between the infill and the frame is shown,

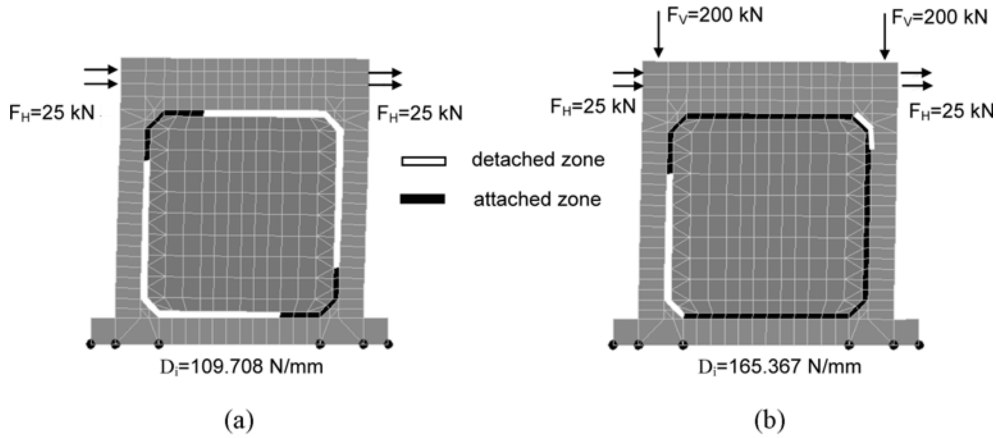


Fig. 7 Results of FEM analysis in terms of lateral stiffness D_i and extension of frame-infill joint (hypothesis of infill made of calcarenite masonry) (a) vertical load non applied, (b) vertical load applied (intensity 400 kN)

further the different lateral stiffness is provided in the two cases.

A further analysis evidenced that an increase in the tensile strength of the frame-infill joint produces an increase in the extension of the contact zone with a consequent increase in the stiffness.

In the practice, the technique used by the mason in order to make the frame-infill joint is decisive for the effectiveness of the contact between frame and infill and the consequent transferring of stresses from frame to infill. Likewise, the temporal sequence in the construction of the infills with respect to the rest of the building is decisive, the level of the stresses on the frame-infill joint (that is the degree of frame-infill contact) depending on this sequence.

2.6 Experimental results

2.6.1 Bare frames

The specimens B_1 and B_2 were subjected to an increasing monotonic lateral load up to the collapse and a constant vertical load of 400 kN. At to the collapse a mean horizontal strength of roughly 50 kN was exhibited. Horizontal cracks in the head and in the foot of the columns and vertical cracks on the beam near the beam-column joint appeared before failure, revealing the formation of plastic hinges (Fig. 8). However, some shear cracks developed in the beam-column joint mentioned above. The ultimate load experimentally obtained was very similar to that obtained by means of the limit analysis after the definition of a plastic domain for the section of the column. Eight further bare frames - subsequently infilled - were tested with a low level of the lateral load for the evaluation of the stiffness. The eight specimens exhibited a mean stiffness approximately of 17000 N/mm. In Fig. 9 the force-displacement average curve is pictured. This curve appears with further two curves that will be commented later.

The eight bare frames mentioned, undamaged after the tests, were infilled and subsequently tested again. Four of these infilled frames (I_3 and I_4 - infilled by calcarenite masonry - and I_7 and I_8 - infilled by clay tile masonry) featured a partial frame-infill joint, that is a detachment between the frame and the infill was produced on purpose, so as to make the vertical loads partially ineffective

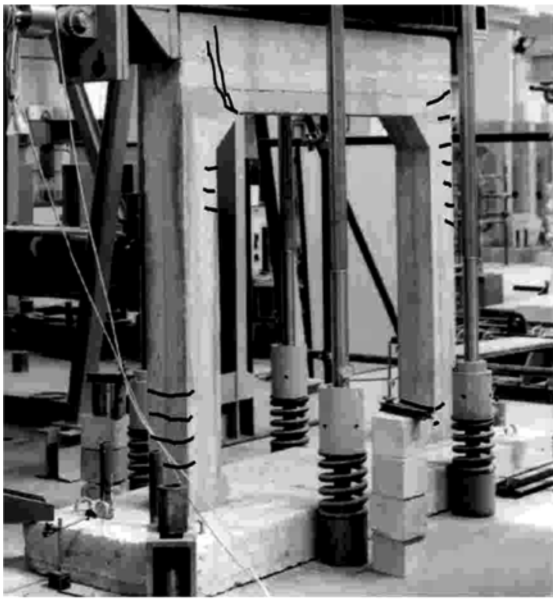


Fig. 8 Bare frame at the collapse: cracks distribution

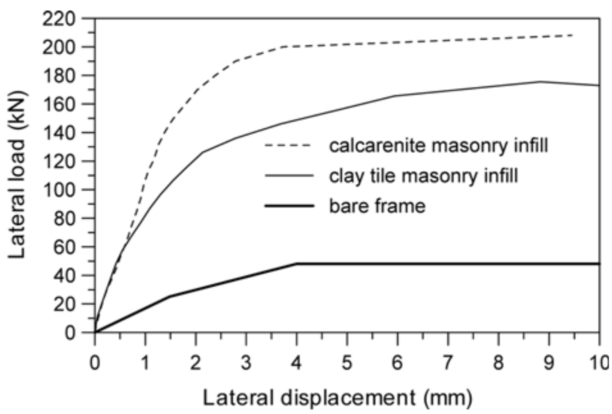
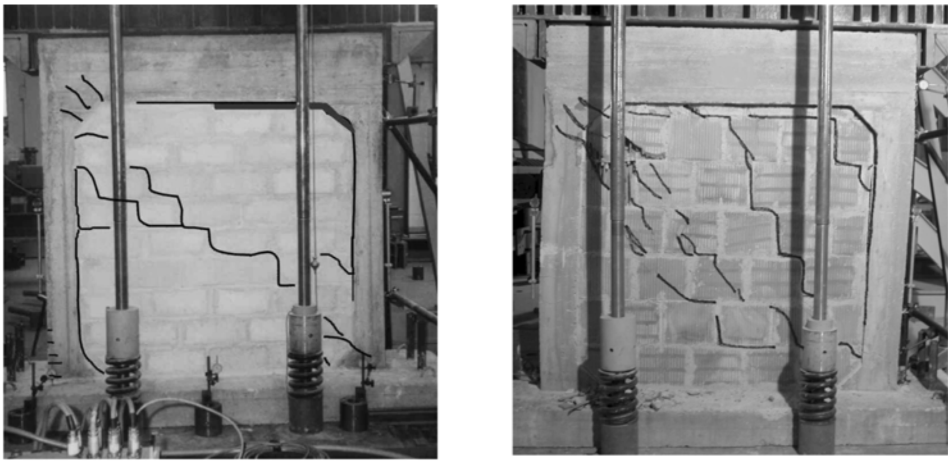


Fig. 9 Results of monotonic tests for bare frames and infilled frames with partial joint frame-infill (curves averaged from two tests)

in the determining of the beam-infill contact length when a monotonically increasing lateral load was applied. The remaining four frames (I_1 and I_2 - infilled by calcarenite masonry - and I_5 and I_6 - infilled by clay tile masonry) featured a full contact frame-infill (full joint).

2.6.2 Infilled frames with frame-infill partial joint

A strong variation in the infilled frame behaviour was observed with respect to the bare frame behaviour. In details: 1) initial stiffness increased (Fig. 9); 2) the shear stresses on the upper part of the column near the load application point seemed to prevail over the bending stresses; 3) the beam-column joint was affected by a strong shear force; 4) as a consequence of point 3, large diagonal



(a) (b)

Fig. 10 Specimens after the monotonic loading tests (a) infill made of calcarenite masonry, (b) infill made of clay tile masonry

cracks appeared on the beam-column joint; 5) the variation of the axial stresses (caused by the infill) on the column near the point of application of the lateral load with the variation of the lateral load itself was evidenced by the horizontally diffused not severe cracks that appeared on the column along the whole cross section; 6) the frames exhibited a large increase of the collapse strength.

What in point 5 means that a non negligible tensile force acts in the cross section of the column in such a way of influencing the lateral stiffness of the frame, the lateral displacement of the frame depending on the elongation of the columns.

The infill constituted by calcarenite masonry was affected by diagonal cracks mainly concentrated along the vertical and horizontal joints between the calcarenite blocks. The frame-infill joint (where the joint was effective before the application of load) was affected by the detachment of an extended zone, as shown in Fig. 10(a).

The infill constituted by clay tile masonry was also affected by diagonal cracks, more distributed than in the case of calcarenite masonry infill, along the vertical and horizontal mortar beds close to the diagonal. Further the explosion of some clay tile diagonally compressed blocks was observed (Fig. 10b).

The specimen infilled with calcarenite masonry (I_3 and I_4) exhibited a strength higher than 205 kN (roughly four times the strength of the bare frame). Conversely, the specimen infilled with clay tile masonry (I_7 and I_8) exhibited a strength lower than 180 kN. Specimens I_3 and I_4 maintained a quasi linear behaviour up to a value of load higher than in the case of specimens I_7 and I_8. The displacements corresponding to a load equal to the 80% of the strength were similar in the cases of infilled frames and bare frames, meaning that the collapse of the frame corresponds with the collapse of the system.

2.6.3 Infilled frames with full frame-infill joint

As mentioned before, infilled frames with full frame-infill joint were subjected to cyclic lateral loads and constant vertical ones. The response of these specimens is shown in Fig. 11. During the

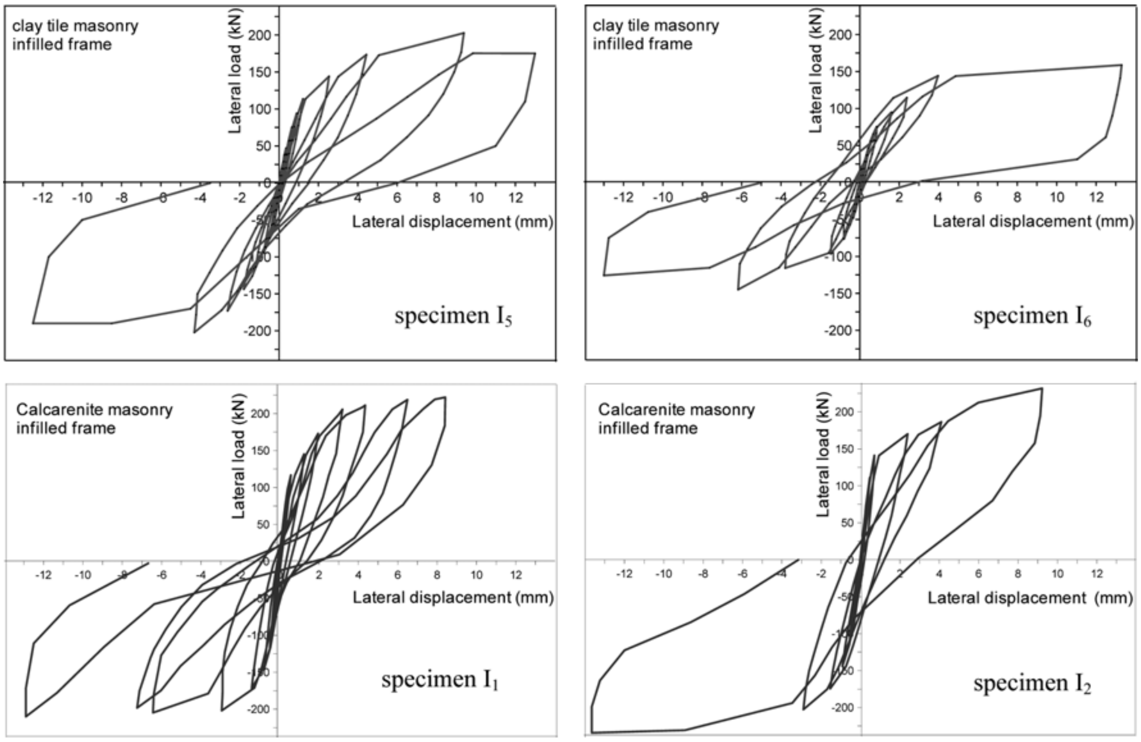


Fig. 11 Cyclic response of clay tile masonry infilled frames and calcarenite masonry infilled frames

first cycle, when the load was approximately 50 kN, frames infilled by clay tile masonry exhibited a behaviour different from frames infilled by calcarenite masonry in terms of stiffness. Further, the latter exhibited a stiffness higher than the infilled frames with a partial frame-infill joint were, confirming the influence of the extension of the contact zone between frame and infill before loading and the influence of the vertical loads that modify the contact zone extension mentioned before.

The clay tile masonry infilled frames with full frame infill joint do not exhibited a so marked difference from the corresponding infilled frames with partial frame-infill joint differently from the case of infill made of calcarenite masonry.

Referring to calcarenite masonry infilled frames, in the case of partial joint, a mean stiffness value approximately of 125 kN/mm was obtained (similar to that obtainable by the FEM analysis under the hypothesis of absence of vertical loads); while a mean value of approximately 245 kN/mm was obtained in the case of full joint (similar to that obtainable by the FEM analysis under the hypothesis of vertical loads and weak tensile strength of the frame-infill joint). It must be observed that, after 3 cycles as soon as the level of the lateral force caused the tensile strength of the joint to be exceeded, the stiffness was reduced to the value (167000 N/mm) predicted in the case of no tensile strength of the joint itself.

As mentioned before, frames infilled by clay tile masonry exhibited a stiffness similar in the two cases characterised respectively by a full frame-infill joint and a partial frame-infill joint, namely the partialization of the joint before loading appeared not reducing the influence of the vertical loads. A

Table 3 Stiffness of the infilled specimens

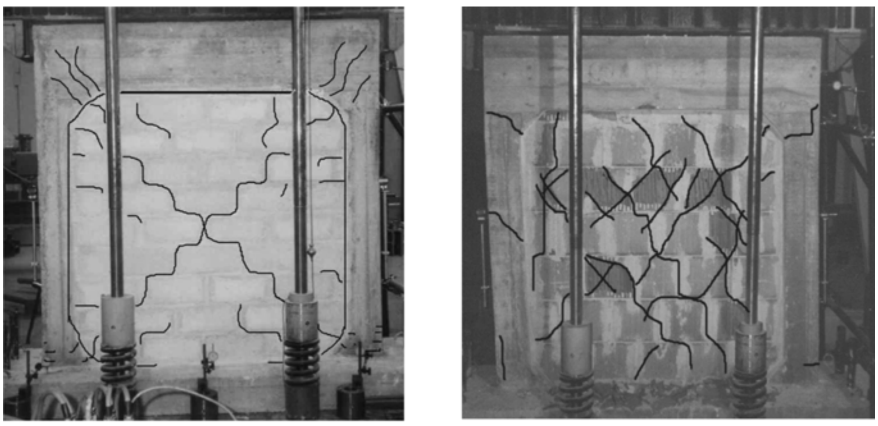
Specimens	Infill type	Joint frame-infill	Lateral load type	Secant stiffness (*) [kN/mm]
I_1	calcarenite masonry	total	cyclic	243
I_2	calcarenite masonry	total	cyclic	247
I_3	calcarenite masonry	partial	monotonic	125
I_4	calcarenite masonry	partial	monotonic	133
I_5	clay tile masonry	total	cyclic	132
I_6	clay tile masonry	total	cyclic	93
I_7	clay tile masonry	partial	monotonic	115
I_8	clay tile masonry	partial	monotonic	92

(*) Evaluated when the load was 50 kN the first time

FEM model of the frame infilled by clay tile masonry, in absence of vertical loads, gave a stiffness much lower than that experimentally found, meaning that probably vertical loads, in this case, influenced the infill by means of the reduced surface of contact frame-infill fixed before the experimental test. As a consequence, a surface of contact much lower than that lift before the experimental test would be observed in absence of the vertical loads, namely, the reduced length of contact between frame and infill was not enough for removing the influence of vertical loads.

This circumstance was clearly caused by the very low level of the elastic modulus of the clay tile masonry in the horizontal direction (see the characteristics of the material inserted in Table 2), influencing both shear stiffness and diagonal stiffness of the infill. Hence, in this case, the mechanical orthotropic elastic features of the infill appeared to influence the lateral stiffness of the system much more than the vertical load. In Table 3 the values of stiffness measured on each specimen are inserted.

During the most severe cycles complete detachment of the column-infill joint and the upper beam-infill joint was observed. Then the damage in the infill with diagonal cracks and the damage



(a) (b)

Fig. 12 Specimens after the cyclic loading tests (a) calcarenite masonry infill, (b) clay tile masonry infill

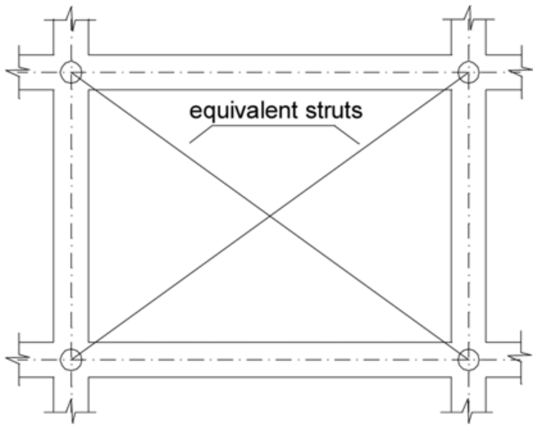


Fig. 13 Scheme of frame with struts equivalent to infill

in the beam-column joint due to shear stresses were recognized, revealing the most vulnerable parts of the frame due to the presence of the infill (Figs. 11, 13). The infilled frames characterised by a full frame-infill joint showed a maximum strength similar to that one exhibited by the specimens featuring a partial frame-infill joint, meaning that, when the ratio between lateral load and vertical load increases, the influence of vertical loads on the response of the system decreases, namely vertical loads reduce their confining effect on the infill thus it does not provide further contribution to the strength.

The curves obtained by the cyclic tests (Fig. 11) reveal that the cycles reduce their amplitude close to the origin of the axes evidencing a phenomenon similar to the pinching. In Fig. 10 and in Fig. 12 the state of some specimens at the end of the tests is shown. It can be observed a larger diffusion of the cracks in the infill made of clay tile masonry than in the infill made of calcarenite masonry.

3. Analytical model

As has been pointed out, many parameters influence the behaviour of infilled frames, making the prediction of the response computationally very expensive. In this connection, a pin jointed strut equivalent to the infill may be a solution although only the global behaviour can be predicted in terms of ductility, dissipation of energy and level of the collapse forces, and many local effects may be lost. In spite of these limits the equivalent strut is really considered a useful tool for the prediction of the response of infilled frames as confirmed in the literature (e.g., Klingner and Bertero 1978, Madan *et al.* 1997, Liaw and Lee 1977, Doudoumis and Mitsopolou 1986, NCEER 1994).

Experimental results evidence a cyclic mechanical behaviour with reducing of strength and stiffness when the cycles and the lateral displacements increase denoting damaging. The state of the system at an assigned cycle is normally influenced by the level of initial stiffness and the peak of strength of the system. Both these parameters are related to the mechanical characteristics of the material which constitutes the infill (these characteristics have to be previously obtained by experimental tests) and the geometrical characteristics assigned to the equivalent strut (from both geometrical and mechanical characteristics mentioned, the initial axial stiffness of the strut and its strength can be defined) and finally from the characteristics of the frame members. From what said above the definition of the analytical behaviour requests: a) the definition of the geometrical features of the strut, b) the characterisation of the material that constitutes the infill (and the strut), c) a proper cyclic mechanical law depending on the story of the lateral displacements of the system (or, what is the same, depending on the axial deformation of the strut); d) a proper law for the members that constitutes the frame. In the following two paragraphs, first, how the geometrical features of the strut can be rapidly obtained will be discussed, depending on some known parameters of the system, further, how in the past the problem of the cyclic behaviour of this kind of system has been solved will be discussed and a new analytical law, obtained as improvement of previous proposals available in the literature, will be proposed, described and tested for fitting the experimental results.

3.1 Initial stiffness of the strut

Many attempts to translate the initial stiffening effect of the infill in the initial stiffening effect of an equivalent strut can be found through the literature (e.g., Holmes 1961, Stafford Smith 1966, Stafford Smith and Carter 1969, Klingner and Bertero 1978, Mainstone 1971, Mainstone 1974, Durrani and Luo 1994, Saneinejad and Hobbs 1995).

The proposals available in the literature have been extensively discussed in (Papia *et al.* 2003) remarking: a) the difference of the approaches, b) the difference of the results obtainable for the initial stiffness when different approaches are used (namely, the discussed approaches do not converge to the same solution), c) the fact that the available approaches do not consider the real state of axial stresses in the columns of frames against the experimental evidence, d) the fact that the available approaches do not consider the effect of vertical loads and the role of the Poisson ratio of the material constituting the infill while they would be considered as also pointed in (NCEER 1994).

On the basis of what discussed a new tool for the definition of the initial stiffness - namely, of the equivalent strut - has been proposed in (Papia *et al.* 2003). The procedure consists of: 1) to determine the parameter λ^* depending on the geometrical features of the infilled mesh and on the elastic properties of the materials, which are considered assigned, 2) to determine the width of the diagonal strut as function of the parameter λ^* (the thickness of the diagonal strut is previously assigned equal to the thickness of the infill) depending also on the Poisson ratio of the material that constitutes the infill. The effect of vertical loads has been considered here by adding a further parameter as will be explained later.

The parameter λ^* is determined by means of the following expression

$$\lambda^* = \frac{E_d}{E_f}\frac{th'}{A_c}\left(\frac{h'^2}{\ell'^2} + \frac{1}{4}\frac{A_c}{A_b}\frac{\ell'}{h'}\right) \tag{1}$$

where E_d, E_f are the Young modulus of the infill along the diagonal direction and the Young modulus of the materials that constitute the frame members respectively; t is the thickness of the infill; A_c and A_b are the mean cross-sectional areas of the columns and of the upper beam; h' and ℓ' are the height and the length of the frame. Once λ^* is calculated, the width of the diagonal strut can be determined by means of the following equations

$$\frac{w}{d} = \kappa \frac{c}{z} \frac{1}{(\lambda^*)^\beta} \tag{2}$$

where d is the diagonal length of infill,

$$c = 0.249 - 0.0116\,\nu + 0.567\,\nu^2 \tag{3}$$

and

$$\beta = 0.146 + 0.0073\,\nu + 0.126\,\nu^2 \tag{4}$$

ν being the Poisson ratio of the material constituting the infill in the diagonal direction; z is a coefficient varying with the aspect ratio of the infill, that is

$$z = \begin{cases} 1 & \text{if} \quad \ell/h = 1 \\ 1.125 & \text{if} \quad \ell/h = 1.5 \end{cases} \tag{5}$$

l and h being the dimensions of the infill; finally κ is a coefficient taking the effect of vertical loads into account and it assumes the values in the range 1-1.6 (1 to be applied to the case of vertical loads not influencing, 1.6 to be applied to the case of vertical loads strongly influencing).

In practical application it is very difficult to assign a value for the parameter κ because the real influence of vertical loads is unknown, depending on the date of their application (before or after the construction of infills?) and on the real state of the frame-infill joints (related to the procedure used by the masons). For this reason the evaluation of the stiffening effect of the infill, that is, the evaluation of the dimensions of the equivalent strut for existing buildings may be done by using a dynamic identification technique as explained in (Cavaleri and Papia 2003), less immediate than the above tool but more accurate.

3.2 Analytical law for cyclic behaviour

Different authors have proposed analytical model for the prediction of the cyclic behaviour of infilled frames. Among them a special interest is encountered in that one proposed by Klingner and Bertero (1978). In details the bounding frame is considered as the assemblage of beam elements with linear elastic perfectly plastic moment-rotation characteristics of the cross-sections, while a pair of pin-jointed struts, as shown in Fig. 13, are considered for the infill. The analytical law for the mechanical characteristics of each strut is shown in Fig. 14. Observe that: 1) the strut has a limited tensile strength; 2) the unloading, when the strut is compressed, is elastic with stiffness identical to the elastic initial stiffness; 3) the reloading, with value of stiffness different from zero, begins from the origin axes (deformation of the strut $\delta = 0$) and is linear with a slope that depends from the maximum deformation - positive or negative - experienced by the strut. This model gives optimal results as shown in (Klingner and Bertero 1978) for infilled frames where infill is connected to the frame by means of diffused steel reinforcements. In this case the cycle lateral force-lateral displacement of infilled frames has the shape shown in Fig. 15. It can be observed that it is substantially different from the typical lateral force - lateral displacement cycle (Fig. 15) of infilled frames featured by infill not connected to the frame members. Hence the model proposed by

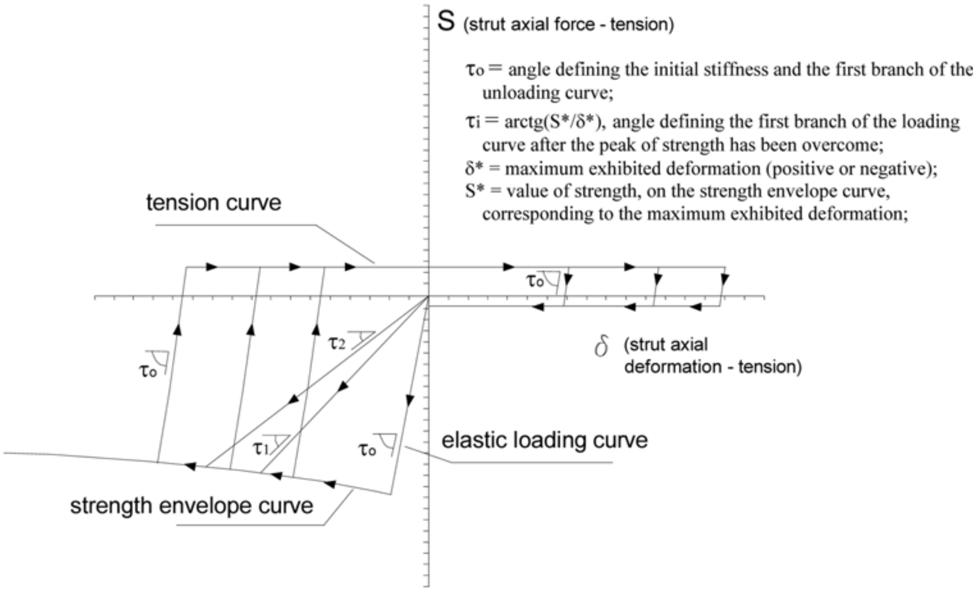


Fig. 14 Cyclic behaviour of the strut proposed by Klingner and Bertero (1978)

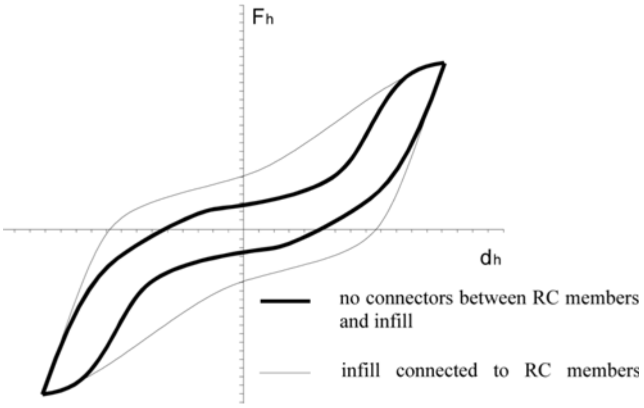


Fig. 15 Lateral force - lateral displacement cycle of infilled frames

Klingner and Bertero has to be modified if one wants to take into account the above different behaviour.

The examination of other laws available in literature evidences some limits.

For example, in (Doudoumis and Mitsopoulou 1986) is proposed a cyclic mechanical behaviour for the equivalent strut in which the strut is inactive in tension and remains inactive in compression until a proper level of negative deformation of the strut (positive values of deformation correspond to extension) - the latter characteristic seems in accordance enough to the experimental evidence; the strength is defined by means of an envelope curve and the unloading is featured by a branch with a constant slope that does not depend on the deformation history against the experimental evidence.

Panagiatakos and Fardis (1996) propose a lateral force-lateral displacement law to be applied to a pair of diagonal struts whose shape is in agreement with the experimental results obtained on infilled frames without connectors between infill and frame. In this law the initial stiffness depends on the infill panels (geometry and elastic shear modulus of the material that constitutes the infill) but it is not clear as it is applied to large buildings where the introduction of diagonal struts requests the definition of their geometry and their mechanic characteristics.

Madan *et al.* (1997), similarly to the previous authors proposed a law taking into account the reduction of stiffness and strength of the system by evaluating the envelope curve on the basis of an approach proposed in Saneinejad and Hobbs (1995): first a pairs of diagonal struts are considered, then a classical Bouc-Wen model for the definition of the histeretic damaging behaviour is introduced to be associate to a macroelement different from the strut named "infill panel element" associated to the infill: this approach seems to disregard the possibility to formulate a FEM model characterised by the introduction of diagonal struts of assigned geometry and assigned mechanical law for the infill.

Differently from the approaches mentioned before the model of Klingner and Bertero considered a specific mechanical law for a pair of struts with specific dimensions to be connected to the nodes of the frames - namely simply to be used in a finite element model - but it is not appropriate for the case of infills without connectors as explained before.

Taking into account what above, a new law, by improving the law available in (Klingner and Bertero 1978), is here proposed. The most important changes are: 1) the introduction, for the strut, of a double slope of the unloading branch before the restoring force vanishes; 2) the introduction of a loading branch characterised by a zero value of the restoring force before the system begins to exhibit non zero stiffness (as first proposed by Doudomis and Mitsopoulou 1986). Further a different envelope strength curve for the strut is considered in agreement to the experimental results. In Fig. 16 one can see the differences between a possible cycle obtained by the law proposed by Klingner and Bertero for the strut and a possible cycle obtained by the law proposed here, while in

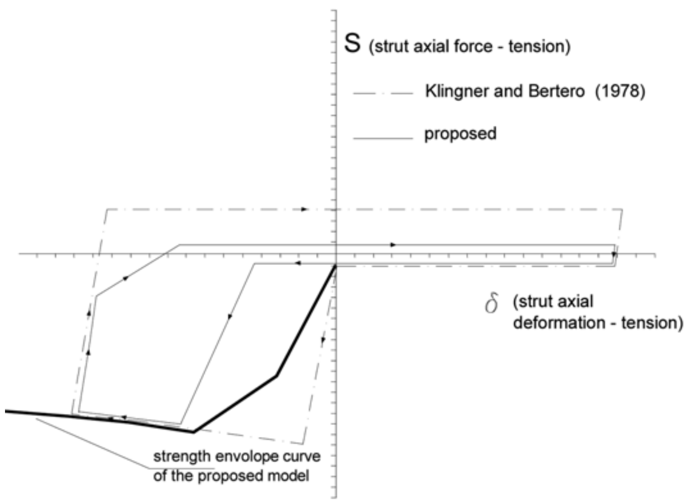


Fig. 16 Comparison between cyclic laws for the behaviour of the strut

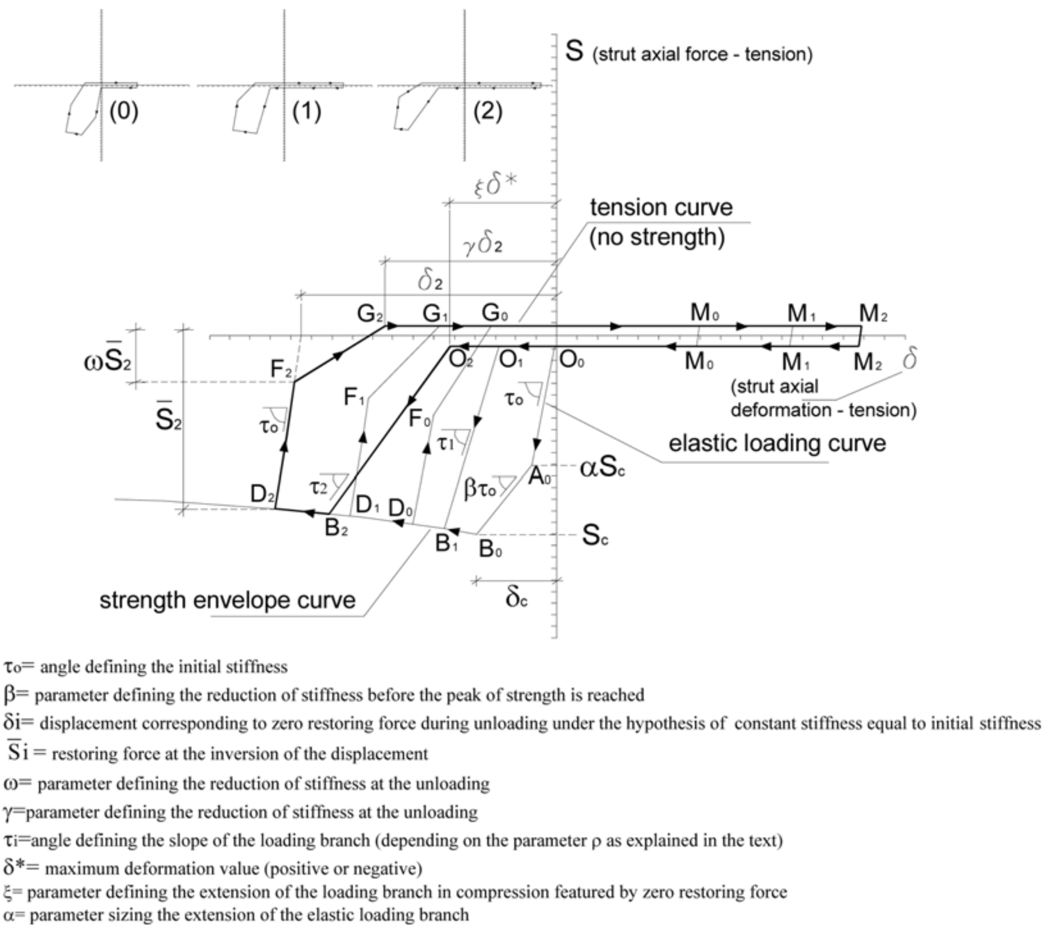


Fig. 17 Details of the proposed cyclic behaviour of the strut

Fig. 17 the details of three different cycles - labelled as 0, 1, 2 - covered by using the model proposed here are shown.

The different branches of the analytical curve proposed here are defined as follows.

<u>1. Linear elastic loading (path OA).</u> This is defined by the equation

$$S(\delta) = \frac{E_d A_i}{L}\delta \tag{6}$$

in which S is the axial force in the strut; E_d is the Young's modulus for the infill material in the diagonal direction; δ is the axial deformation in the strut, positive values corresponding to extension; L is the length of the strut, taken here as the distance between diagonally opposite nodes; and A_i is the product of the panel thickness (assumed equal to the thickens of the strut) by the width of the equivalent strut itself; this path is covered at the first loading and may be covered at each reloading if the deformation of the strut (positive or negative) does not overcome the maximum deformation corresponding to point B. The point A_0 corresponds to the restoring force αS_c, S_c being the compressive strength in diagonal direction, while α is a parameter lower than 1 established on the basis of the experience.

2. Non linear loading (path AB). It is covered when the deformation corresponding to point A is overcome and features the begin of the non linear behaviour of the strut. The branch AB is covered at the first loading and may be covered at each reloading until the maximum deformation of the strut (positive or negative) does not overcome the deformation corresponding to point B. The slope of this linear branch is established by means of the calibrating parameter β. The equation that characterises this branch is

$$S(\delta) = \alpha S_c \frac{L}{E_d A_i} + \left(\delta - \alpha S_c \frac{L}{E_d A_i}\right) \beta \frac{E_d A_i}{L} \tag{7}$$

where each symbol has been described above.

The unloading from each point of the branch AB follows the same rules of the unloading as explained at the following points 4 and 5.

3. Strength envelope curve (path BC). The curve is defined by

$$S(\delta) = \frac{S_c}{\exp(\varsigma \delta_c)} \exp(\varsigma \delta) \tag{8}$$

in which δ_c is the deformation corresponding to S_c, that is

$$\delta_c = \frac{\alpha S_c}{K_0} + \frac{S_c - \alpha S_c}{\beta K_0} \tag{9}$$

Further, ζ is a parameter that defines the strength degradation, selected on the basis of experience, K_0 is the axial stiffness of the strut in the branch OA ($K_0 = \tan(\tau_0) = E_d A_i / L$).

4. Unloading curve (path DF). It is featured by a slope equal to that of the first loading elastic branch. The point F corresponds to a level of the force equal to $\omega \bar{S}$, $\bar{S}$ being the restoring force at the inversion of the load and ω being a calibrating parameter lower than 1. The governing equation is

$$S(\delta) = \bar{\delta} - (\delta - \bar{\delta}) \frac{E_d A_i}{L} \tag{10}$$

$\bar{\delta}$ being the deformation at the inversion of load.

5. Unloading curve (path FG). In this branch the slope reduces with respect to the branch DF. The reduction of the slope is calibrated by the parameter γ. Referring, for sake of simplicity, to the cycle 2 of Fig. 17 the slope $\tilde{K}_2$ of the branch F_2G_2, is defined as

$$\tilde{K}_2 = \frac{\omega \bar{S}_2}{\bar{\delta}_2 - \gamma \delta_2 - \dfrac{\bar{S}_2 - \omega \bar{S}_2}{K_0}} \tag{11}$$

where $\bar{\delta}_2$ is the deformation experienced by the strut at the load inversion point D_2, $\bar{S}_2$ is the force at the point D_2, δ_2 is the deformation that would assume the strut at the zero restoring force under the hypothesis of unloading with constant slope from point D_2 (see Fig. 17). The parameter γ is calibrated on the basis of experience.

6. Tensile curve (path GM). In this stage the strut does not exhibit any strength (the branches GM depicted in Fig. 17 are not properly coincident with the axis of the displacements for a higher clarity, thus the figure is only apparently in contrast with the above statement).

7. Reloading curve (path MO). Also in this case the strut does not exhibit any strength until the point O is reached, featured by a level of deformation in compression different from zero. The position of the point O depends on the deformations before. In details, referring for example to the cycle 2, the extension of the branch O_0O_2 is equal to $\xi\delta^*$, ξ being a parameter to be calibrated on the basis of the experience and δ^* the maximum deformation value (positive) experienced by the strut.

8. Reloading linear curve (path OB). This branch is covered after the deformation corresponding to point O is overcome and the deformation corresponding to point B_0 (positive or negative) is also previously overcome. The slope of this linear branch is influenced by the maximum deformation (positive or negative) experienced by the strut. In specific the governing equation is

$$S(\delta) \;=\; \xi\delta^* + (\delta - \xi\delta^*)\rho Tan(\tau_{FG}) \tag{12}$$

ρ being a calibrating parameter to be chosen on the basis of the experience - generally greater than 1 - and τ_{FG} the angle defining the slope of the unloading branch nearer to the zero value of the restoring force (branch FG) experienced by the strut.

4. Comparison between the analytical model and the experimental results

In this section the reliability of the model proposed for the strut will be shown. Namely, the experimental response exhibited by the infilled frames will be compared to the one obtainable by using the proposed model.

For sake of simplicity the response of the infilled frames will be considered as the sum of the response of a bare frame featured by an elastic perfectly plastic cyclic response without reducing of stiffness and strength and of a truss system (Fig. 18). This choice allows to simplify the problem and to do a reduced error, considering that the contribution of the bare frame is reduced respect to

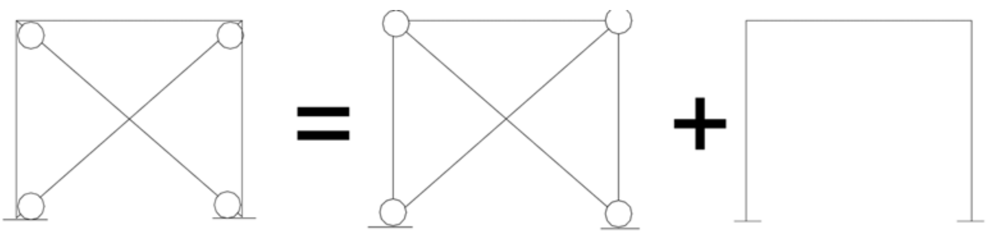


Fig. 18 Decomposition of the equivalent scheme of the infilled frame

contribution of the infill.

The mechanical cyclic response of the bare frame has been considered having a stiffness of about 17 kN/mm and a strength of 50 kN as in the experimental tests.

4.1 Geometric and elastic characteristics of the equivalent strut

For the studied cases the equivalent strut has been defined referring to the procedure explained in the section 3.1. To this aim the elastic modulus, the tangent modulus and the Poisson ratio in the diagonal direction have been used. The determination of these mechanical characteristics have been done by calculating the elastic mechanical properties in the horizontal direction by means of a proper technique of homogenisation (Salomon 1968) starting from the elastic properties obtained for the constituting materials (mortar and block). Then the elastic mechanical parameters along the diagonal direction have been calculated referring to the theory of orthotropic materials in plane stress state (Jones 1999).

In the case of calcarenite masonry infill, the procedure for the calculation of the elastic parameters along the diagonal directions has evidenced that this kind of masonry can be considered almost isotropic. Thus, the Young modulus along the diagonal direction was fixed equal to the Young modulus experimentally found along the vertical direction, that is 9000 N/mm^2 was fixed for E_d (see Table 2) . Further the value 0.25 was fixed for the Poisson ratio ν.

For taking into account the effect of vertical loads evidenced during the experimental campaign, the parameter κ in Eq. (2) was assigned equal to 1.6. Thus, the width of the strut made of calcarenite masonry, evaluated as explained above, was about 900 mm.

Referring to the clay tile masonry infill, the procedure for the calculation of the elastic parameters along the diagonal directions has evidenced that this kind of masonry must be considered orthotropic. By applying the above homogenisation technique involving the clay tile blocks and the mortar, along the horizontal direction for the elastic modulus one approximately obtains $E_o = 1261$ N/mm^2. The vertical elastic modulus E_v was known by experimental tests, that is $E_v = 3810$ N/mm^2. Further by fixing for the Poisson ratio $\nu_{ov} = -\varepsilon_o/\varepsilon_v = 0.3$, as reasonable for this kind of material, and for the tangent modulus $G_{ov} = 1000$ N/mm^2, and by using the procedure proposed in (Jones 1999) one obtains to $E_d = 500$ N/mm^2 , $\nu_d = 0.1$.

For taking into account the effect of vertical loads, the parameter κ of Eq. (2) was assigned equal to 1.6. Thus, the width of the strut made of clay tile masonry, evaluated as explained above, was about 1030 mm.

4.2 Strength of the equivalent strut

In order to assign the strengths S_c, diagonal compressive tests would be needed on masonry. Nevertheless the scope of the work is to demonstrate the possibility to use the analytical model proposed for this kind of infilled frames, thus in this case, the strengths S_c for the clay tile masonry and the calcarenite masonry were evaluated in such a way the sum of the strength of the bare frame and of the contribution of the strut was equivalent to the experimental strength of the analysed infilled frame in agreement to the following equation

$$S_f + \overline{S}_c = S_e \tag{13}$$

$\overline{S}_c$ being the horizontal component of the strength diagonal force exhibited from the strut, that is,

$$\overline{S}_c = S_c \cos(arctg(h/l)) \tag{14}$$

where each symbol has been defined above.

4.3 Parameters for the non linear behaviour of the equivalent strut

For the examined cases, in which infills are featured by two different kinds of masonry, the following parameters were fixed for both types of infill

$$\alpha = 0.55;\ \beta = 0.15;\ \gamma = 0.2;\ \varsigma = 0.005;\ \omega = 0.6 \tag{15}$$

Further, in order to fit the behaviour of the frames infilled by calcarenite masonry the following parameters were chosen

$$\rho = 1.15;\ \xi = 1.8 \tag{16}$$

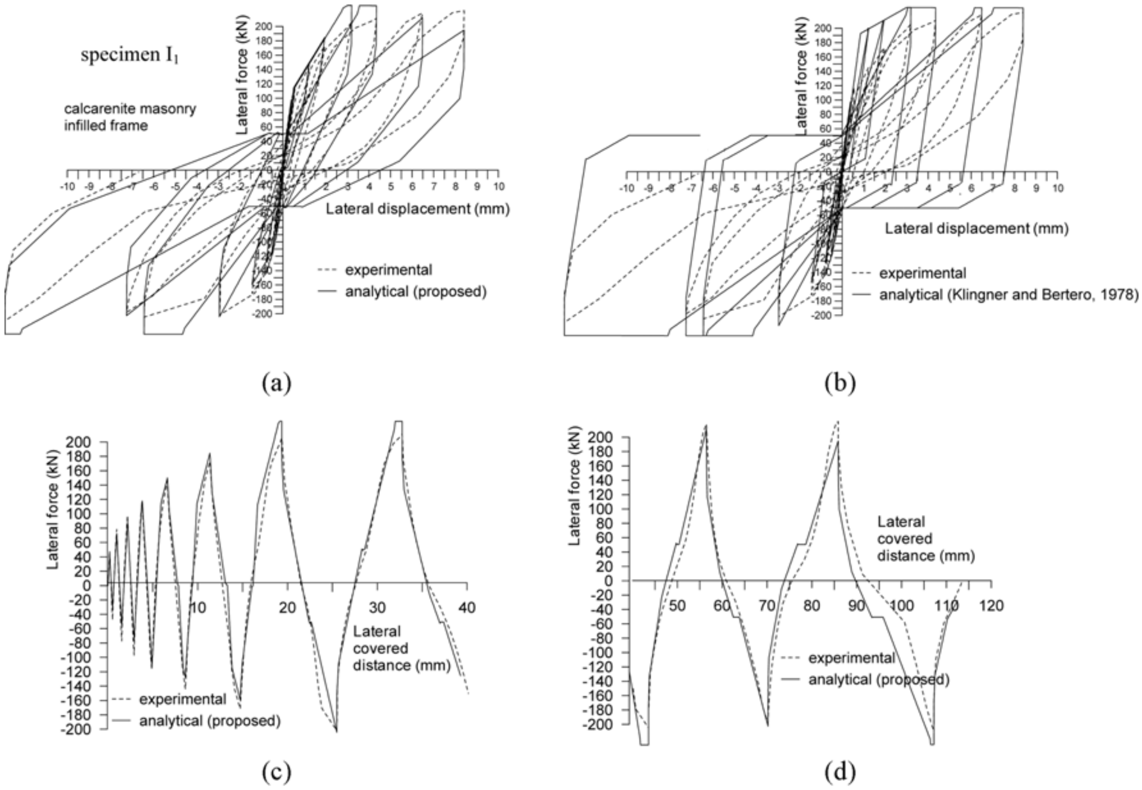


Fig. 19 Frame infilled by calcarenite masonry: comparison between experimental and analytical response (a) and (b) cyclic response, (c) and (d) lateral force with variation in lateral covered distance

while, in order to fit the behaviour of the frames infilled by clay tile masonry the parameters ρ and ξ were assigned as follows

$$\rho = 2.2; \; \xi = 0.4 \tag{17}$$

Hence, the different behaviour of the two types of infilled frames can be predicted by changing the values of two of the parameters that define the analytical model.

In Figs. 19 and 20 the comparisons between the experimental responses and the analytical ones for frames I_1 and I_5 are pictured, showing the adaptability of the law proposed for the equivalent strut. While Figs. 19(a) and 20(a) show a classical representation of the curve force-displacement, in Figs. 19(c), 19(d), 20(c), 20(d) the distance covered by the upper beam of the frame against the restoring force is shown for a clearer comparison of the responses. Moreover in Figs. 19(b) and 20(b) the comparisons are made between the experimental responses and the analytical ones obtainable by using the mechanical law proposed by Klingner and Bertero (1978) showing clearly the improvement of the results obtainable by means of the proposed analytical approach (see the shapes of the cycles). In order to obtain the analytical responses by means of the model of Klingner and Bertero, the mechanical characteristics of the equivalent pin-jointed strut (stiffness, maximum strength and exponential branch of the strength envelope curve) and of the frame were fixed equal to those used in the proposed approach.

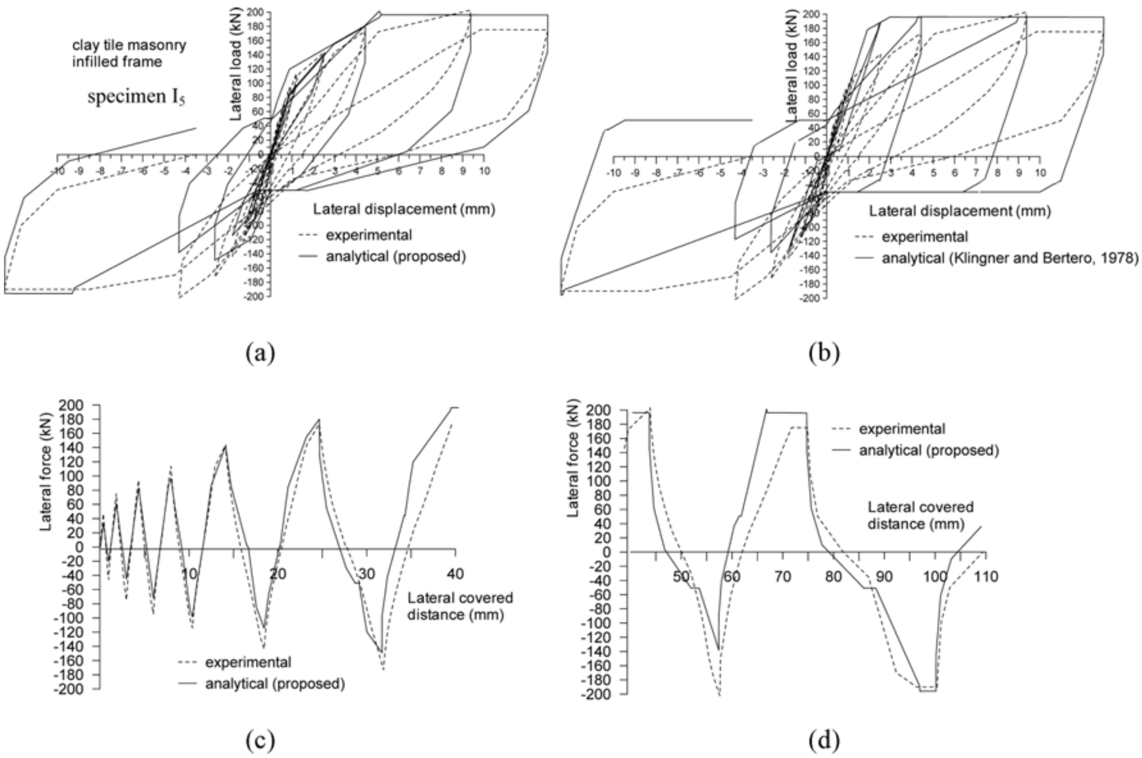


Fig. 20 Frame infilled by clay tile masonry: comparison between experimental and analytical response (a) and b) cyclic response, (c) and (d) lateral force with variation in lateral covered distance

The analytical curve of the frame I_1 (infill was made of calcarenite masonry) in the first cycles fits the experimental results better than the analytical curve of the frame I_5 does. Nevertheless both analytical responses can be considered good.

Referring to the last cycles, the difference encountered between the experimental curves and the analytical curves, for both frames, is mainly due to the hypotheses assumed for the bare frame, undamaging in stiffness and strength, meaning that a proper law for the frame members leads to a better prediction of the response of the system. Anyway, the adaptability of the analytical law for the strut is evident in the two cases.

5. Conclusions

The evaluation of the effects of infilling panels on the response of infilled frames is a very difficult problem depending on so much parameters.

The effect of infills made of two type of masonry on reinforced concrete frames has been studied and discussed: the results of an experimental investigation have been presented and the reliability of the models known in the literature in order to fit the above results have been commented. This study has evidenced that:

1) many models are available in the literature, converging to different solutions, evidently influenced by the types of tests and the types of specimens used for their validation;
2) the above models are not so appropriated for the two kinds of infilled frames experimentally studied and discussed here;
3) it has been shown that an improvement of the models known in the literature for the evaluating of the response of infilled frames, as those studied here, is possible.

Then a new model for the prediction of the response of infilled frames has been presented basing on the equivalent strut approach. It has been shown that:

1. the proposed model is supported by a tool for the identification of the equivalent strut depending on some parameters never considered before in the literature (axial stress in the columns, vertical loads, Poisson ratio of the infill, etc.) but basic for a proper characterisation of the system;
2. the proposed model, because of the criteria by means of that it has been formulated, has a great adaptability that allows to be used in many real situations;
3. the proposed model has been used in order to predict the effect of infills made of calcarenite masonry and of clay tile masonry with good results.

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