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EFFECT OF VERTICAL LOADS ON LATERAL RESPONSE OF INFILLED FRAMES

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SUMMARY

Many parameters influence the interaction between the generic mesh of a framed structure and its infilling walls. One of these is the level of the vertical loads on the mesh. The approximated procedures known in the literature for the evaluation of the influences of the infills on the behaviour of the frames under lateral excitations, based on the equivalent strut approach, neglect the effect of vertical loads, probably because the mechanism that governs the phenomenon is not clear, making it difficult to take it into account. Nevertheless, in some cases, a non-negligible variation in the behaviour of infilled meshes can be produced because of vertical loads, leading to a substantial inaccuracy in the evaluation of the response of the system. In this paper how and how much the vertical loads influence the behaviour of infilled frames is investigated by a numerical and an experimental approach and once again the non-negligible effect of vertical loads is proved and the need to consider it is stressed. The frame-infill interface behaviour, recognised as basic in this interaction, is observed when lateral loads are applied. Then the effect of the variation in the extension of the frame-infill contact region on the lateral stiffness and the lateral strength of infilled frames is discussed. After having recognized the key role of the interface frame-infill some remarks are made on the most proper approach to be used for the interface mentioned when "exact" FEM models or FEM-BEM models for the infill are used.

INTRODUCTION

In the last few decades growing interest in the effects of infill walls on the behaviour of frames has been recorded. It is known that the infill panels, usually considered as non-structural elements, have a significant effect on the global seismic response of framed structures. In a typical situation, referring to the generic mesh of a framed structure, the infill may increase the lateral stiffness and strength even by one order of greatness. Hence, infill has a beneficial effect for the single mesh, but it may not prove beneficial to the performance of the structure under lateral loads, in some cases anticipating structure collapse: it may occur when infills are not uniformly distributed in plan (Fig.1) and/or not uniformly distributed in height (Fig.2).

On the other hand, while the evaluation of the stiffening and the strengthening effects of infills is basic, in the characterisation of the behaviour of a framed system, this evaluation is very difficult because stiffness

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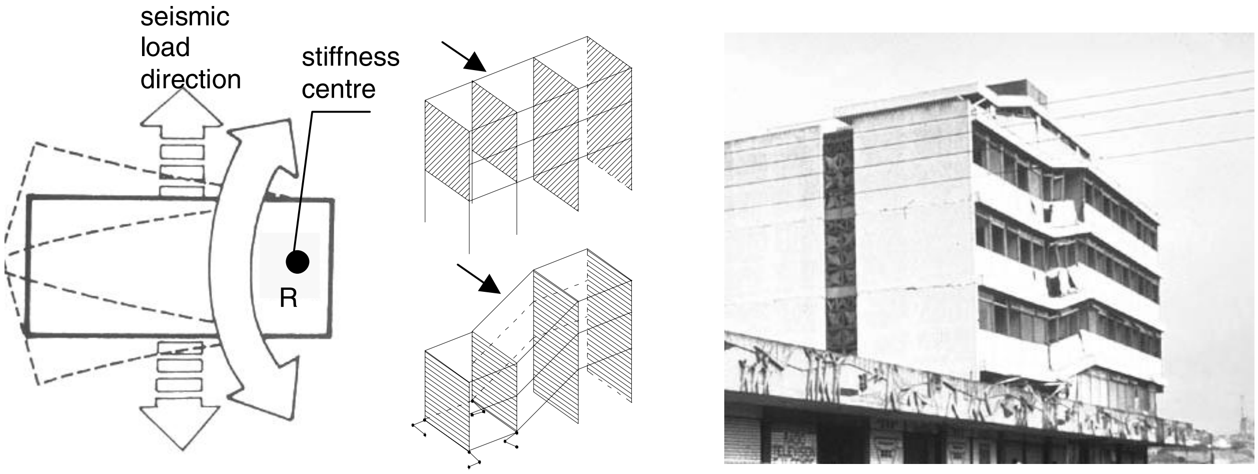
and strength are conditioned by complex phenomena of interaction occurring at the interface mesh-infill. These phenomena depend on numerous variables like mechanical properties of infill and of frame members, details of frame members, frame-infill stiffness ratio and even vertical load transferred from the frame to the infill.



a) b) c)

Figure 1. Effect of infills not uniformly distributed in plan: a) plan view: torsional effect ; b) axonometric view: scheme before and after collapse; c) building which has collapsed under seismic action

Figure 2. Effect of infills not uniformly distributed in height for a building under seismic action

Referring to the latter aspect of the problem, namely vertical loads, very few authors have recognised and studied their effects. In 1968 Stafford Smith [1] investigated the influence of a uniformly distributed vertical load imposed on the upper beam of a single story-single bay steel frame on the lateral stiffness and the lateral resistance of the infilled frame itself (the infill was made of mortar), and found a considerable increase in the lateral stiffness and the lateral strength.

More recently (1989) Valiasis [2], studying RC frames infilled with brick masonry walls, observed that the presence of a compressive axial load on the columns considerably improved the lateral strength of the system investigated.

In spite of their conclusions, Stafford Smith and Valiasis have not inserted the effects of vertical loads in the criteria postulated by them for the approximated evaluation of the effects of infills by means of a strut equivalent to the infill (see Fig. 3). They show no dependence on the vertical loads in the identification of the strut, as if they considered this effect negligible or conservative. Indeed, the effect is conservative for a single mesh just as the presence of the infill is in general conservative; but it may not be conservative for a more complex framed structure with a non-uniform distribution of infills.

In 1994 during the NCEER workshop on the seismic response of masonry infills [3] two important resolutions were stated: a) vertical loads should be included in the development of an equivalent strut model; b) future research investigations should examine the effects of vertical loads on equivalent struts. These two resolutions prove that the problem is real and had not been sufficiently treated, as evidenced by the techniques available for the identification of the equivalent strut, which do not take the effects of vertical loads into account and absolutely do not cite the vertical loads as influencing the lateral behaviour of infilled frames.

In spite of the NCEER resolutions, interest in the problem of vertical loads has not increased, as proved by the papers that can be found in the literature produced since 1994 [e.g. 4, 5, 6, 7]. Evidently this problem is not yet sufficiently felt.

In order to take the effects of vertical loads into account in the formulation of the equivalent strut, it is basic to clarify how vertical loads influence the behaviour of infilled frames under lateral loads: properly combined experimental tests and numerical “exact” tests (the word “exact” here refers to a complete model of the infills, namely one in which infill is not substituted with an equivalent element) are to be carried out.

The work presented in this paper is set in the above context and has the objective of recognising the mechanisms that govern the variation in behaviour of a framed structure under lateral loads with variation in the vertical ones. First, a numerical analysis was carried out, which indicated which is the basic parameter influenced by the vertical loads from which the lateral stiffness and the lateral strength derive, namely the extension of the frame–infill contact zone (see Fig.3-a). After a lateral load was applied, the extension of the frame-infill joint was evaluated and the associated stiffness of the system was computed. The analysis was repeated for different levels of vertical load. The increase in the extension of the frame-infill contact regions and the consequent increase in lateral stiffness were observed for an increasing level of vertical loads. The numerical analysis was first carried out using a FEM model and then repeated using a BEM-FEM model for more accurate modelling of the contact regions.

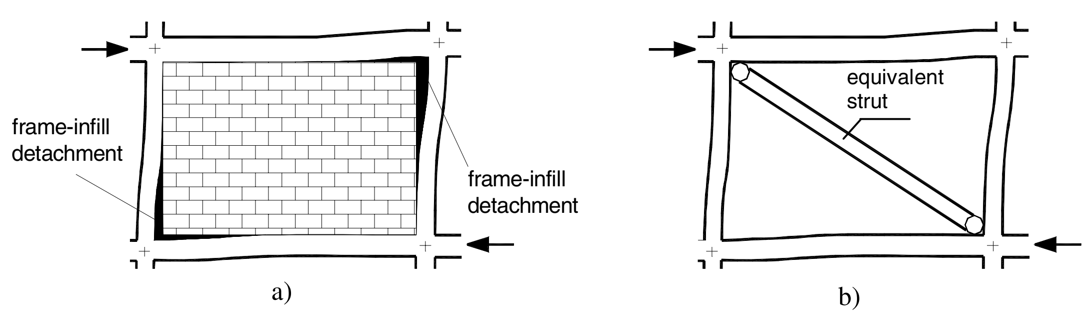


Figure 3. Infilled mesh: a) trend to detachment of frame from infill under lateral loads; b) strut equivalent to the infill

The numerical investigation made it possible to orientate an experimental investigation in which the behaviour of infilled RC frames (one-storey and one-bay frames) under vertical and horizontal loads was observed. During the tests, the condition of the frame-infill interface was controlled in such a way as to limit the extension of the joint frame-infill with respect to the natural trend of the system; then the stiffness and strength were evaluated.

In the following sections the results of the numerical and the experimental investigations are described. First a preliminary numerical analysis is discussed, which made it possible to orientate the experimental investigation. Then the details of the experimental investigation are discussed. Finally, the results of a more detailed numerical analysis and the results of the experimental investigation are compared and discussed.

PRELIMINARY NUMERICAL ANALYSIS

The experimental studies were preceded by a finite element analysis, in order to know the features of the frame-infill interaction and to define the experimental program properly.

A one storey-one bay frame was considered, representing a mesh of a more complex frame. The geometric features of the investigated system were scaled with respect to the features of real frames and are detailed in the next paragraphs. Bi-dimensional elements were used to model the infill panel and the bounding members. The interface between infill and the bounding frame was modelled using very stiff gap elements which support compressive stresses but not tensile ones. The physical detachment of the frame from the infill was controlled by applying a step-by-step increasing lateral load and checking, at each step, the axial force in each link which, if found to be in tension, becomes inactive. During the analysis vertical loads were considered invariable as more or less happens during a seismic event. The mechanical and geometric features assigned to the materials are the ones evaluated by the experimental tests as detailed in the following sections.

The analysis was repeated for different values of the vertical loads. Further, the analysis was repeated in the two following limit conditions: 1) vertical loads applied before the infill is inserted in the mesh (it is approximately like considering only the horizontal forces in the model); 2) vertical loads applied after the infill is inserted in the mesh. The actual state is generally represented by an intermediate condition: in a first stage the framed structure and the floors are made and, in this stage, a share of the total vertical loads is absorbed by the vertical members; then the nonstructural parts of the building, such as the infills, are made, and therefore they are only affected by the load applied subsequently.

An example of the different extension of the contact zones between the infill and the frame and the lateral secant stiffness, D, obtained for a lateral force of 50 kN in the abovementioned limit conditions, is presented in Figure 4.

The analysis showed that in the scheme presented in Figure 4-a the stresses in the masonry are better distributed than in the scheme in Figure 4-b: in the first scheme the principal tensile stresses tend to decrease while the principal compressive stresses tend to increase. In this condition, at least as long as the compressive stresses are lower than the strength of the masonry, the infill panel makes a greater contribution to the lateral stiffness and to the lateral strength of the system.

The results presented in Figure 4 are based on the non-tensile strength of the mortar that constitutes the joint. Nevertheless, in real cases, the tensile strength of the mortar may condition the behavior of such a system because it modifies the length of the frame-infill contact. This aspect of the problem has been investigated by comparing the results of the analysis performed for an infilled frame characterized by a mortar joint having an unlimited tensile strength – which produces a full frame-infill contact at every point on the boundary for any value of the vertical and lateral loads – with the results given by the model described before. As was expected, the tensile strength of the mortar mainly conditions the system in the scheme in Figure 4-b. As a matter of fact in the scheme in Figure 4-a, unlike the scheme in Figure 4-b, the stresses in the joint are mainly compressive. Table 1 summarizes the results of these analyses in terms of variation percentage in lateral displacement obtained by comparing the bare frame and the infilled frame.

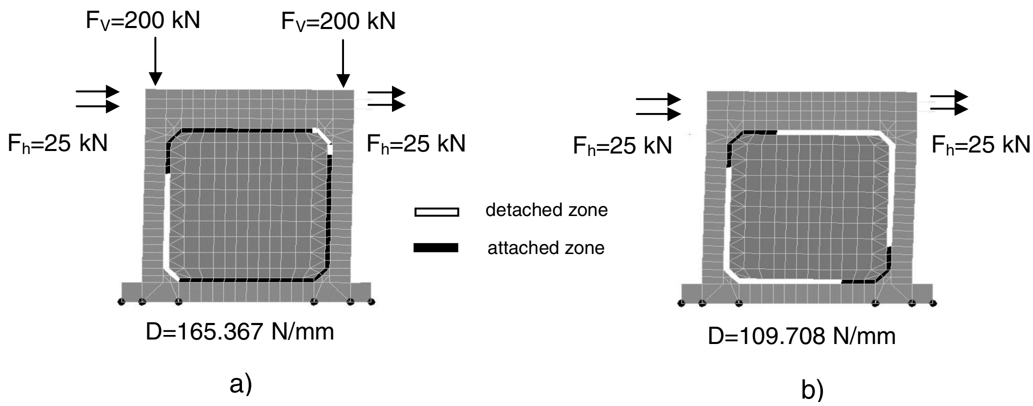


Figure 4. Some results of the preliminary FEM analysis: infill made before (a) and after (b) the application of vertical loads

Table 1. Comparison between the behaviour of the infilled frame and the bare frame

Lateral displacements: variation from bare frame [%]			
Unlimited tensile strength of joint		Non-tensile strength of joint	
Scheme i Fig. 4-a	Scheme i Fig. 4-b	Scheme i Fig. 4-a	Scheme i Fig. 4-b
- 94.94	- 94.86	- 91.25	- 84.72

In order to know how the length of the frame-infill contact is conditioned by the vertical loads the system was studied subjected to a constant horizontal force and an increasing vertical load. The results are plotted in Figure 5: the curve representing the length of contact near the upper right corner versus the level of the vertical load is drawn.

It is interesting to note that a vertical load produces a variation in the length of the beam-infill contact while it does not produce any modification in the behavior of the vertical joint. The analysis shows that the length of the frame-infill contact is a basic indicator of the effect of vertical loads.

The analyses described above were repeated using a further model based on a different discretization of the frame and the infill and the frame-infill interface. The frame was modeled using finite elements while the boundary element method was applied for modelling the infill. The double approach permitted a more reliable definition of the contact problem in the regions in which frame and infill transmit compressive stresses to each other.

Unlike the previous model, this one takes into account the tangential stresses transmitted at the interface region, which was assumed to be governed by the Coulomb friction law. No tensile strength was associated with the joint at the frame-infill interface. In this case the analysis revealed the main characteristics of the behavior of the system, giving results similar, from the qualitative point of view, to that ones derived from the previous analysis.

The analytical model is described in detail by Papia [8]; the results will be described in detail in the section after the next one in comparison with the results of the previous analysis and of the experimental investigation. It must be observed that the analysis was carried out considering the infill too as an isotropic material and as an orthotropic material.

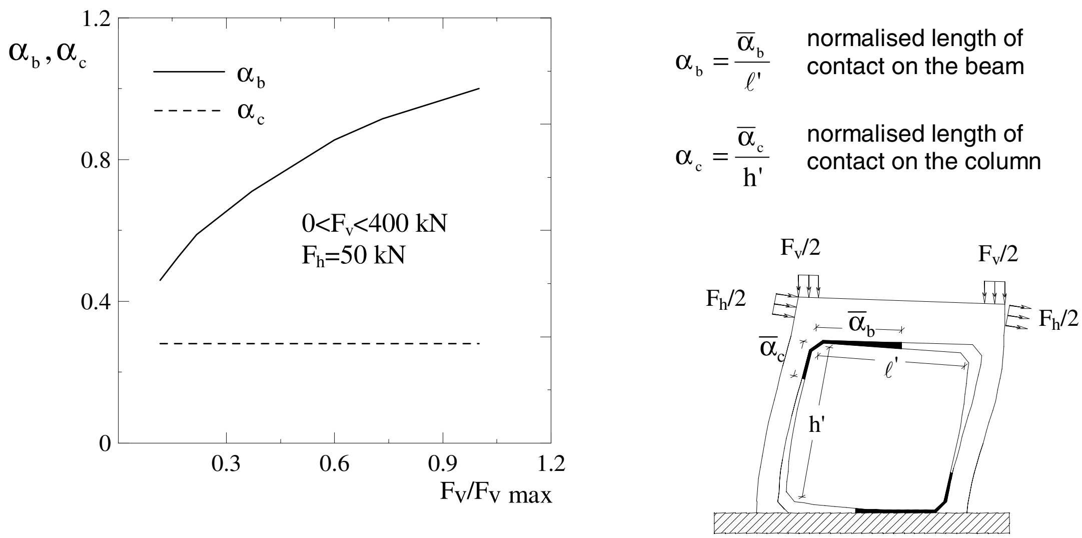


Figure 5. Lengths of contact (α_b, α_c) at the right upper corner

EXPERIMENTAL INVESTIGATION

As stressed before, the numerical analysis revealed that the length of the frame-infill contact is basic in the evaluation of the effects of a vertical load, since an increase in the vertical load produces an increase in the length of the beam-infill contact: consequently the experimental investigation was addressed to confirming the numerical results, namely the basic dependence of the phenomenon on variation in the length of the beam-infill contact. The problem was first studied by measuring the evolution in stiffness and strength of a framed system under a lateral load for an assigned value of the vertical load and then by preventing any increase in the length of the beam-infill contact for the same vertical load with respect to the case of a missing vertical load, as will be better explained in the following sub-sections.

Observe that the experimental analysis also regarded the cyclic behavior of a framed infilled system. The cyclic load was not applied specifically in order to highlight aspects of the effects of vertical loads; nevertheless, it was possible to use some of the results for the aim of this work.

Specimen description

A single storey-single bay moment-resisting frame was selected as a prototype structure under vertical and horizontal loads, reproducing the scaled geometrical features of very widespread infilled meshes of framed structure. Infill consisted of a masonry made of calcarenite blocks. The joints between the frame and the infill masonry were made of mortar. The specimens were tested at least 28 days after the construction of the infill.

Three different models were investigated, labelled as S1, S2 and S3. Preliminarily some bare frames (S1) were tested in order to observe the variation in stiffness and strength due to infill. Then two kinds of infilled frames were tested. For the first kind (S2), the frame was everywhere jointed to the infill while for the second one (S3) a partial joint between the upper beam and the infill was provided in order to limit the possibilities of contact between the upper beam and the infill (Figure 6). While the first one was loaded cyclically, for the second one obviously monotonic loading made sense. Table 2 points out some characteristics of each kind of specimen. Further, in Figure 7 the specimen details are given.

Test setup, instrumentation and loading procedure

The test setup is shown in Figure 8. The vertical loads were applied by four manually controlled hydraulic jacks, whose forces were monitored by measuring the oil pressure. The lateral loads were applied by a horizontal jack and the forces were monitored by a load cell. The device for the application of the vertical loads was constrained with respect to the horizontal displacement in order to maintain the loads vertical and to permit free sliding of the head of the frame.

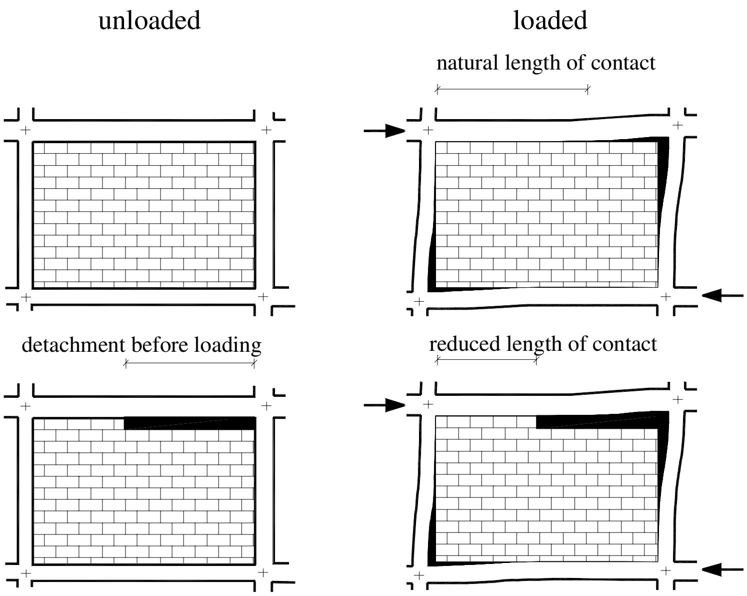


Figure 6. Control of the length of contact at the right upper corner

Table 2. Some characteristics of specimens and loading procedure.

Specimen	Infill		Mortar	Frame-infill joints	Vertical load [kN]	Lateral load
	Material	Block Dimensions [cm]				
S1	/	/	/	/	400	Monotonic
S2	calcarenite	(36x16x21)	type (*)	continuous	400	Cyclic
S3	calcarenite	(36x16x21)	type (*)	partial	400	Monotonic

(*) Hydrated lime (1 vol.); cement (1 vol.); calcareous sand (5 vol.)

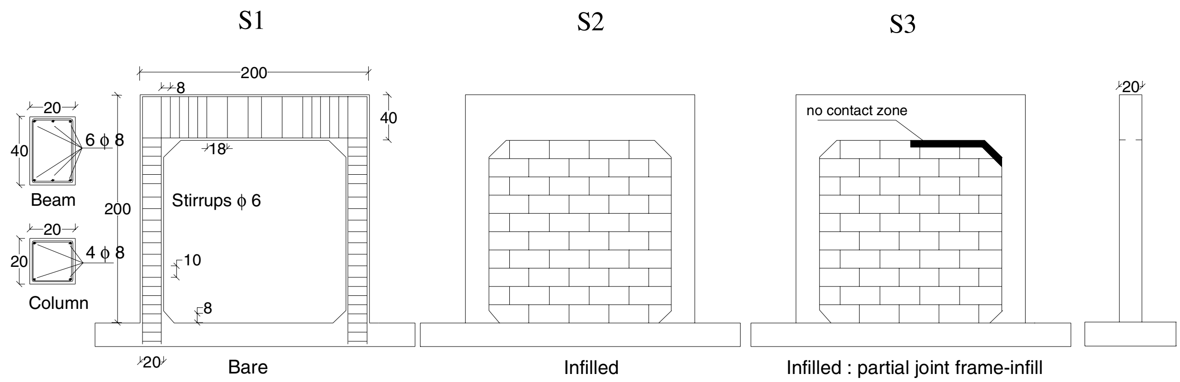


Figure 7. Specimen details

The friction force caused by the vertical loading device was measured by a load cell. The displacements of the specimen were measured by transducers located as shown in Figure 8.

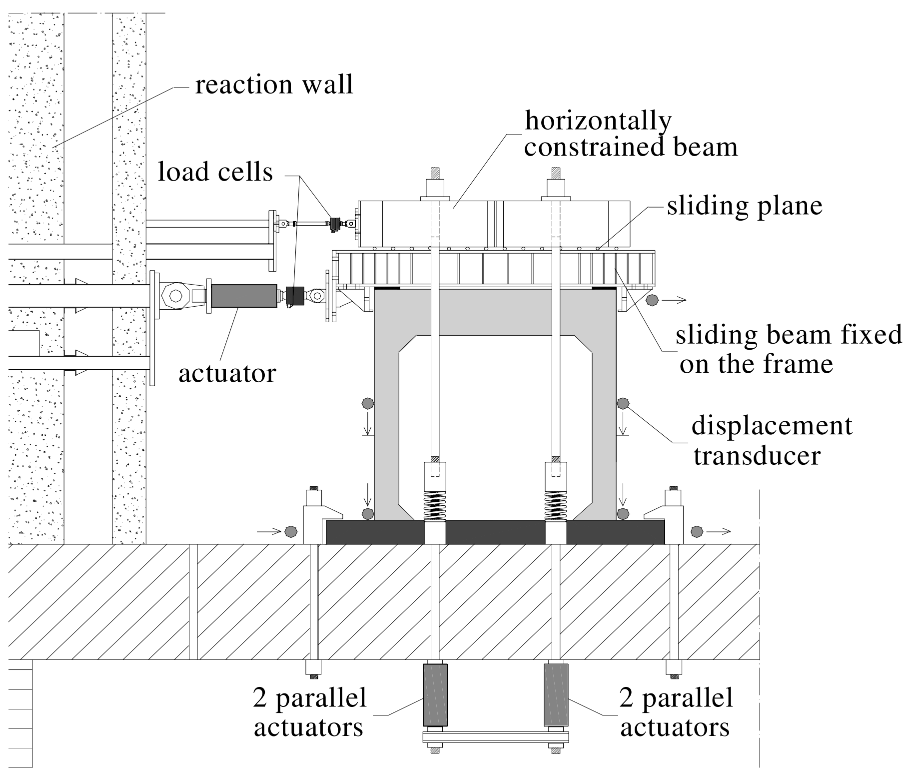


Figure 8. Test set-up

The specimens were subjected to different combinations of vertical and lateral loads. The vertical loads (dead and live vertical loads) were applied on the columns after the infill was made, and were maintained constant during each test. Table 2 summarizes the loading patterns. Usually a test was stopped when severe damage was observed in the specimen.

Experimental results

Bare frames

Two bare frames were loaded with a monotonic lateral load up to collapse, the main goal being to measure the stiffness and the strength of the system. Horizontal cracks at the head and at the foot of the columns and vertical cracks at the beam near the beam-column joint appeared before failure, denoting the formation of plastic hinges. However, some shear cracks developed in the beam-column joint mentioned above. The ultimate load experimentally obtained was very similar (on average 50 kN) to that obtained by means of a limit analysis after the definition of a plastic domain for the section of the column. Three further bare frames were tested with a low level of the lateral load for the evaluation of the stiffness. These three frames, undamaged after the tests, were infilled and subsequently tested again. The initial stiffness exhibited by the specimen on average was around 17000 N/mm.

Infilled frames with continuous frame-infill joints

Two infilled frames were characterized by a continuous frame-infill joint and subjected to cyclic lateral loads and constant vertical ones. As long as the lateral load was lower than 50 kN, a negligible reduction in stiffness was observed, then the level of the lateral force caused the tensile strength of the joint to be exceeded and the stiffness reduced. During each test, when the lateral load increased, a corresponding decrease in the length of the beam-infill contact was observed and only when the lateral ultimate resistance was reached did the length of contact become lower than the half span of the beam. For a level of the lateral load higher than 120 kN the damage to the infill revealed by diagonal cracks and the damage to the beam-column joint due to shear stresses were recorded, revealing the more vulnerable parts of the frame due to the presence of the infill (Figure 9).

For the purpose of this work from the measures of the response we extracted the maximum positive force and the corresponding positive displacement for each cycle.

Infilled frames with a partial frame-infill joint

One of these infilled frames featured a partial frame-infill joint, that is to say a detachment between the frame and the infill was produced on purpose, so as to make the vertical loads partially ineffective for the length of the beam-infill contact when a monotonically increasing lateral load was applied. In the specimens the shear stresses on the upper part of the column near the load application point appeared to prevail over the bending stresses and the beam-column joint itself was affected by a strong shear force. As a consequence large diagonal cracks appeared on the beam-column joint. Further, the level of the tensile stresses produced by the presence of the infill on the column near the application point of the load was evidenced by the horizontally diffused not severe cracks that appeared along the height of the column. The infill was affected by diagonal cracks mainly concentrated along the vertical and horizontal joints between the calcarenite blocks (Figure 9). The frame-infill joint was affected by the detachment of an extended zone.

Discussion of test results

Observation of the tests on the three kinds of specimens highlighted the fact that, as expected, infilled frames have higher stiffness and ultimate strength than bare frames, as was already known. But what is note worthy is the higher stiffness observed in the infilled frames with continuous joint frame-infill compared to infilled frames with partial frame-infill joint. Clearly, in the first case, thanks to the continuous joint, the vertical load favours the frame-infill contact, limiting the detachment zone and involving the infill mainly as a shell rather than a diagonal strut (see the flow of the stresses in Figure 10). This means that really vertical loads have a basic role in modifying the lateral response of the system if vertical loads themselves are transferred to the infill.

Referring to the strength, contrary to the conclusions of Stafford Smith [1] and Valiasis [2] reduced differences have been recorded between the specimen of type S3 and the specimens of type S2. Probably there are two reasons: the first one is that the S2 specimens were cyclically loaded with increasing peak load at each cycle and this could have been produced progressive damage to the system by reducing the strength with respect to the monotonic case; the second reason is that, for a high lateral load level, the difference between the S2 specimens and the S3 specimen decreased because in the S2 type a detachment in the beam-infill joint higher than the half span of beam was produced, namely for low loads the difference in the length of contact was relevant and this difference decreased when the lateral load increased. At all events, a more definitive statement for the causes that produce the observed results can be given after further infilled frames with continuous beam-infill joint have been tested under monotonic lateral loads.

In Figure 11 the mean curves F_h-δ (F_h being the lateral force and δ the frame head lateral displacement) derived from the specimens of the S1, S2 and S3 types are plotted. It must be remembered that while the curves referring to specimens S1 and S2 actually derive from monotonic tests, the curve associated with the S2 specimens is the mean of the curves obtained by extracting from the cyclic tests the points associated with the maximum positive load at each cycle. In Table 3 the stiffness and maximum strength values of each sample are inserted.

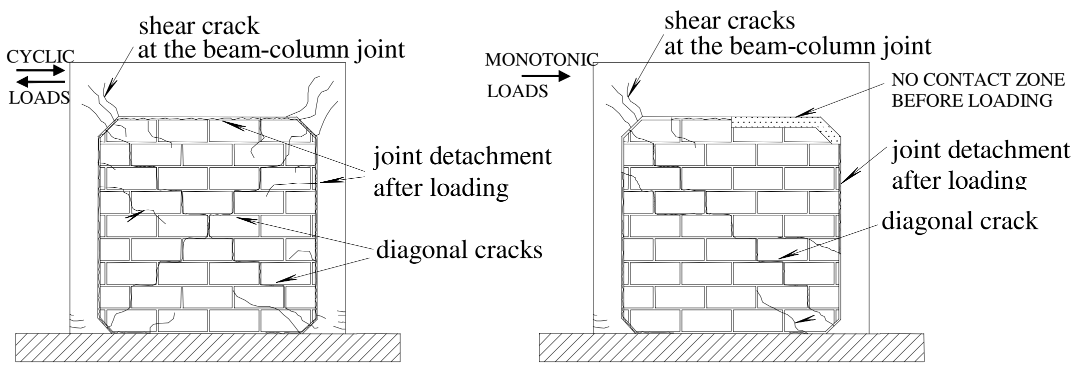


Figure 9. Crack distribution: a) infilled frame under cyclic lateral loads; b) infilled frame with partial frame-infill joint under monotonically increasing lateral loads.

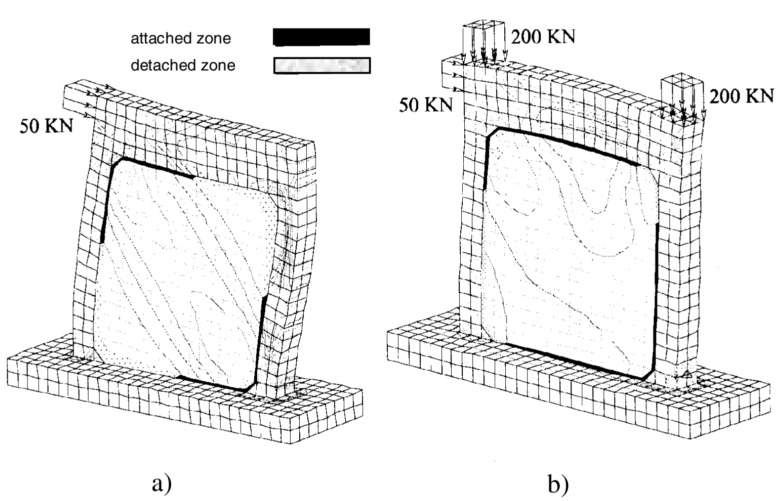


Figure 10. Flow of the stresses: a) reduced contact frame-infill; b) extended contact frame-infill

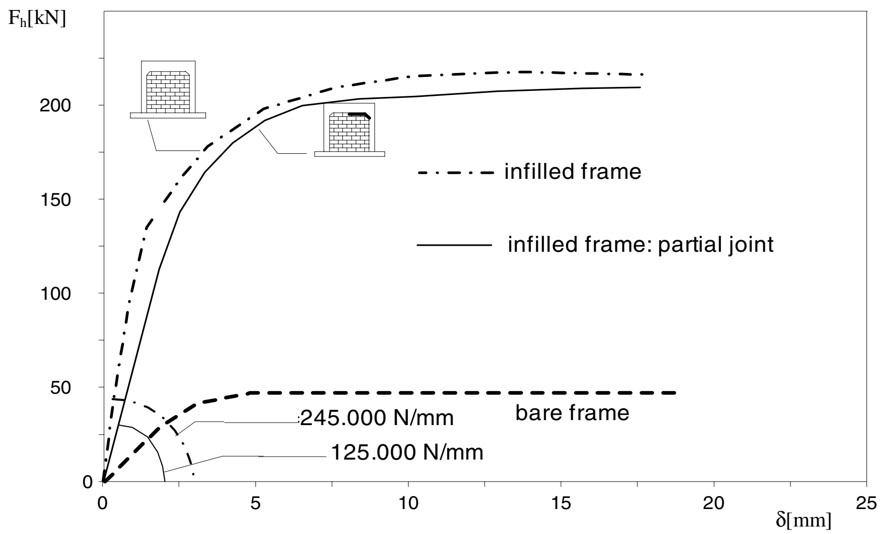


Figure 11. Mean F_h-δ curves

Table 3. Lateral stiffness and strength: experimental values

Specimen type (sample)	Lateral Stiffness [kN/mm]			Maximum Strength [kN]		
	BARE	INFILLED		BARE	INFILLED	
		Continuous joints	Partial joints		Continuous joints	Partial joints
S1 (1)	170.00	/	/	57.00	/	/
S1 (2)	167.40	/	/	43.00	/	/
S2 (1)	166.50	243.20	/	/	231.00	/
S2 (2)	159.50	247.60	/	/	215.00	/
S3 (2)	170.50	/	125.13	/	/	210.00

MODELS OF THE FRAME-INFILL INTERFACE AND COMPARISON WITH EXPERIMENTAL RESULTS

As explained above, different analytical models have been used in order to understand how and how much vertical loads influence infilled frame behaviour under lateral loads. Two schemes have been analyzed: the first characterized by constant vertical loads (400 kN) and varying lateral loads, representing the case of infill realized before the application of vertical loads; the second without vertical loads, representing the limit case of infill realized after the application of the total vertical loads.

The material properties used in the analytical simulation were determined by experimental tests. The infill was modelled as an isotropic material (BEM-FEM, FEM analysis) and as an orthotropic material (FEM analysis).
The parameters that were used in order to model the infill with orthotropic material in a plane stress state were calculated by the elastic modulus and the Poisson ratios of the mortar (E=950 N/mm^2, ν=0.2) and of calcarenite (E=12000 N/mm^2, ν=0.1) by applying twice the homogenization procedure given by Salomon [9] for the analysis of stratified rocks. The concrete frame members was characterized by an elastic modulus of (E=23000 N/mm^2).

Both member frame and infill were considered as constituted by elastic materials while a nonlinear behaviour was associated with the frame-infill joint. This choice is compatible with the level of the lateral loads that were applied: the analysis was stopped when the lateral load was around 120 kN corresponding to a sufficiently low level of the stresses in the infill and in the frame members.

Since vertical loads change the trend of infilled frames to frame-infill detachment when lateral loads are applied and vertical loads have to be taken into account for the identification of the equivalent strut, if an "exact" model of the infill is used, there arises the problem of the choice of the most proper models for the interface frame infill. Nowadays, there is not deep knowledge of the problem and of its solutions, as confirmed by the few cases in which the modelling of the frame-infill joint has been undertaken in order also the to take into account effects of the non linear behaviour of the interface itself compared with experimental results (one of these cases is available in [10]). Two different models of the interface frame infill were tested. In the first case gap elements were used while in the second case a Coulomb sliding law was associated with the interface as was stated above.

Referring to the homogenization of the infill, since the masonry is constituted by isotropic layers along two orthogonal directions, a double homogenization was carried out: first vertically between the mortar horizontal joint and the block; then horizontally between the material resulting from the first homogenization and mortar vertical joint. The following equivalent mechanical properties were evaluated: E_o=7350 N/mm^2; E_v=5400 N/mm^2; G_{ov}=1900 N/mm^2 and ν_{ov}=0.11, where "o" and "v" indicate the horizontal and vertical directions respectively.

The parameters (E_d=5000 N/mm^2; G_d= 2850 N/mm^2 and ν_d=0.28) that are used in order to model the infill as isotropic material were calculated from the previous values by evaluating the elastic features along the diagonal direction.

Figure 12 shows the secant stiffness versus the lateral load curves obtained from these analyses and from the experimental tests.

The comparison between the experimental response and the analytical models, presented with greater detail in Table 4, suggests greater reliability of the analytical approach based on a Coulomb sliding law for the frame-infill interface; nevertheless, the approach based on gap elements also gives good results.

CONCLUSIONS

The experimental and analytical study of a single bay-single storey infilled frame under horizontal and vertical loads has shown that vertical loads condition in a non-negligible way the lateral behaviour of the frame. The analysis, as confirmed by the experimental investigation, has shown that the basic parameter that conditions the lateral behaviour is the length of the beam-infill contact, at least for the prototype analysed, representing a very widespread type among existing framed structures. Hence the evaluation of the lateral response based on approximated procedures, such as the equivalent strut approach, must take into account vertical loads, that is variation in the beam-infill length of contact. The identification of this length poses the problem of modelling the interface when an "exact" approach is used (FEM or BEM-FEM model). As regards this point, better solutions can be obtained by using a Coulomb law for the interface than by using gaps not featuring any tensile strength.

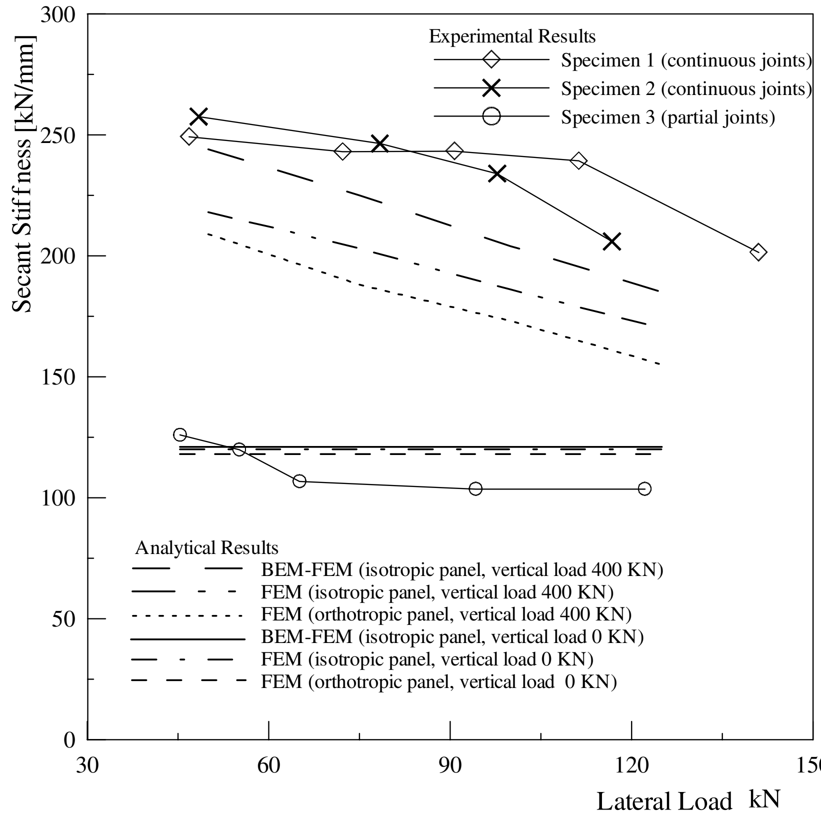


Figure 12. Comparison between experimental and analytical results.

Table 4. Ratio between calculated and observed initial lateral stiffness.

Specimen type	Total Vertical Load [KN]	Isotropic Panel		Orthotropic Panel
		BEM-FEM	FEM	FEM
S1	400	0,982	0,8775	0,8413
S2	400	0,949	0,8482	0,8132
S3	0	0,961	0,953	0,9373

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