APPLICATION OF THE LOCAL TO GLOBAL APPROACH TO THE STUDY OF INFILLED FRAME STRUCTURES UNDER SEISMIC LOADING

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SUMMARY

This paper aims at presenting the numerical studies associated to a testing program carried out at the National Laboratory for Civil Enginnering of Portugal (LNEC, Lisbon). The extensive experimental study concerns a serie of one-bay reinforced concrete frames without and with masonry panels tested under cyclic loading. Associated to these tests, some calculations with the same cyclic loading have been performed using refined material models (fibre-type model for RC frame, joint model for the interface between frame and infill and plasticity based model for masonry) and global models which allows cyclic and dynamic computation on large structures. The numerical and experimental results show quite good agreement: the use of these material models give some useful information on both the failure pattern and the global characteristics of this type of structure (maximum strength, stiffness, hysteretic behaviour…).

INTRODUCTION

In the southern European countries, the building structures are commonly made by reinforced-concrete frames infilled with unreinforced masonry panels. The infill panels, usually considered as non-structural elements in design, have a significant effect on the global seismic linear and non-linear responses of R/C frame structure [Fardis et al, 1994]. For instance, the failure mode planned by the capacity design procedure of the EUROCODE 8 -strong columns/weak beams- is no longer ensured in presence of strong infill panels. Furthermore, their influences can be of a major importance for the seismic assessment of existing buildings built in the years 1950-70 when the design provisions for seismic loading were reduced or did not exist at all.

In order to quantify the effect of the infill panel on the global behaviour of the building structures, a campaign of tests concerning one-bay masonry infilled frames has been performed at LNEC (Lisbon) under cyclic loading (C3ES Report 1996). Associated to these experimental programs, several numerical models are used for the analysis of the infilled frame structures. The two modelling levels - the local level where the properties of each constituent such as masonry, concrete, reinforcement … are considered as refined constitutive law and the global level where each structural element has a simplified law - are used in a complementary way: the refined modelling allows a better understanding of the resistance and failure mechanisms and provides a basis for the identification of the parameters used in the global models which allow to perform dynamic or hysteretic analysis. Both experimental and numerical results given by the two levels of modelling are given in this paper.

EXPERIMENTAL RESULTS USED FOR VALIDATION

Model characteristics and experimental set-up

A series of 9 one-bay RC frames has been tested under cyclic loading in the framework of the SEISMIR research program supported by the European Commission. The geometric characteristics and the reinforcement details of the models, as well as the applied loads, tried to simulate the real conditions of a reinforced concrete frame located in the ground floor of an ordinary building. The models had an height of 1.80 m and a length of 2.40 m. The columns and the beams cross sections have, respectively, 0.15 m x 0.15 m and 0.15 m x 0.20 m. The columns were reinforced with 8ø10 longitudinal bars and ø8//0.04 hooks. The beams were reinforced with 6ø8

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longitudinal bars and ø6//0.05 stirrups. The infill walls were built with 0.30 m x 0.20 m x 0.15 m horizontally hollow bricks, usual in Portugal, bedded using mortars with the proportions 1:4 in volume (cement:river sand). The materials used in the construction of the frames were a C20/25 concrete and a S400 steel. The models were built on reinforced concrete blocks with a 3.24 m x 0.74 m x 0.35 m volume. These concrete blocks were used to fasten the model to the shaking table. Fig 1-a illustrates the geometric characteristics and the reinforcement details of an infilled model with a window opening.

The models were tested in the platform of a shaking table. The tests consisted basically in the application of a relative horizontal displacement history between the base and the top of the models. A vertical force of 100 kN was applied at the top of the columns. This force was kept approximately constant during the entire tests. Each stage of the tests consisted in the application of 2 complete sine waves of relative horizontal displacement between the base and the top of the models. The maximum amplitude of the imposed displacement increased from stage to stage of the tests (0.6 mm, 25 mm, 50 mm, 75 mm and 100 mm). The experimental set-up and the main test results are described in details in [C3ES Reports, 1998] and [Pires et al, 1998].

Main results

Table 1 shows the maximum strength of the 9 specimens and the increase of initial stiffness due to the presence of the infill panel. Note the great influence of the infill panel for these frames. All the uniformly infilled frames had similar failure patterns: cracking accurs at the interface between the frame and the masonry panel, crushing of masonry in the corners of the wall and some cracking of masonry in the wall itself (Fig 1-c). The force-displacement relationship are caracterized by softening and important pinching after the beginning of the masonry crushing (Fig 1-b). Strength degradation under cyclic loading is also visible on the global force-displacement curves: after one cycle, the specimens do not find again the initial strength but a reduced strength. The infill frames with the window opening had a different failure pattern (Fig 1-d): the masonry on both sides of the window acts as 2 small rocking walls which crushed at the extremities of one diagonal and horizontal cracking occurs at the lower and the upper mortar joint.

Table 1: Increase of strength and stiffness due to the masonry infill panel

Specimen	Bare frame		Uniformly infilled frame				Infill frame with window		
	I3	I4	I1	I7	I8	I9	I2	I5	I6
Max. shear strength	60 kN	64 kN	190 kN	250 kN	181 kN	193 kN	156 kN	123 kN	123 kN
Initial stiffness (kN/mm)	4.8	4.99	206	182.4	155.7	170	50	74.4	75.1
Increase of initial stiffness due to infill *	/	/	x42.9	x38	x32.4	x35.4	x10.4	x15.5	x15.6

*compare to the initial stiffness of the I3 specimen

THE LOCAL TO GLOBAL MODELLLING APPROACH

Definition of the local and global modelling levels

Two modelling approaches, global and local, are classically used to analyse the infilled frame structures under horizontal seismic loading. In the global approach (Fig 2-a), each masonry panel is often replaced by two trusses with an uniaxial behaviour law [Klingner et al, 1976]. The complexity of the behaviour depends on the various phenomena taken into account by the model (pinching due to crack closure, crushing of masonry at the corners, decrease of stiffness due to cracking, etc...). The frame is modelled by beam and column elements with moment-curvature relationships or fibre type model. This approach allows to perform a large number of computations with dynamic or cyclic loading but the identification of the truss parameters is often based on empirical rules. In case of a modification in the panel characteristics, the limit of validity of the formulae may be reached.

In order to cope with this difficulty, it is proposed to use the refined material models not only to identify the parameters of the panel element but also to highlight the limitation of such a global model by studying, for example, the interaction between different infills in a multi-storey structure [Combescure 1998]. In the local approach, each part (the frame and the infill panels) is discretized. Both materials -masonry and RC concrete- are considered as homogeneous media with an elastic or a non-linear, isotropic or anisotropic behaviour law. In this local modelling, the hypothesis made for the contact between the frame and the infill panels becomes important since the global stiffness is highly dependent on the presence of cracks at this interface. All the computations presented here have been performed with the Finite Element code CASTEM 2000 developed by CEA-France.

Within such an environment , the user can easily compare the two levels of modelling and use them in a complementary way and it becomes easy to identify the parameters of the global models using refined modelling.

Local modelling

R/C frame

2D Timoshenko beam elements supporting a fibre type model have been used for the frame [Guedes and Pegon,]. Each column has been discretized by 10 elements with 6 concrete fibre and 2 or 3 steel fibres, each fibre having 2 Gauss points. Simplified uniaxial laws have been considered for both concrete and steel: parabolic curve with a perfectly plastic plateau in compression and no strength in tension for concrete (similar to the concrete law of the French BAEL concrete code) and a plastic model with kinematic hardening for steel. Shear behaviour is assumed elastic. Note that such a modelling allows to know the shear forces and the axial forces in the frame and thus to quantify the effect of the presence of the masonry infill onto the surrounding frame.

A masonry plasticity based model

The experimental results and some previous studies have shown that the specimen failure is reached when the masonry crushes [Pires, 1993], [Combescure, 1996]. Furthermore, the ultimate strength depends on the number of cycles applied to the specimen. In order to cope with the former property, a plasticity-based model with two yield surfaces and softening behaviour in compression and traction has been developed. Details about this model and its numerical implementation are available in [Combescure, 1996]. As for the classical plasticity-based models, unilateral phenomena due to cracking is not considered. This fact has a minor importance also under cyclic loading since the main cracking is assumed localized at the interface between frame and infill and is modelled by a joint/interface element.

The Young modulus is identified with the results of diagonal test ($E=4.G$ for $\nu=0.2$ if G is calculated with the RILEM rules) whereas the compressive strength of the isotropic model of masonry is directly given by the compression tests (perpendicular to the holes). Note that the identification of the masonry parameters must be realized with tests performed on complete masonry wallettes since masonry has a very complex behaviour due to the difference of Poisson ratio between bricks and mortar.

Contact modelling

The modelling of the interface has a major influence on the failure pattern, the initial stiffness and the global strength. A plasticity-type joint model with a Coulomb yield surface is used [Snyman et al. 1991]. While the sliding behaviour is governed by plasticity rules, the unilateral phenomenon is reproduced in tension: the joint opens without creating plastic strain. Associated or non associated plastic flow and dilatancy phenomenon can be considered. In our case, the dilatancy angle is assumed equal to zero. The considered tensile strength of the joint is equal to 10 percent of the masonry compressive strength. A classical value of 40 degrees taken from the results of the tests described by [Mehrabi et al., 1995] on mortar-brick interfaces is used for defining the Coulomb failure surface.

Global modelling

Simplified modelling of the RC frames

The mesh of the surrounding frame is reduced for the global computation: each column is discretized with one linear Bernoulli beam element with a reduced elastic stiffness (2/3rd of the elastic stiffness) placed between two Timoshenko elements supporting the non linear fibre model. A constant length equal to the column width has been considered for the plastic hinges.

A global model for infill panels

Since the work performed by [Klingner and Bertero, 1976], the non-linear analysis of infilled frames have been usually performed by replacing each individual panel by two -or more- diagonal struts with a uniaxial compressive law. The model introduced in CASTEM 2000 is also supported by a truss element and the behaviour law (Fig 2-a and b) is able to reproduce the classical models by choosing the appropriate parameters. The phenomena reproduced are the stiffness degradation due to cracking -mainly at the interface between the frame and the panel-, the development of plastic strain and the softening due to crushing, the strength degradation under cyclic loading and the pinching associated with sliding. The strut has no tensile strength and the stress-strain curve under monotonic compressive loading is multilinear and may be identified by using the results given by refined modelling.

Special attention must be brought to the phenomena of compressive strength degradation under cyclic loading which characterizes the masonry components. This effect is not easy to quantify but is taken into account by multiplying the force Fmax associated with the plastic strain dplastic by a factor which is a function of the cumulated cyclic plastic displacement (this cumulated cyclic plastic strain is defined as the sum of the increments of plastic strain). A decreasing exponential function is considered. For a constant plastic strain, the force can decrease down to the residual stress Fmax,res=θ.Fmax.

REFINED ANALYSIS OF THE ONE-BAY INFILLED FRAMES

The numerical study of the specimens has been first performed with the refined models. Monotonic and cyclic loading have been applied at the uniformly infilled frame whereas the infill frame with a window opening has been studied only under monotonic loading. These computations aimed at understanding the resistance and failure mechanisms, at identifying the characteristics of the diagonal strut and finally at estimating the axial and shear forces generated by the infill panel in the surrounding frame.

Behaviour of the uniform infilled frame

In the present study, the Young modulus and the compressive strength of masonry has been taken equal to 4000 Mpa and 2.2 Mpa respectively. The bricks were horizontally perforated with a void ratio of 60% and have an average compressive strength perpendicular to the holes equal to 4.8 MPa.

The first analysis with a monotonic loading can help to understand the failure mechanism. The failure pattern observed during the tests is well captured by the refined modelling: an equivalent diagonal appears between two opposite corners and the maximum strength is reached when masonry begins to crush in the corners. Failure is also characterized by the motion of the diagonal strut down to the base of the windward column (Fig 3-a).

The study under cyclic loading has been performed neglecting the cyclic degradation of strength of masonry. The previous conclusions can be extended to the cyclic case: the panel acts as two diagonal struts which fail in compression. The cycles are characterized by an elastic unloading followed by a sliding phase and the reloading of second diagonal (Fig 4-a). The pinching effect increases with the infill damage. Note the force-displacement curves exhibit some strength degradation although this phenomena was neglected in the masonry constitutive law. This fact can only be explained by the change of contact condition between two cycles. The global strength and the softening slope after the maximum strength are well captured by the refined modelling.

Influence of the window opening

A monotonic horizontal displacement up to 50mm has been applied at the model with a window opening in the infill panel (Fig 4-b). The experimental failure pattern is well reproduced (Fig 3-b). The computed initial stiffness is overestimated (128 kN/mm against 75 kN/mm for the specimen I6 and 50 kN/mm for the specimen I2).

Analysis of the forces induced by the infill panel onto the RC frame

During past earthquakes, failure of RC frames with limited damage in the infill has been observed (short column effect). It is thus very interesting to know the interaction between the frame and the infill in the refined modelling. For this purpose, the distribution on the height of shear and axial forces and the evolution of their maximum in function of top displacement has been analysed (for monotonic loading only). Fig 3 shows the distribution of shear force for the uniform infilled frame and the infill with window opening. Note the increase of shear in the parts of the columns at the extremities of the diagonal strut. The maximum values of shear force and axial force are given in Table 2. The computed values of shear stress are very high but the columns had sufficient stirrups to avoid brittle shear failure.

Table 2: Maximum values of shear force and axial force in the columns

	Uniform infill	Uniform infill	Infill with window	Infill with window
Left column	112 kN (4.98 MPa)	39 kN	78.2 kN (3.47 MPa)	41.3 kN
Right column	123 kN (5.47 MPa)	192 kN	28.2 kN (1.25 MPa)	134.9 kN

*: For axial force, the maximum value –positive is compression- is given for the right column and the minimum value for the left column. These values may be compared to the axial force corresponding to the vertical load which is 80.5kN per column.

GLOBAL MODELLING

Identification of the diagonal characteristics

The refined modelling shows the validity of the diagonal strut model commonly used for dynamic analysis of infilled frame. But the identification of the diagonal properties remains one of the key points for a realistic modelling of the infill frames. The results of the refined modelling have been used to determine the initial and cracked stiffness and the strength of the diagonal. The shear force – top displacement relationship for the infill panel only has been found by doing the difference –for similar displacements- between the shear forces for the infill frame and the bare frame. The shear force and the top displacement have been converted to axial force and strain in the diagonal strut. Table 3 shows the values of forces for several characteristic displacements. Seismic analysis of a complete structure requires simplified rules for the identification of the diagonal strut properties. The previous results have been converted in width of the equivalent diagonal for both stiffness and strength (expressed as a percentage of the diagonal length). If a 4000 MPa Young modulus and a 2.2 MPa compressive strength are considered for masonry, the diagonal widths are:

- for initial stiffness: 51% of the diagonal length

- for cracked stiffness, 24.5% of the diagonal length (it means a decrease of 50% of the stiffness due to cracking at the interface between the frame and the infill panel)

- for maximum strength, 24.9% of the diagonal length

Such values have been considered for the global modelling. The axial strain at the beginning of softening has been taken equal to 0.5% and the strain at the end of softening equal to 1.5% (Fig 2-c).

Main results

Two computation have been performed with two sets of parameters for the phenomena of strength degradation under cyclic loading (the same asymptotic strength degradation of 50% has been considered):

- model 1: 40% strength degradation for an horizontal plastic displacement of 300mm

- model 3: 40% strength degradation for an horizontal plastic displacement of 30mm

The comparison between experimental and numerical results is shown in Fig 4 for both assumptions and shows the second set of parameters allows a better correlation.

Table 3: Values of shear forces for several characteristic displacements

	Top displacement	Axial strain in the strut	Infilled frame shear force	Bare frame shear force	Infill shear force	Axial force in the strut
Cracking	0.4mm	0.0119%	78.9 kN	1.68 kN	77.2 kN	97.6 kN
Masonry crushing	1.75mm	0.052%	167.4kN	6.85kN	161.kN	203.1kN
Maximum strength	7mm	0.21%	204.7kN	21.6kN	183.1kN	231.5kN
1% drift	17.25mm	1.03%	202.6kN	41.6kN	161kN	203.6kN
Max. displacement	50mm	1.49%	136.6kN	53.6kN	83.02kN	105kN

CONCLUSION

The present paper shows the numerical analysis of one-bay one-storey infilled frames with and without window opening using two levels of modelling: the non linear FEM model allows to understand the failure pattern under monotonic and cyclic loading, to estimate the forces created by the infill panel in the surrounding frame and to identify the properties of the global model of infill. Simple rules are also given for the identification of the diagonal properties. The correlation between numerical and experimental results is good for the refined models and the global models if the phenomena of strength degradation under cyclic loading taken into account. The present modelling approach has now to be used for extensive parametrical studies in order to extend the results to other geometry and infilled configuration (different stiffness and strength for frame and other opening geometries for infill). The same models can also be applied at the study of retrofitting and strengthening techniques.

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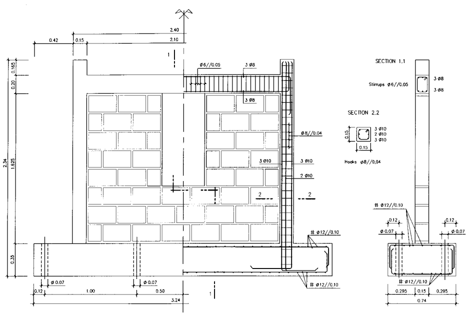
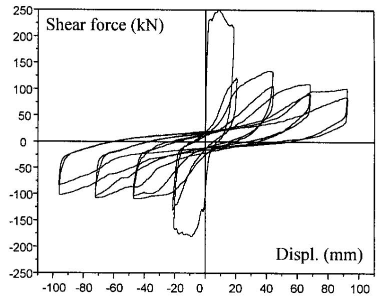
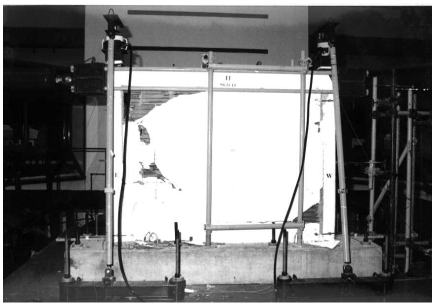


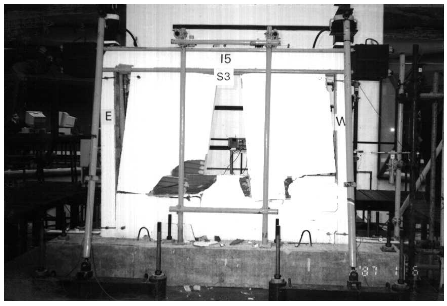
a/ Infilled frame with opening



b/ Shear force vs top displacement (test I7 – Uniform infill)

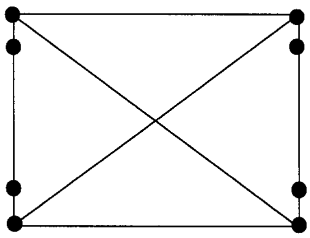


c/ Failure pattern (Test I1 – uniform infill)

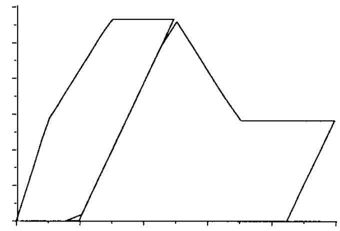


d/ Failure pattern (Test I5 – infill with window)

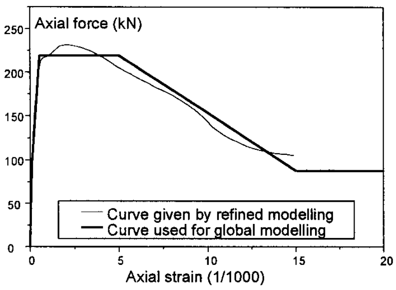
Figure 1 – Experimental study of infilled frames performed at LNEC



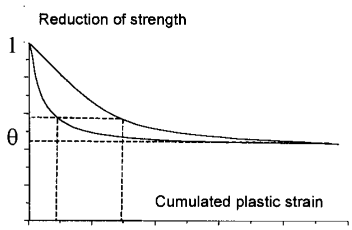
a/ Global modelling of the infilled frame



b/ Traction-Compression law of the strut

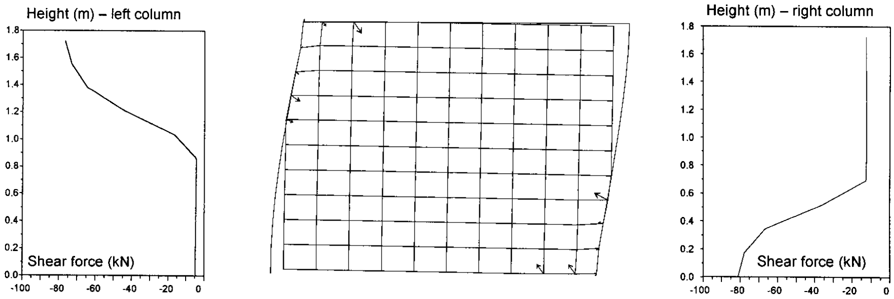


c/ Identification of the first loading curve using refined modelling

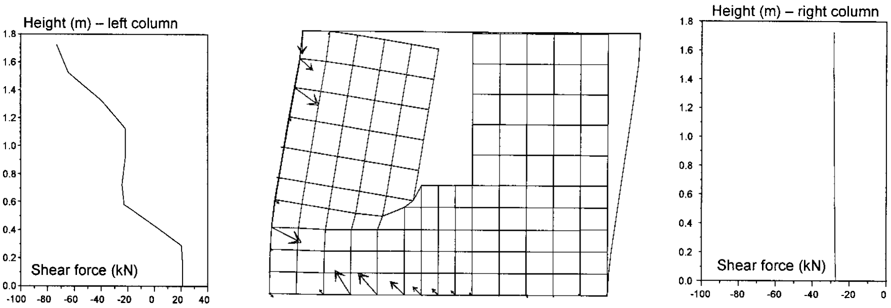


d/ Decrease of strength due to cyclic loading

Figure 2 – Global modelling of infilled frames

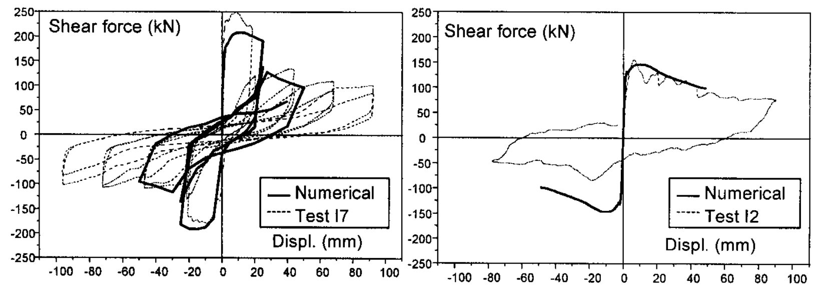


a/ Deformed mesh and shear forces in the columns for a top displacement of 50 mm – Uniform infilled frame

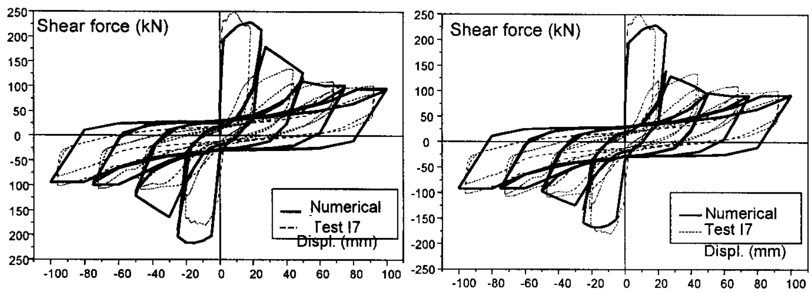


b/ Deformed mesh and shear forces in the columns for a top displacement of 50 mm – infilled frame with opening

Figure 3 – Deformed mesh and repartition of shear forces in the surrounding frame (refined modelling)



a/ Refined modelling – Uniform infill *b/ Refined modelling –Infill with window*



c/ Global modelling – Model 1 *d/ Global modelling – Model 3*

Figure 4 -Force-displacement relationships