8TH
CANADIAN
MASONRY
SYMPOSIUM

Jasper, Alberta
May 31 - June 3, 1998

EXPERIMENTAL STUDY OF THE BEHAVIOUR OF MASONRY INFILLED R/C FRAMES UNDER HORIZONTAL ACTIONS

Felicita Pires, A. Campos-Costa, Ema Coelho and Jorge Rodrigues
LNEC – Laboratório Nacional de Engenharia Civil
Av. do Brasil, 101, 1799 Lisboa Codex, Portugal

ABSTRACT

This paper reports an experimental study aiming at the analysis of the behaviour under horizontal actions of reinforced concrete frames infilled with different brick masonry walls, conducted at the Centre for Studies and Equipments in Earthquake Engineering (C3ES) of the National Laboratory for Civil Engineering of Portugal (LNEC).

Nine models, in a scale 2:3, were tested, named: two bare frames, four fully infilled frames and three infilled frames with a window opening. Two different horizontal histories of displacements under identical velocities were imposed at the level of the beam centreline: cyclic (six models) and monotonic (three models). Constant vertical forces were applied at the top of the columns in order to reproduce the effect of the upper floors of a building. The characteristics of the models, the test set-up and instrumentation and the testing procedure are reported. Some results of this experimental study are also presented and analysed.

INTRODUCTION

The modern seismic design of reinforced concrete structures is usually based on the capacity design concept. This design approach is associated to the exploitation of the structural ductility that results from the development of stable dissipation mechanisms previously defined. The existence of irregularities can induce some fragility on the capacity design criteria if those irregularities are not taken into account properly. One of the causes of irregularities is the existence of infill masonry walls that can change significantly the dynamic characteristics of a reinforced concrete frame "properly designed" in the assumption that such irregularity doesn't exist. The usual structural design considering the infill masonry walls as "non-structural" elements can therefore compromise the integrity of the structures (Fardis and Panagiotakos, 1997).

In past earthquakes and in laboratory tests, the damage in infilled reinforced concrete frames shows that the existence of the infill masonry walls can change the behaviour of those structures, namely:

- Increase considerably the global resistance to lateral loads and the energy dissipation capacity;
- Increase the lateral stiffness of the structures and, thus, the seismic forces which may not be counterbalanced by the increase in lateral resistance;
- Affect the initial collapse mechanism of the bare frames (short column effect);
- Originate torsional effects due to the irregular arrangement of the walls or due to the walls failure at one floor;
- Originate the development of soft storey mechanisms due to the collapse of the infill masonry walls, which creates a vertical discontinuity of stiffness and strength of a floor in relation to the others.

Several experimental and analytical works have been carried out with the major aim of studying the phenomena of interaction between infill walls and frames, and the parameters likely to influence such phenomena, as well as developing analytical models to simulate the behaviour of infilled frames (CEB, 1996; Combescure, 1996).

Since the knowledge of the behaviour of a single masonry wall panel is very important and reproduce reasonably the interaction referred above, an extensive experimental programme of tests was performed at LNEC, Portugal, (Felicita Pires, 1990 and 1998). The main purpose of this programme was to study the behaviour of single structures made of one-storey, one-bay reinforced concrete frames infilled with brick masonry as the one usually used in Portugal, under monotonic and cyclic horizontal actions.

In this paper the experimental work is reported and some of the results of the nine models tested are presented.

MODELS DESCRIPTION

The experimental programme comprised the testing of nine models in a 2:3 scale. Seven of them consisted of one-storey, one-bay reinforced concrete frames infilled with masonry walls (three with a window – I2, I5 and I6; four fully infilled – I1, I7, I8, and I9) and the remaining two consisted in just the bare frame – I3 and I4.

The geometric characteristics of the models and the loads applied reproduced a reinforced concrete frame infilled with brick masonry, 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 8ϕ10 longitudinal bars and ϕ8//0.04 hooks. The beams were reinforced with 6ϕ8 longitudinal bars and ϕ6//0.05 stirrups. The infill was 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 frame 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 models to the shaking table.

Fig. 1 illustrates the characteristics of a model constituted by an infilled frame with a window opening.

TEST SET-UP AND INSTRUMENTATION

In this experimental programme it was decided to use the platform of a shaking table to impose a relative horizontal displacement between the base of the frame and the top beam centreline.

Fig. 2 shows a scheme of the test set-up. As it can be seen in this figure, the top beam centreline was linked, with a steel rod, to a reaction wall that is part of the shaking table laboratory building. A load cell was installed between the steel rod and a steel structure connected to the reaction wall, in order to measure the horizontal force generated at the steel rod due to the displacements imposed at the base of the frame with the shaking table control system. In order to avoid out of plane deformations of the test specimen a steel guiding system was used.

Vertical forces were simultaneously applied at the top of both reinforced concrete columns by means of two single acting servo-hydraulic actuators connected to a hydraulic pump whose oil pressure was duly monitored during the test.

Besides the already mentioned devices for the measurement of forces, the models were also instrumented with displacement transducers, namely, Hottinger Baldwin Messtechnik inductive displacement transducers (LVDT) and Hamamatsu optical position sensors C2399.

The acquisition of the data was performed with a 28 channel multiplexed Kaye-MDAS-7000 A/D unit, using a data acquisition software developed with *Labview*. Before entering the A/D unit the acquired electrical signals from the different transducers were corrected with appropriate conditioning equipment.

TESTING PROCEDURE

Before starting the test of the models an impact test was carried out in order to evaluate their natural frequency in the initial (undamaged) state. This impact testing consisted in the measurement of the acceleration responses, both at the top and at the base of the models, induced by an impact excitation introduced at the beam level with a stiff hammer shock. The acceleration responses were measured with 7290A Microtron ENDEVCO accelerometers, placed at the top and at the base of the model, and with a sampling frequency of 200 Hz.

Following the initial impact test, a vertical force of 100 kN was applied at the top of the columns. This force was kept approximately constant during the entire test. After application of the vertical force, the steel rod was connected to the guiding steel structure already placed at the top of the model.

The tests of models I1, I2 and I3 were intended to characterise the monotonic behaviour of the three different types of models. They consisted in the application of a relative horizontal displacement history, between the base and the top of the model, with peak values of 0.10 m in both directions. This horizontal displacement history was imposed in 8 different stages at a velocity of 5 mm/s, as it can be seen in Fig. 3. In the test of model I1 the last stage wasn't applied.

The tests of models I4 to I9 were intended to characterise their behaviour under cyclic loading. They comprised 5 different stages that consisted in the application of 2 complete sine waves of relative horizontal displacement between the base and the top of the model, as it can be seen in Fig. 4. The maximum amplitude of the imposed displacement increased from stage to stage of the test (0.6 mm, 25 mm, 50 mm, 75 mm and 100 mm) and, since the displacement history was applied without exceeding a velocity of 5 mm/s, the correspondent frequency decreased. Models I8 and I9 were also used in another experimental study with the aim of checking the efficiency of two different strengthening methods, therefore, in order to avoid excessive damages, the last two stages weren't applied in the tests reported in this paper.

PRESENTATION OF RESULTS

Some results showing the behaviour of the tested models are presented in Tables 1 and 2, respectively for the monotonic and cyclic tests. In those tables the initial elastic stiffness and the maximum strength of the nine models are presented and compared in relation to the bare frame models.

The photos presented in Figs. 5 to 7 shows the nine models in the final stage of the tests, illustrating the failure modes observed for each case. The corresponding horizontal force-top displacement diagrams are also presented in those figures and the hysteretic energy dissipation histories for the cyclic tests are shown in Fig. 8.

ANALYSIS OF RESULTS

Failure Mechanisms

The bare frames (models I3 and I4) presented a hysteretic mechanism originated by the formation of hinges at the top and base of the columns. No significant damage was observed along the columns and beams neither the spreading of the plastic hinges was verified.

The behaviour of the infilled frames was conditioned by the initial cracking pattern of the masonry panel, which began in all models with the separation of the masonry from the reinforced concrete frame along their vertical and horizontal interfaces. Simultaneously, the first cracking in masonry panel defined two different zones in that element. Some of those tracks may be due to tensile failure when they are parallel to the compressed diagonal and other cracks may be attributed to shear or sliding along the brick-mortar interfaces of horizontal joints.

In all the fully infilled frames local crushing of the masonry panel corners was observed at a latter stage of the tests.

In the infilled frames with window opening the crushing of the masonry panels occurred mainly in the bottom corners of the panel and at the level of the first horizontal crack (bottom of the window opening). After the development of that first horizontal crack, the upper part of these models was completely separated from the reinforced concrete frame due to the existence of the window opening, therefore, the crushing of the upper corners wasn't so extensive as in the fully infilled frames. In these models, especially in the monotonic test (model I2), the short column effect could be clearly observed at a latter stage of the tests.

As it can be observed in Figs. 5 to 7, for the level of imposed displacements in the tests, similar hysteretic mechanisms can be assumed for the reinforced concrete frames of the bare frame models and the infilled frames with a window opening. This is very evident in the last stages of the cyclic tests illustrated by the horizontal force-top displacement hysteretic loops presented in Fig. 6.

In all the infilled frames, for higher displacement demands, it is predictable that the inelastic deformation in the columns would be developed at the level of the first horizontal crack in the masonry panel.

Evolution of the Hysteretic Response

As it can be seen in Figs. 5 to 7 and in Tables 1 and 2, the infilled frames presented an initial response with significantly higher stiffness and strength.

The maximum strength of the fully infilled frames was about 3 times the maximum strength of the bare frames, with exception of model I7 that presented a higher maximum strength. This might be due to differences in the construction of the masonry walls.

In relation to the infilled frames with window opening the maximum strength was about 2 times the one of the bare frames. In the test of model I2 (monotonic test) that strength relation was higher, probably due to the type of loading (monotonic).

In what concerns the initial elastic stiffness in the cyclic tests, the fully infilled frames had a value of about 35 times the one of the bare frame. In the monotonic test this stiffness relation has a similar value.

In the case of the infilled frames with window opening, the initial elastic stiffness in the cyclic tests had a value of about 22 times the one of the bare frame. In the monotonic test this stiffness relation had a significantly lower value, probably due to the existence of some initial cracks along the interface between the masonry panel and the reinforced concrete frame. These initial cracks occurred eventually during the placement of the model in the shaking table.

The high initial values of stiffness and strength observed in the infilled frames suffer an important decrease after the first hysteretic cycle. In the case of the model with window this decrease is such that the response after the third stage is almost coincident with the one of the bare frame model. This coincidence is also illustrated in the evolution of the dissipated energy.

The envelopes of the hysteretic loops of the models subjected to cyclic tests, models I4 to I9, and the corresponding horizontal force-top displacements diagrams of the models subjected to monotonic tests, models I1 to I3, are presented in Fig. 9.

Comparing the envelopes of the hysteretic response of models I4 to I9 (see Fig. 9) it is possible to see that the bare frame and the infilled frames with window have the same response after about 3% of drift. It is also evident that the fully infilled frame subjected to all the stages of imposed displacements (model I7) presents a strength reserve of about 100% in relation to the bare frame at the maximum imposed drift.

Comparing the cyclic behaviour of each model with a similar model monotonically loaded, one can assess the importance of the loading pattern (monotonic/cyclic) in the exploitation of the strength reserve of the infilled frames in relation to the bare frame.

In Fig. 9 it is clear that the cyclic behaviour exploits the strength reserve in a larger extent than the monotonic one. In fact the strength reserve at the final stage of the cyclic tests (6% of drift) of the infilled frames with window is about 50% lower than the one exhibited by the monotonically loaded. This value decreases to about 20% and 10% respectively, for the fully infilled frame and for the bare frame.

CONCLUSIONS

The main conclusions that may be outlined from the present study are the following:

- The infilled frames with window under drifts over about 3% presented a hysteretic behaviour similar to the one of the bare frame, meaning that all the strength reserve due to the existence of the masonry panel was totally expended.
- The hysteretic behaviour of the fully infilled frame, for drifts of about 6%, still presents a considerable strength reserve of about 100% in relation to the bare frame.
- The loading history affects the final bearing capacity of reinforced concrete frame structures infilled with unreinforced masonry walls. The tests showed that the final strength reserves of the monotonically loaded models compared to the cyclically loaded ones are 10%, 20% and 50% respectively, for the bare frame, fully infilled frame and infilled frame with window.

This paper presents the results of the tests of nine models. As part of a research program that is still in development, some of the tested models were retrofitted and are being tested under the same imposed displacement history.

ACKNOWLEDGEMENTS

The tests presented in this paper were part of a joint research program with the European Union Joint Research Centre in Ispra, Italy. Financial support was received from the European Union as part of the SEISMIER project and from the Portuguese Science and Technology Foundation - FCT.

REFERENCES

CEB - Comite Euro-International du Béton, 1996. RC frames under earthquake loading. State of the art report, Bulletin n° 231, Thomas Telford Services Ltd., Great Britain.

Combescure, D. 1996. Modélisation du comportment sous chargement sismique des structures de bâtiment comportant des murs de remplissage en maçonnerie, Thesis, Paris, École Centrale de Paris.

Fardis, M. N. and Panagiotakos, T. B. 1997. Seismic design and response of bare and masonry-infilled reinforced concrete buildings. Part II: Infilled structures, Journal of Earthquake Engineering 1 (2), Imperial College Press.

Pires, Felicita, 1990. Influence of masonry walls over the behaviour of reinforced concrete frames under horizontal actions. Thesis (in Portuguese), Lisbon, LNEC.

Pires, Felicita and al. 1998. Study of the earthquake behaviour of masonry infilled reinforced concrete frames. Test of models I1, I2, I3, I4, I5, I6, I7, I8 and I9, LNEC Reports, Lisbon, LNEC.

Table 1 – Monotonic Tests. Comparison between parameters of infilled and bare frames

Model	Maximum strength Fmáx [kN]	Initial elastic stiffness Ke [kN/m]	$\frac{\text{fmáx In}}{\text{fmáx I3}}$	$\frac{\text{Ke In}}{\text{Ke I3}}$
I1	190	207 400	3.2	31.0
I2	156	54 700	2.6	8.2
I3	60	6 700	1.0	1.0

Table 2 – Cyclic tests. Comparison between parameters of infilled and bare frames

Model	Maximum strength Fmáx [kN]	Initial elastic stiffness Ke [kN/m]	$\frac{\text{fmáx In}}{\text{fmáx I4}}$	$\frac{\text{Ke In}}{\text{Ke I4}}$
I4	64	6 800	1.0	1.0
I5	123	166 700	1.9	24.5
I6	123	135 400	1.9	19.9
I7	250	258 200	3.9	38.0
I8	181	240 400	2.8	35.4
I9	193	227 800	3.0	33.5

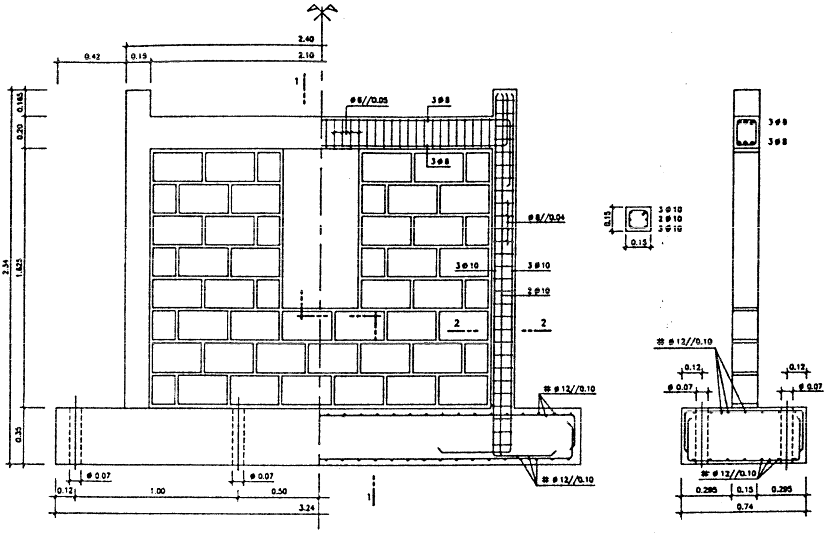


Fig. 1 - Geometrical characteristics and reinforcements of a model with a window

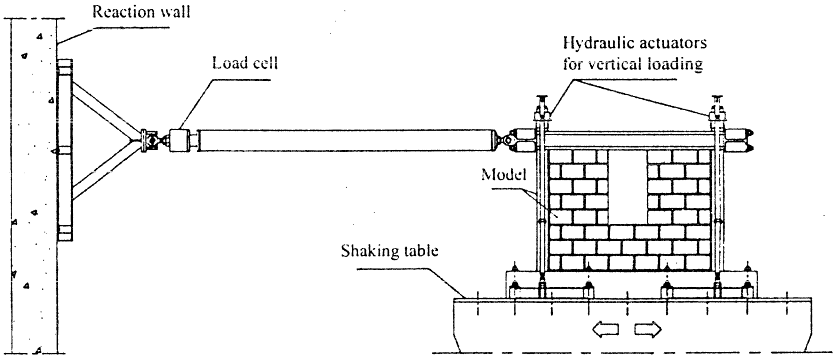


Fig. 2 - Scheme of the test set-up

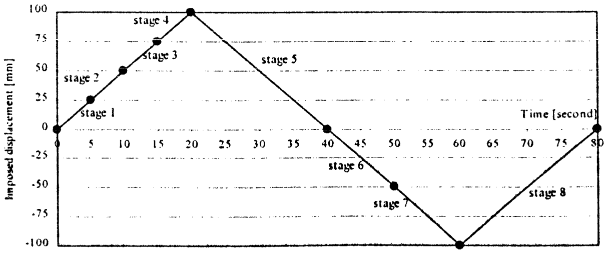


Fig. 3 – Horizontal displacement history imposed in the monotonic tests

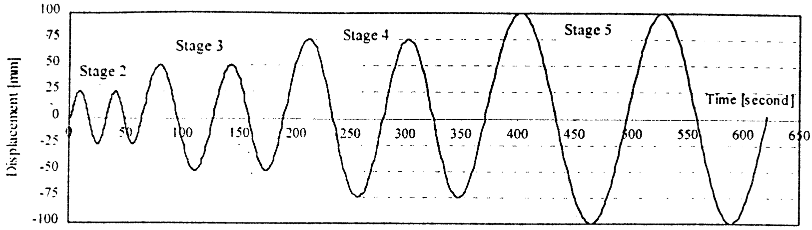
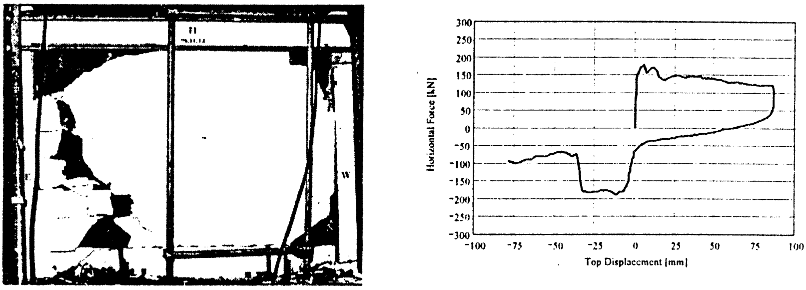
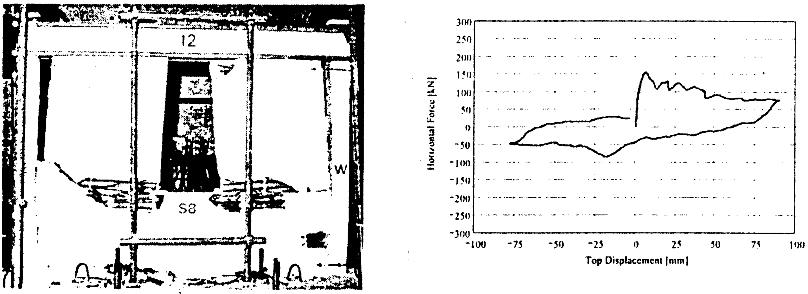


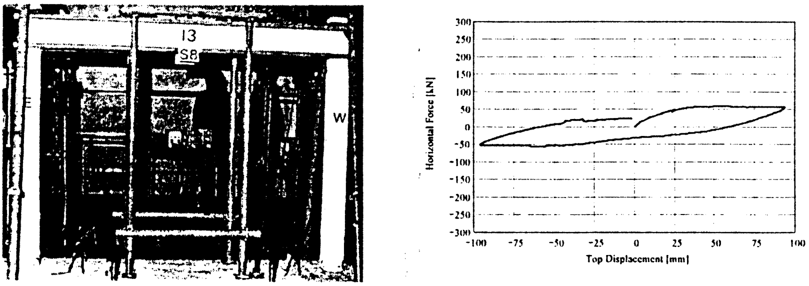
Fig. 4 – Horizontal displacement history imposed in the cyclic tests



Model I1 – Fully infilled frame

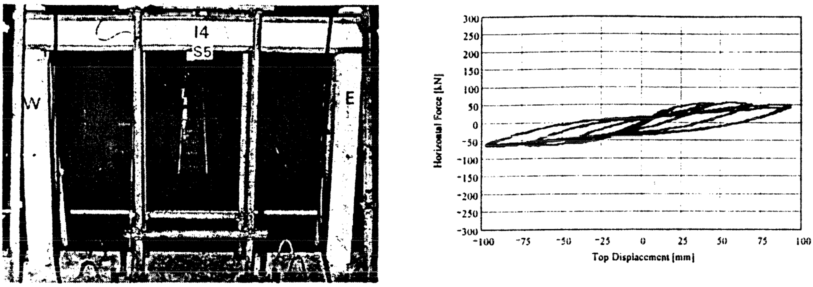


Model I2 – Infilled frame with window

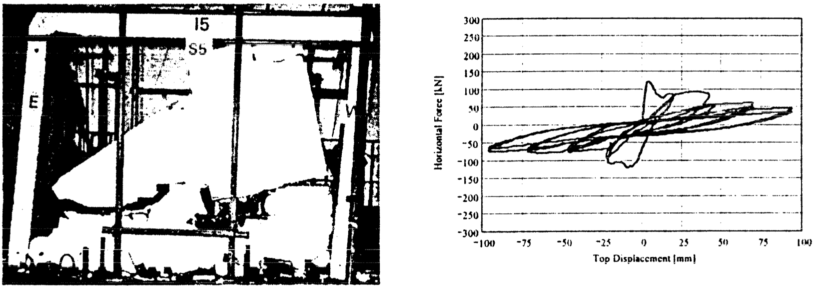


Model I3 – Bare frame

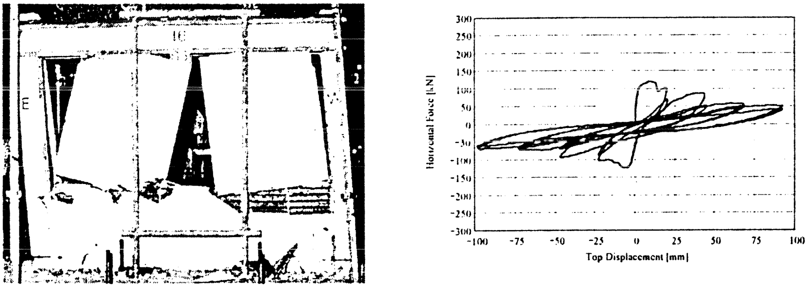
Fig. 5 – Monotonic tests. Failure mechanisms and horizontal force-top displacement diagrams



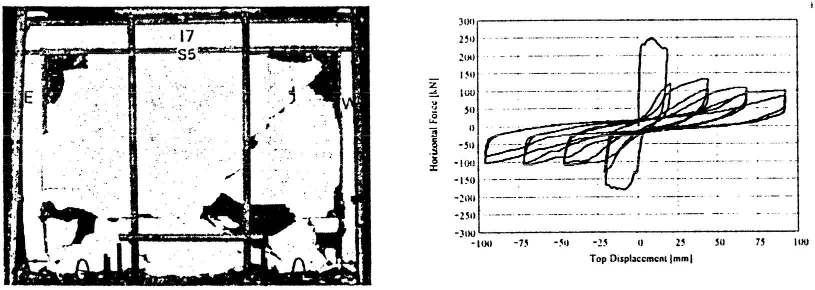
Model I4 – Bare frame



Model I5 – Infilled frame with window

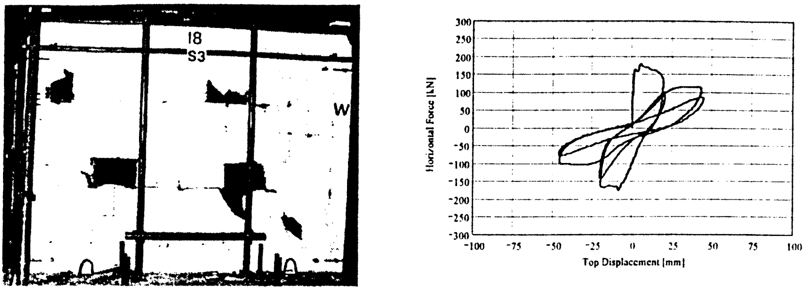


Model I6 – Infilled frame with window

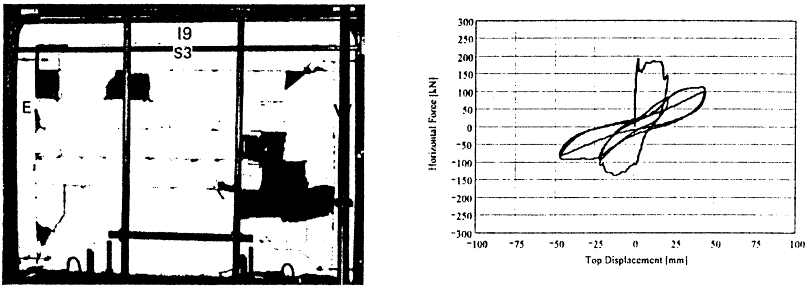


Model I7 – Fully infilled frame

Fig. 6 – Cyclic tests – Models I4, I5, I6 and I7. Failure mechanisms and horizontal force-top displacement hysteretic loops



Model I8 – Fully infilled frame



Model I9 – Fully infilled frame

Fig. 7 – Cyclic tests – Models I8 and I9. Failure mechanisms and horizontal force-top displacement hysteretic loops

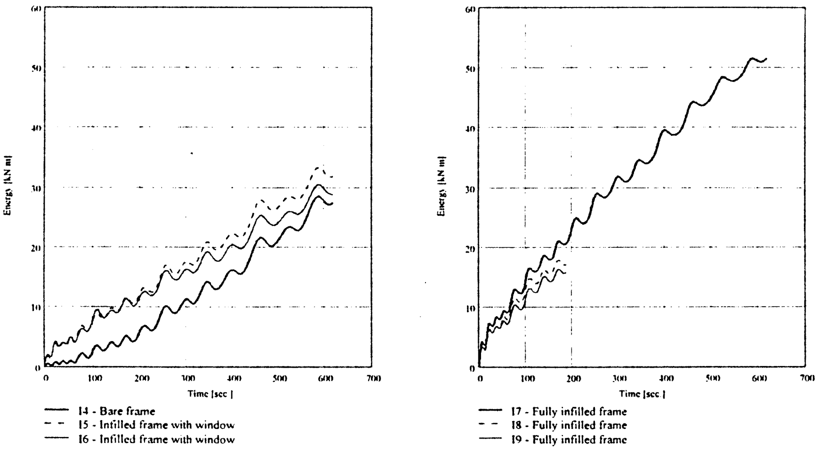


Fig. 8 – Histories of dissipated energy in the cyclic tests – Models I4 to I9

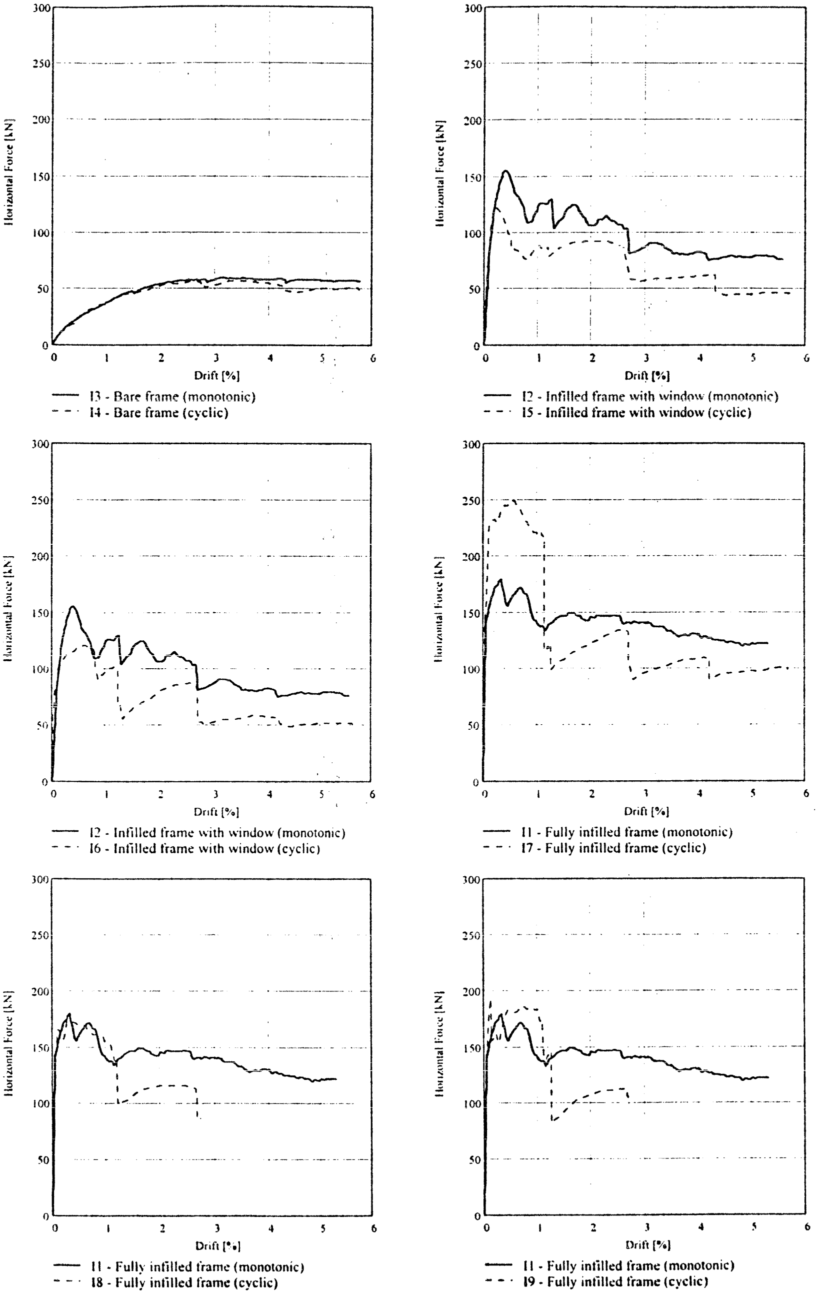


Fig. 9 – Envelopes of the hysteretic response of models I4 to I9 and horizontal force-top displacement diagrams of the monotonic tests of models I1 to I3