NEW DEVELOPMENT IN RESEARCH OF INFILLED FRAMES

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SUMMARY

Based on recent findings, this paper is presented with the view to summarize the characteristics of infilled frames with different interface conditions, and to propose the plastic theory for the design of infilled frame structures.

INTRODUCTION

The proper use of infill panels incorporated within the plane of a frame as represented in various forms of infilled frames has emerged with great practical and economical significance in resisting earthquake forces. The infill panels can be of various materials, and can be constructed to upgrade seismic resistance of existing buildings or as part of the infilled frames.

PHILOSOPHY OF INFILLED FRAMES

There are two schools of thought behind seismic design of a structure: (1) to provide the survival of a structure with toughness, ductility and energy dissipation characteristics while reconcile with damage of secondary elements due to large inelastic and permanent deformations; (2) to provide strength and stiffness characteristics to control the structural deformations, thereby preventing the damage of secondary elements. Many important structures are designed in accordance with the second school of thought (e.g. dams, nuclear power stations, historical monuments etc.) at the expense of higher cost. However, a compromise of the two schools, offering the advantages of both the 'flexible' and the 'stiff' approaches, is the structural system of infilled frames which are functionally most suitable for buildings.

The advantageous behaviour of infilled frames is derived mainly from the interaction developed at the interface between the infills and the frame, and the characteristics of infilled frames are also largely dependent upon the interface conditions, i.e. whether or not the interface on four sides of an infill element is integral/partially integral/non-integral with the frame. There are also two schools of thought on the question of interface conditions: (1) to separate the infills from the columns of the frame in order to avoid premature failure of masonry infills under vibration due to the clattering effect at the interface; (2) to connect the infills to the frame in order to avoid the clattering effect in an integral structure under vibration.

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GENERAL BEHAVIOUR

The general behaviour of infilled frames subject to lateral load has been studied analytically by the use of non-linear finite element analysis (Ref. 1), and also experimentally by the use of scaled down models of 4-storey steel frames with reinforced micro-concrete infills. All models had the same storey height of 305 mm (12 in.). For models with span/storey height ratio of 2.0, the span was 610 mm (24 in.) while for models with span/storey height ratio of 3.0, the span was 915 mm (36 in.).

A-Models

In the A-models, no connectors were provided at the structural interface. The analytical and experimental load-deflection curves of the models for deflections up to 2% of the height are shown in Fig. 1.

There was initial lack of fit between the infilled panels and the frame because of shringkage of the infilled material. It was observed that separation at the tensile corners occurred almost immediately after the models were loaded so that the panels were in contact with the frame only at the vicinity of compressive corners. However, at slightly higher load the interface configuration became stable after the frame had gained firm contact with the panels. At greater load, the stiffness of the models gradually decreased when the compressive corners of the panels yielded. The models reached their peak strength when the corners were crushed. Crushing of the infill appeared to occur progressively outwards from the corners. During crushing of the infill, obvious signs of yielding at the steel columns were also observed. After peak load, the models continued to sustain substantial loading (more than 85% of peak load) for a very large range of deflection. Both models A-2 and A-3 failed with the same collapse mode and the development of the collapse mechanism at various stages as observed in the test is shown in Fig. 2.

B-Models

In the B-models, connectors were provided along the infill/beam interface and vertical slits of 4 mm width were provided at the infill/column interface. The function of the vertical slits is to separate the columns from the high contact pressure with the infilled panels so as to avoid premature shear failure of the columns which are considered as the most important structural elements.

The B-models behaved linearly at small deflection, Fig. 1. Cracks at approximately 45^{o} to the beams were developed at about one third peak load onwards. The stiffness gradually decreased as the infill/beam connection yielded. Peak load was reached when the connection failed in concrete shear. Then, the load dropped fairly rapidly. As the models were further deformed, the infilled panels gained firm contact with the columns thus enabling the models to regain part of the strength at the expense of inducing shear forces and bending moments at the columns. When the compressive corners of the panels were crushed, the models collapsed with a failure mode similar to those without connectors. The same failure mode was observed in all the B-models and the development of collapse mechanism at various stages is shown in Fig. 2.

C-Models

In the C-models, connectors were provided along all infill/frame interface to improve structural interaction between the infilled panels and the frame.

The C-models generally had higher stiffness and strength, Fig. 1. Furthermore, they maintained their strength up to very large deflection leading to tremendous energy absorption before failure. Numerous cracks at 45^{o} to the beams were developed continuously from about one quarter peak load onwards. In general, more cracks appeared in C-models than A and B-models. The stiffness dropped gradually as the compressive corners of the infilled panels and the infill/beam connection yeilded. The models finally failed in shear at the infill/beam connection and crushing of the panels at the compressive corners. Obvious signs of yielding of the columns were also observed. All the C-models failed with the same collapse mode and the development of the collapse mechanism is shown in Fig. 2.

GENERAL PLASTIC THEORY

In developing a general plastic theory for infilled frames with different interface conditions, the most important aspect is to recognise the characteristics of the interaction between the infills and the frame at the interface due to the different interface conditions. In the following, the theory for the fully integral infilled frames, C-models, (Ref. 2) is given first, taking into account the shear strength of the connectors. Then, as the non-integral infilled frames (A-models) have no shear connectors at the interface, the A-models can be derived directly from the C-models by setting the shear strength of the connectors to zero. Lastly, as the semi-integral infilled frames (B-models) have no contact between the infills and the columns of the frame, the B-models become the A-models when the shear connection fails between the infills and the beams.

Fully Integrated Infilled Frames

The behaviour of integral infilled frames ranging from elastic to collapse modes has been studied by non-linear finite element analysis (Ref. 1), according to which it can be shown that the cracks develop approximately at 45^{o} to the beams. For single storey integral infilled frames, four collapse modes are identified as shown in Fig. 3. The actual collapse mode is the one which leads to the smallest value of collapse shear strength.

For multistorey infilled frames, the terms storey shear and collapse shear are defined as follows: The storey shear is the total lateral shear force acting at and above the storey referred to, whereas the collapse shear of a storey is the property of the storey such that if the collapse shear of each storey is not exceeded by the corresponding storey shear, the structure is safe against collapse. The collapse modes of multistorey infilled frames are basically the same as those of single storey infilled frames. However, there can be many such modes and simple design rules are preferred. Grouping the results for all collapse modes together, the collapse shear in storeys other than the top can be obtained from Table 1. The collapse shear on the top storey can be similarly obtained. Each storey of the infilled frame should be designed so that adequate collapse shear, as calculated from above, is greater than the storey shear in each storey of the infilled frames.

Table 1 Collapse Shear of Integral Infilled Frames

	when $\ell > h$	when $h < \ell$
	$m_c\sigma_c th + s(\ell - \frac{h}{2})$	$m_c\sigma_c th + \frac{s\ell}{2}$
	$\frac{m_b}{\tan\theta}\sigma_c th + \frac{sh}{2\tan\theta}$	$\frac{m_b}{\tan\theta}\sigma_c th + \frac{s(h - \frac{\ell}{2})}{\tan\theta}$
	$m_c^2\sigma_c th + \frac{\sigma_c th}{6} + s(\ell - \frac{h}{2})$	$m_c^2\sigma_c th + \frac{\sigma_c th}{6} + \frac{s\ell}{2}$
H_u = min.	$m_c^2\sigma_c th + \frac{\sigma_c th}{6\tan^2\theta} + \frac{sh}{2\tan\theta}$	min. $m_c^2\sigma_c th + \frac{\sigma_c th}{6\tan^2\theta} + \frac{s(h - \frac{\ell}{2})}{\tan\theta}$
	$\frac{m_b^2}{2}\sigma_c th + \frac{\sigma_c th}{6} + s(\ell - \frac{h}{2})$	$\frac{m_b^2}{2}\sigma_c th + \frac{\sigma_c th}{6} + \frac{s\ell}{2}$
	$\frac{m_b^2}{2}\sigma_c th + \frac{\sigma_c th}{6\tan^2\theta} + \frac{sh}{2\tan\theta}$	$\frac{m_b^2}{2}\sigma_c th + \frac{\sigma_c th}{6\tan^2\theta} + \frac{s(h - \frac{\ell}{2})}{\tan\theta}$

Non-Integral Infilled Frames

The mode of failure in a single storey non-integral infilled frames depends on the panel proportions and the relative strengths of the columns, the beams and the infills. Based on the study by non-linear finite element analysis and the laboratory experiments, three collapse modes are identified as shown in Fig. 4. The actual collapse mode is the one which gives the smallest collapse shear strength. The stress redistribution and the plastic hinges forming the collapse mechanism for the three modes are also shown in Fig. 4. These three modes of failure correspond to the respective modes of failure for the fully integral infilled frames (C-models), except that there is no shear connectors in the case of A-models and the shear strength of concrete is not mobilized. Therefore, all the previously derived equations for C-models in Table 1 can be used for A-models if the shear strength s is set to zero. The equations thus derived for A-models are given in Table 2.

Table 2 Collapse Shear of Non-integral Infilled Frames

	when $\ell > h$	when $h < \ell$
$H_u =$	$\min. \begin{cases} m_c \sigma_c th \\ \dfrac{m_b}{\tan\theta} \sigma_c th \\ m_c^2 \sigma_c th + \dfrac{\sigma_c th}{6} \\ \dfrac{m_b 2}{2} \sigma_c th + \dfrac{\sigma_c th}{6} \end{cases}$	$\min. \begin{cases} m_c \sigma_c th \\ \dfrac{m_b}{\tan\theta} \sigma_c th \\ m_c^2 \sigma_c th + \dfrac{\sigma_c th}{6\tan^2\theta} \\ \dfrac{m_b 2}{2} \sigma_c th + \dfrac{\sigma_c th}{6\tan^2\theta} \end{cases}$

Semi-Integral Infilled Frames

In the laterally loaded B-models where the columns are separated from the panels by vertical slits, the panels act merely as shear panels and nearly all the lateral shear is taken by the connectors at the infill/beam interface. Hence the column shears are negligible and the corresponding moments in the frame are also small. With increasing load, the interface shear stresses will approach the shear strength of the interface connection until a collapse mechanism is formed as in the integral infilled frames. The peak load is reached at this stage, and the panel moves against the columns, thereby temporarily retarding the load from dropping further. The infilled frame now becomes non-integral infilled frame as the interface connection has failed.

Therefore, the collapse strength of a semi-integral infilled frame depends upon the strength of the interface connection in the first place, or the strength of non-integral infilled frame, whichever is the larger. However, if the former is less than the latter, there is no point in the provision of shear connectors. Hence, from practical and economical points of view, the semi-integral infilled frames should be designed with adequate shear connectors so that the shear strength of the connection is the governing factor. Hence, it is prudent to take the shear term as the criterion for the collapse strength. Therefore, all the previously derived equations for C-models can be used for B-models if the shear terms only are taken into account. Setting other terms to zero except the shear terms in Table 1, the collapse shear H_u for B-models can be obtained. If the collapse shear in any storey as obtained is not exceeded by the storey shear, then the structure is safe against collapse.

The above plastic theory has been compared with many experimental works of the Authors and other researchers, and generally good agreement has been demonstrated (Ref. 2 and 3).

CONCLUSION

Experimental study and non-linear finite element anlaysis on infilled frames have produced deeper understanding on the different characteristics of such structures with different structural interface conditions. The understanding, which covers the whole spectrum from elastic to collapse state of the structures, has given rise to the proposal of the general plastic theory based on which simple design rules become possible for a complex structural system.

REFERENCES

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Notations

H_u - collapse shear
h - storey height
ℓ - span of the infilled frame
m_b - relative strength parameter for beams, $\sqrt{(4M_{pb}/\sigma_c th^2)}$ where M_{pb} is plastic moment of the beam
m_c - relative strength parameter for columns, $\sqrt{(4M_{pc}/\sigma_c th^2)}$ where M_{pc} is plastic moment of the column
s - shear strength of interface connection in force per unit length
t - thickness of the infilled panel
θ - angle between the diagonal of the infilled panel and the horizontal
σ_c - crushing stress of the panel material

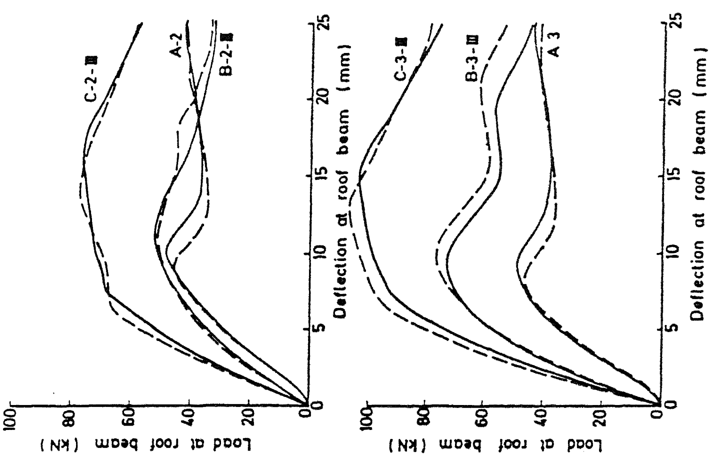


Fig. 1 Load-deflection curves of models A, B and C up to 25 mm deflection (solid line: experiment; dotted line: theory)

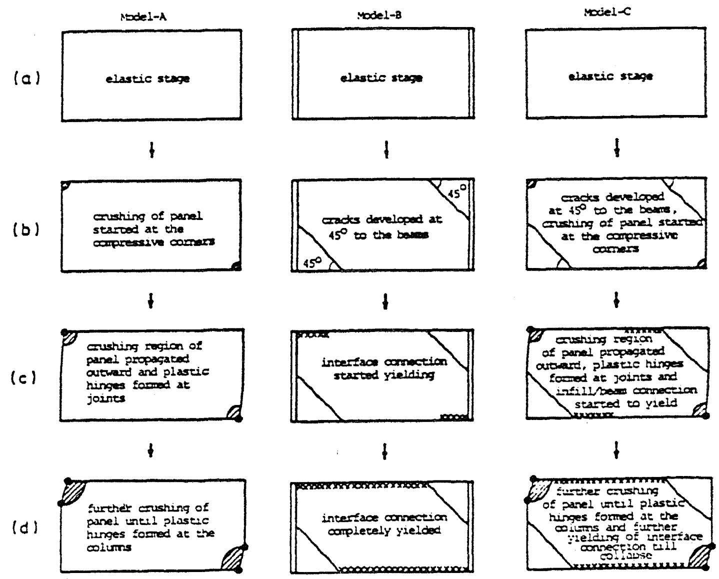


Fig. 2 Stages of collapse of collapsing storey of models A, B and C (shaded area: crushing region; crosses: yielded connection; dot: plastic hinge of the frame).

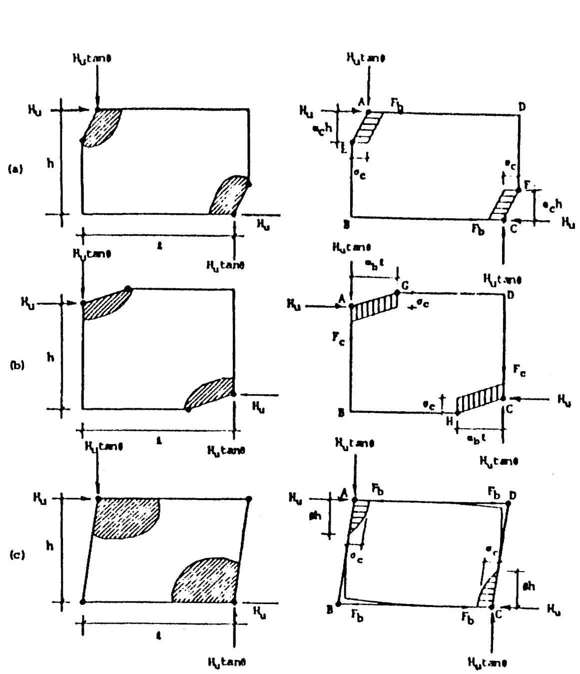
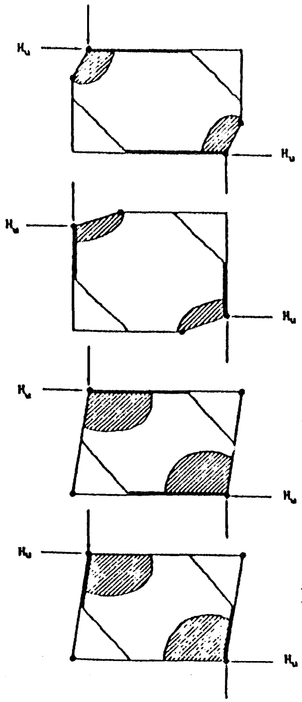


Fig. 4 Failure modes of single storey non-integral infilled frames, (shaded area shows the crushing regions), (a) mode 1 (b) mode 2 and (c) mode 3.



Mode 1 — corner crushing with failure in columns and infill/beam conncetions

Mode 2 — corner crushing with failure in beams and infill/column connections

Mode 3 — diagonal crushing with failure in infill/beam connections

Mode 4 — diagonal crushing with failure in infill/column connections.

Fig. 3 Failure modes of single storey integral infilled frames, (shaded area and thick lines show the crushing regions and yielded connections respectively).