CHAPTER 1

INTRODUCTION

1.1 GENERAL

Rapid industrialization and high concentration of population in the cities have given impetus to the growth of high-rise buildings. For example, the recent survey of high rise buildings in India shown in Figure 1.1 throws light on this fact (Emporis 2008). The necessity of maximum utilization of space in the vertical direction with a comparatively less occupational area on ground has risen because of the high cost of land in urban areas. The design of tall buildings essentially involves a conceptual design, approximate analysis, preliminary design and optimization, to safely carry gravity and lateral loads. The design criteria are strength, stiffness, serviceability, stability and human comfort. The strength is satisfied by limiting the stresses, while serviceability is satisfied by limiting the drift in the range of H/500 to H/1000. Stability is satisfied by providing sufficient factor of safety against buckling and P-Delta effects. The factor of safety is around 1.67 to 1.92. The human comfort aspects are satisfied by limiting the accelerations in the range of 10 to 25 milli-g, where g=acceleration due to gravity, about 9.81m/sec². The aim of the Structural Engineer is to arrive at suitable structural schemes, to satisfy these criteria, and assess their structural weights in weight/unit area in square meters or square feet. In tall buildings, occurrence of vertical loads (dead and live loads) do not cause much problems in the analysis and design, but horizontal forces due to wind, earthquake, blast loads and/or any accidental loads are the matter of great concern and need very careful consideration. The quantity of materials needed for tall buildings increases in a non-proportional manner as the number of storeys increases. For example, the weight of steel in tall building increases as shown by the typical graph in Figure 1.2. The horizontal force can produce critical stress condition in the structure and in addition cause lateral sway of the structure. Some of the commonly used lateral load resistant structural elements are shown in Figure 1.3 (Stafford Smith and Coull 1991, Beedle 1986 and Taranath 1998).
<table>
<thead>
<tr>
<th>Sno</th>
<th>City</th>
<th>population</th>
<th>Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mumbai</td>
<td>11,914,398</td>
<td>877</td>
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<tr>
<td>2.</td>
<td>Kolkatta</td>
<td>4,580,544</td>
<td>173</td>
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<tr>
<td>3.</td>
<td>Gurgaon</td>
<td>173,542</td>
<td>153</td>
</tr>
<tr>
<td>4.</td>
<td>Navi Mumbai</td>
<td>703,947</td>
<td>126</td>
</tr>
<tr>
<td>5.</td>
<td>Pune</td>
<td>2,540,069</td>
<td>121</td>
</tr>
<tr>
<td>7.</td>
<td>Thane</td>
<td>1,261,517</td>
<td>92</td>
</tr>
<tr>
<td>8.</td>
<td>Cochin</td>
<td>564,589</td>
<td>86</td>
</tr>
<tr>
<td>9.</td>
<td>New Delhi</td>
<td>301,000</td>
<td>74</td>
</tr>
<tr>
<td>10.</td>
<td>Ghaziabad</td>
<td>968,521</td>
<td>59</td>
</tr>
<tr>
<td>11.</td>
<td>Chennai</td>
<td>4,216,268</td>
<td>41</td>
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<tr>
<td>12.</td>
<td>Hyderabad</td>
<td>3,339,878</td>
<td>33</td>
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<tr>
<td>13.</td>
<td>Trivandram</td>
<td>744,800</td>
<td>25</td>
</tr>
<tr>
<td>14.</td>
<td>Lucknow</td>
<td>2,207,340</td>
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</tr>
<tr>
<td>15.</td>
<td>Greater Noida</td>
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<td>16.</td>
<td>Mangalore</td>
<td>490,000</td>
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<tr>
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<td>Bidhan Nagar</td>
<td>167,848</td>
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<td>18.</td>
<td>Noida</td>
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<tr>
<td>19.</td>
<td>Surat</td>
<td>2,433,787</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 1.1 High-rise buildings in India (Emporis 2008)
Figure 1.2 Influence of increase in height on the total weight of steel in tall buildings (Stafford Smith and Coull 1991)
(a) Steel Framed structure

(b) R.C.C Framed structure

(c) Shear Wall - Framed structure

(d) Infilled Framed

Figure 1.3 Lateral load resistant plane frames
1.2 DEFICIENCIES OF BARE FRAMES

Rigid jointed bare frames are the commonly used structural systems to resist lateral loads. However it has been found that they have inadequate lateral stiffness and strength beyond some height, though they are efficient in carrying vertical gravity loads. This is mainly due to presence of open panels that introduce secondary shear displacements and resultant high flexibility of the system. (Stafford Smith and Coull 1991). Further in the case of reinforced concrete frames the windward columns may get heavily cracked due to the large amount of combined bending and direct tensile forces induced by the lateral forces. Reinforced concrete bare frames tend to give rise to ductile systems only if some of the detailing criteria at the joints (IS 1893:2002) (IS 13920:1993) are catered to.

1.3 REMEDIAL METHODS APPLIED TO BARE FRAMES

Bare frame systems provide a common type of system and the actual applications of this type of construction will be more frequent and numerous if some methods can be developed for remedying their deficiencies. Some of the remedial measures include provision of diagonal members in the end panels, interconnecting with shear walls, prestressing the end columns or infilling the open panels either fully or partially with brick masonry or concrete block masonry. Of these different remedial measures, the method of infilling wherever possible is the simplest and the best from practical, economical and functional considerations. In a particular study, Das and Murthy (2004a) and Das and Murthy (2004b) have evaluated five R.C. buildings for seismic performance and concluded that consideration of the infill action results in a more economical system.
1.4 INFILLED FRAME

1.4.1 Definition

Infilled frame is a composite structure formed through the interactive behaviour of the infill with the bounding frame members under inplane lateral loads.

A typical infilled frame is shown in Figure 1.4.

1.4.2 Behaviour

Usually building frames are provided with partition walls for some functional use. It is found that bounding frame and filler walls act compositely and alter the characteristics of the bounding frame. It is evident from the schematic plot of lateral load Vs deflection in conventional buildings as shown in Figure 1.5 that the total resistance of the bounding frame increases due to the interaction with infill (Satyanarayanan 1987). Therefore composite action between the frame and infill should be considered for assessing the strength and stiffness in the design of multistoried buildings. When the composite action is considered, it is possible to use smaller cross sections of frame members with lesser quantity of reinforcements thus leading to overall economy.

The use of a masonry infill to brace a frame combines some of the desirable structural characteristics of each, while overcoming some of their individual deficiencies. The high in-plane rigidity of the masonry wall significantly stiffens the otherwise flexible frame, while the ductile frame contains the brittle masonry, enabling it to take up larger loads and displacements than it could achieve without the frame. The result is, therefore, a relatively stiff and tough bracing system.

The wall braces the frame partly by its in-plane shear resistance and partly by its behaviour as a diagonal bracing strut in the frame, Figure 1.6 (a) illustrates these modes of behaviour. When the frame is subjected to horizontal loading, it deforms
with double-curvature bending of the columns and girders. The translation of the upper part of the column in each storey and the shortening of the leading diagonal of the frame cause the column to lean against the wall as well as to compress the wall along its diagonal. It is roughly analogous to a diagonally braced frame, as shown in Figure 1.6 (b).

Figure 1.4 Typical infilled frame
Figure 1.5 Schematic plot of lateral load Vs storey deflection in conventional buildings (Satyanarayanan 1987)
Figure 1.6 Behaviour of infilled frame
Three potential modes of failure of the wall arise as a result of its interaction with the frame, and these are illustrated in Figure 1.7a. The first is a shear failure stepping down through the joints of the masonry, and precipitated by the horizontal shear stress in the bed joints. The second is a diagonal cracking of the wall through the masonry along a line, or lines, parallel to the leading diagonal, and caused by tensile stresses perpendicular to the leading diagonal. The perpendicular tensile stresses are caused by the divergence of the compressive stress trajectories on opposite sides of the leading diagonal as they approach the middle region of the infill. The diagonal cracking is initiated at and spreads from the middle of the infill, where the tensile stresses are maximum, tending to stop near the compression corners, where the tension is suppressed. In the third mode of failure, a corner of the infill at one of the ends of the diagonal strut may be crushed against the frame due to the high compressive stresses in the corner.

![Diagram of modes of infill failure and frame failure](image)

(a) Modes of infill failure  
(b) Modes of frame failure

Figure 1.7 Failure modes
The nature of the forces in the frame can be understood by referring to the analogous braced frame in Figure 1.6b. The windward column is in tension and the leeward column is in compression. Since the infill bears on the frame not as a concentrated force exactly at the corners, but over short lengths of the beam and column adjacent to each compression corner, the frame members are subjected to transverse shear and a small amount of bending too. Consequently, the frame members or their connections are liable to fail by axial force or shear, and especially by tension at the base of the windward column, as shown in Figure 1.7b. The bracing action of the infill is reported to reduce the bending moments in the columns, which can be used advantageously in design of the frame members with reduced steel content and better performance (Perumal Pillai et al 2003).

1.4.3 Classification

Classification of infilled frames is based on materials, interface condition and presence of opening as shown in Figure 1.8.

1.4.4 Factors affecting the behaviour

The main factors that affect the behaviour of infilled frames pertain to the frame, infill and interface. The frame behaviour depends on its strength, material strength, presence of duct opening etc., while the interface is characterized by the interface materials, the initial gap, provision of shear connectors etc. The characteristics of infill depend on the panel aspect ratio, its strength, presence of openings, its relative size, position and provision of stiffeners. The total behaviour of the infilled frames is governed by the relative stiffness and strength characteristics of each of the above individual parameters. Out of these factors the interface characteristics are the vital ones that decide the degree of composite action.
Figure 1.8 Classification of infilled frames
Figure 1.9 Factors affecting the behaviour of infilled frames

The contact length between the column and the infill or beam and the infill is a function of the $\lambda h$ values. Frames that are relatively stronger than the infill have a value of $\lambda h$ lesser than 5.0 and it is reported that increasing the stiffness of column members has more effect on the contact length than that of increasing the stiffness of beams.
(ii) Type, strength and stiffness of infill

The type of infill, whether plain or reinforced has an influence on the behavior of frames infilled, especially under cyclic loading conditions such as earthquake forces. The material strength of infill either in terms of absolute or relative sense affects the mode of failure and load carrying capacity of the infilled frame. The ultimate load carrying capacity of the frame increases if the frame is relatively stiffer than infill. The cracking strength of infill especially brick masonry depends on the relative values of the strength of brick masonry in shear, in splitting tension and compression. Plain infill is brittle and tends to fall out but reinforcing the infill increases ductility, strength and stiffness of the entire system. Various techniques have been used for strengthening masonry infill such as: the use of shear connectors at the interface of frame and infill, exterior welded wire (Govindan et al 1986), horizontal reinforcement and the use of a reinforced concrete bond beam at mid height of a panel. The last two methods are still being under research and so far proved to have effectiveness when the mode of failure of infill is due to diagonal cracking (Moghaddam et al 2006).

(iii) Opening in infill

Openings (doors and windows) in the infill are provided for functional purposes. The position, relative size of openings and the presence of stiffeners around the openings have effect on strength and stiffness characteristics (Sathyanarayanan and Govindan 1989) and (Selvakoodalingam et al 1999).

(iv) Interface characteristics

The stresses at the interface are more complex and can be classified into tensile or compressive stresses combined with shear. At the region where the frame and the infill are in contact, the stresses are compressive and tend to become tensile in nature where there is a tendency for separation. Normally the material of the
bounding frame is steel or reinforced concrete (R.C). In general, infilling is done with either brick masonry or concrete block masonry. This creates a condition of two different materials meeting at the interface. Even if the materials are similar, for example concrete masonry with R.C frame, there exists a physical plane of discontinuity at interface. This discontinuity in terms of either material or construction practice or both on either side of the interface plays a vital role in determining the degree of composite action.

Some of the typical practices that are commonly adopted for interfaces include:

(a) **Leaving a gap between the beam and/or column of the frame and the infill in order to avoid transfer of load between frame and infill:** - In this case the frame acts like a bare frame with a characteristic low stiffness till it touches the infill, from that load level the composite action ensues.

(b) **Breaking of bonding between frame and infill (Non-integral interface):** - A case of non-integral infilled frame can be achieved through intentional debonding between the frame and the infill by applying a coat of oil or debonding agent at interface.

(c) **Connecting the frame and the infill by provision of connectors (Integral interface):** - The provision of connectors by means of deliberate bonding or by using connectors result in integral infilled frames. It has been reported that such a positive connection creates advantages like reduced risk of lack of fit, elimination of separation and slip, increased stiffness and strength and sufficient warning before failure (Liauw and Kwan 1983a). However provision of such connectors in case of reinforced concrete frames creates practical constructional difficulties.

(d) **Connecting the frame and the infill by cement mortar (Conventional type):** - The frame is partially connected to the infill using materials that have low tensile strength. This is a typical case of a normal construction wherein
cement mortar or cement lime mortar of low cement content is used. If the frame is loaded with a racking load, slip and separation occurs over the interface. The vertical loads are transmitted due to the flexion of beams and creep of column to the infill. In addition to this, shrinking of columns and expansion of certain clay type of bricks add to pre-strains in the masonry. Upon action of racking loads these pre-strains can cause crushing and spalling of the corner regions of the infill thereby reducing the composite action. In case of reinforced concrete frames with masonry mortar at interface, separation is not noticed.

(e) **Using of Non-structural materials** : - Modern generation of infilled frames in which a non structural material like lead, rubberized cork etc. are used at the interface between beam and infill is emerging quite fast in construction practice.

1.4.5 **Applications of concept of frame- infill composite action**

The composite action between the frame and infill increases the lateral stiffness and the strength of the frame. It is clearly established that there are major advantages of infilling the frame. It increases the reserved strength of frames by providing alternate load paths to the multi - storeyed building when the columns are knocked out by either earthquake or blast loads (Nasreddin and El Mezaini 2005) and (Mehrdad Sasani 2008). It alters the seismic response of the frame (Dolsek and Fajfar 2008) and (Dolsek and Fajfar 2008a). In addition to converting plane frames as a type of shear wall that is both economical and efficient, the infilling of vierendeel girders can be used widely for diverse situations in general building constructions. They can serve as composite lintel beams over wide door or window openings, as walls on poor soils and as economical and efficient beams in raft and strip foundations. In principle the composite action between the frame and the infill are the same in both infilled frames and infilled vierendeel girders (Mohideen 1977).
1.5 LIMITATIONS OF INFILLED FRAMES

Generally designers neglect the infill walls as non-structural elements and treat the frame as conventional reinforced concrete frame. However, this may not be a wise approach since the presence of infill in the frame can alter (i) its strength and stiffness, (ii) mode of failure by changing the ductile mode to brittle mode (Perumal Pillai and Govindan 1994). This is evident from the typical failures during earthquakes (Figures 1.10 and 1.11) and can create additional slab loads due to infill crushing and spalling on the floor slab that causes unsafe conditions to the inmates (Govindan et al 1986). In addition to these factors it is rather difficult to predict the infilled frames’ behaviour because of the influence of a range of parameters like separation, slip, initial lack of fit and friction at the interface which result from quality of materials, workmanship, contact length between frame and wall, interface characteristics, relative stiffness of the frame and infill, shrinkage and creep of concrete in the frame members, presence of openings (doors, windows), their relative size, position etc. Practically, the uncertainty about the presence of the functional walls in future subsequent to its construction makes the designers to often refrain from making use of the advantages of the composite action. Further, a simple design method considering the composite action between the frame and infill is yet to be incorporated in various codes of practice.

1.6 REMEDIAL METHODS FOR INFILLED FRAMES

Several techniques have been developed over years to minimize the deficiencies of the infilled frame systems and to maximize the advantage of improved lateral stiffness and strength accrued from them.

i. Use of construction methodology in which wall is constructed first and the frame members subsequently, so as to reduce shrinkage stresses and to improve the contact between frame and infill (Mohideen 1977).

Figure 1.10 Typical failure due to earthquake with severe damage to infill wall (Quindia, Colombia 1999 Earthquake, EERI) (Mohammad Aliaari and Memari A.M 2005)

Figure 1.11 Severe damage to column due to partial infilling (Arequipa, Peru, June 2001 Earthquake, EERI) (Mohammad Aliaari and Memari A.M 2005)
iii. Use of ferrocement plastering on the infill walls to prevent cracking, crushing and spalling (Govindan et al 1986) and (Dubey and Deodhar 1996).

iv. Provision of lead at interface to avoid preloading of the infill due to shrinkage and creep of frame members (Riddington and Bolourchi 1989) and (Sahota and Riddington 2001). In literature, works related to the study of influence of strength of masonry mortar in the brick masonry infill on the behaviour of infilled frames have been reported (Achintya et al 1991).

1.7 STRUCTURE OF THESIS

The dissertation is divided into eleven chapters. It is classified on the basis of the type of work (analytical/experimental), type of frame tested (square frame/2D-frame/3D-frame) and the specialized interface.

Chapter One describes the general aspects of infilled frames, their classification, factors affecting the behaviour limitations and various remedial measures for infilled frames in detail.

A comprehensive review of the available literature on infilled frames with a focus on studies related to interface characteristics, need for the present study, research significance and objective and scope of present investigations are covered in Chapter Two.

Chapter Three presents the details of proposed investigations, scheme of work of various phases in analytical and experimental investigations.

Chapter Four gives details of various interface models, their effectiveness and results of the study.

A detailed discussion on the various parameters considered, the model adopted, the influence of the parameters on the lateral stiffness of the frame and identification of available interface material are presented in Chapter Five.
Chapter Six includes details of the study on the effect of panel aspect ratio on bare frames, infilled frames, derivation of equivalent strut width and suggestion for method of analysis for designers.

Discussion on the details of experimental model, test setup, testing procedure and results for square frame models are included in Chapter Seven.

The details of two-bay three-storeyed frames specimens, materials used, procedure for casting and testing with results and comparison are presented in Chapter Eight.

Test on three-dimensional R.C. frames with torsional irregularity, is discussed in Chapter Nine along with the alleviation using cork at interface.

The details of test on square frames and three-storeyed frames with pneumatic interface are included in Chapter Ten.

Chapter Eleven includes conclusions resulting from analytical and experimental investigations along with scope for future work.

1.8 CLOSING REMARKS

The development of concept of composite interaction between the bare frame and the infilling wall has been explained with the composite system’s merits, demerits, factors influencing and applications. The state of the art of the research on infilled frames is reviewed and presented in the next chapter.