CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The beneficial effect of masonry infill panels in framed structures has been well documented in research publications in the last five decades. This topic has been the subject of separate investigations conducted at various institutions throughout the world. Generally, masonry infill panels provide adequate stiffness to otherwise flexible frame systems and in a reciprocal manner, the enclosing frames contain the brittle masonry panels thereby providing necessary ductility. After cracking, a masonry infill panel is capable of sustaining displacements and load much higher than that which could be achieved without the frame (Dawe and Seah, 1989). Generally, the literature shows a wide variation of materials, frame dimensions and testing procedures used in the study of masonry infill frames. Approaches adopted and assumption made by various investigators has also varied widely and as a consequence, there exists a wide spectrum of analytical techniques for predicting the stiffness and strength of infill frames. In spite of extensive research for more than five decades, there is no widely accepted design method for infilled framed structures. Because panels are often considered to be structurally inactive, they are rarely taken into consideration during the design process. This is explained partly by the complexity of the interaction between frame and infill and the great number of variables which influence the behavior of such a composite structure.

Significant parameters affecting system strength may be divided into those which are quantifiable and those which are not. The first category includes variables such as geometry and strength of infills, relative infill-to-frame stiffness, plastic bending moment capacity of the frame members, strength and rigidity of joints, beam-to-column relative stiffness, infill reinforcement, geometry and location of openings, effect of adjacent bays and upper storeys and the type of frame. The second category encompasses parameters including, among others, workmanship, climatic effects, grout and mortar variations due to job conditions, work stoppage, random variation of materials and human error.
The available literature is broadly classified into the following two categories -

i) Studies which mainly concentrate on the experimental behavior of infilled frames.

ii) Studies which are aimed at developing the method of analysis of infilled frames.

This review is limited to reports which contribute mainly to theoretical treatment of infilled frames and seismic behavior of brick masonry infilled reinforced concrete frames. Particular emphasis is given to relevant in-plane stiffness, strength, analytical methods which have been proposed to date and observed failure modes of such composite systems.

2.2 Experimental Studies

Thomas (1953) has reported about racking load tests on full scale concrete encased steel frames with and without masonry infills. The comparison made on the measured load displacement curves of bare and infilled frames clearly indicated the enhancement of bare frame strength and stiffness characteristics even in the case of infill carrying a centrally placed door opening.

Ockleston (1955) during the demolition of hospital building in UK, has investigated the effect of infill on the strength and stiffness of reinforced concrete frames. He has tested the frames with and without brick infill. From the load deflection curve, he observed that there was an increase in strength and stiffness of infilled frame. Investigations revealed different Load deflection relationship and failure modes for the infilled frame and bare frame.

Benjamin and Williams (1957, 1958) carried out extensive tests on scale models of infilled frames. The parameters investigated included scale effect, panel aspect ratio, brick size, column strength and panel reinforcement. Both steel and concrete frame ranging from one-eighth scale to full scale and infill with either concrete or masonry walls were tested. While they concluded that the aspect ratio of the system significantly affected both strength and stiffness of infilled frames, results also indicated that column strength did not alter the stiffness of such systems in the elastic
range. They recommended approximate empirical relationships for the prediction of ultimate strength and stiffness of infilled frames.

**Polyakov** (1957, 1960) in Russia conducted many experiments which included testing of small sixty specimens to evaluate the tensile and shear strength of masonry used as infills. Polyakov described three stages of infilled frame behavior subjected to racking. In the first stage, the masonry infills and members of the structural frame behaved as a monolithic unit. This stage ended with separation cracks around the perimeter at two diagonally opposite corners. The second stage was characterized by a shortening of the compression diagonal and lengthening of the tension diagonal. This stage ended with cracking of the masonry infill along the compression diagonal. In the third stage, the structural assemblage continued to resist an increasing load in spite of the diagonal crack. Existing diagonal cracks continued to widen and new cracks appeared. Based on his own tests, he suggested that an infilled frame system could be idealized as a frame with a diagonal strut which would replace the infill.

**Holmes** (1961, 1963) taking the same approach of Polyakov, developed the semi-empirical method to predict the strength of a frame with the wall as a diagonal brace. His tests were conducted on one-sixth scale model of steel frames infills either with brickwork panels or reinforced concrete walls. He suggested that the width of the diagonal strut be taken as one-third of the length of the infill diagonal. To predict the ultimate strength of the specimens he assumed that the infill would fail when it reaches the predefined average strain along the compression diagonal. Then the strength of the composite system could be determined as the sum of the strength of the frames and that of the strut.

**Stafford Smith** (1966) conducted on one-eighth scale models of steel frames in filled with mortar and loaded either diagonally or back to back concluded that there are two modes of failure of mortar infill. The modes of failure of infill are observed to be either a compressive failure or a diagonal tensile failure. The analytical work based on stress function approach and energy concepts developed by Smith have given rise to a relationship between the length of contact between infill and the load carrying capacity of infill. In his analysis Stafford Smith has defined a relative stiffness factor which is based on the analysis of a beam resting on elastic foundation as defined in equation (2.1). He
has also defined a relationship for the length of contact between the frame and the infill as given below -

\[ \frac{\alpha}{h} = \frac{\pi}{2\lambda h} \]  \hspace{1cm} (2.1)

Where,

\( \alpha \) = Length of contact between bonding frame and infill,
\( h \) = Height of infill,
\( \lambda h \) = Relative stiffness parameter.

His experiments can be categorized into - test on square frames and test on rectangular frames. The width of equivalent strut is obtained by assuming a triangular distribution of contact stresses over the entire contact length as shown in Fig 2.2. The infill strains are calculated along the loaded diagonal by using the finite difference method to determine the stress distribution of the infill. Smith’s (1966) tests on diagonally loaded square infilled frames indicate an extended region within the vicinity of compression corners. He established a relation between the length of contact (\( \alpha \)) and a non-dimensional relative stiffness parameter (\( \lambda h \)), similar to the one used in beams on elastic foundations. The plot of \( \alpha/\lambda_1 \), \( \lambda h \) for two assumed force distributions i.e. parabolic and linear is as shown in Figure 2.1 agreed with experimental results. For determining the strength of infilled frame it has been assumed that the length along the diagonal strut the stress distribution is uniform. For determining the ultimate diagonal splitting strength has been done by limiting the maximum principle tensile stress in the infill to maximum tensile strength of the material. For assessing the compressive crushing failure of the diagonal strut, uniform stress distribution at the interface at failure is assumed. By resolving the resultant force at the interface the diagonal crushing strength of interface is given by the relation,

\[ R_c = \alpha t \sec \theta f_{\text{cu}} \]  \hspace{1cm} (2.2)

Where,

\( R_c \) = The diagonal load in the infill to cause compressive failure,
\[ f_m = \text{compressive failing stress of infill material,} \]
\[ \alpha = \text{length of contact,} \]
\[ t = \text{thickness of infill.} \]

Stafford Smith and Carter (1966) conducted tests on masonry infilled frames and have identified three modes of failure of masonry infill to be a -

1) Bed joint failure of masonry
2) Diagonal tensile failure of masonry infill
3) Compressive failure of infill

They have concluded that in the masonry infill shear, cracking is a predominant failure. Their method of analysis represented the frame and infill by pin jointed axial force element.

![Interaction of frame and infill-analytical model by Smith (1966)](image)

Fig.2.1 Interaction of frame and infill-analytical model by Smith (1966)
Using Smith’s (1966) contact lengths, width of diagonal strut can be found as follows

Where,

\[
\alpha_h = \frac{\pi}{2\lambda_h}
\]

(2.3)

\[
\alpha_i = \frac{\pi}{\lambda_i}
\]

(2.4)

\[
\lambda_i = \frac{4E_f I_f}{E_r I_r h_w \sin \theta}
\]

(2.5)

\[
\theta = \tan^{-1} \frac{h_w}{l_{nr}}
\]

(2.6)

\[
w = \frac{1}{2} \sqrt{\alpha_h^2 + \alpha_i^2}
\]

(2.7)

\(\alpha_h\) and \(\alpha_i\) are contact lengths along the column and beam respectively as shown in Fig.2.1. The effective width \((w)\) of equivalent diagonal strut replacing infill can be obtained on the basis that the corresponding bond is defined by the lengths of contact \(\alpha_h\) and \(\alpha_i\) assuming triangular compressive stress distribution as shown in Fig.2.2.
For analysis of multistoreyed buildings, Smith and Carter (1969) suggested that frame could be idealized as the pin-jointed frame and they found marked reduction in bending moments in infill frames.

**Mainstone** (1971) investigated the behavior of infilled frame under the full range of restraint offered to an infill by using different types of surrounding frames. He studied the effect of surrounding infills. His approach of the analysis of strength and stiffness of infilled frames was also based on the concept of diagonal strut.

\[
\frac{w_e}{w'} = A_w \frac{K_h}{h_w} \sin 2\theta
\]  

\[
K_h = \frac{\bar{h}^4 \bar{E}_w \bar{I}_w \sin 2\theta}{\bar{E}_w \bar{I}_w \bar{h}_{w}}
\]  

**Fig.2.2 Effective width of equivalent diagonal strut (Smith and Carter, 1969)**

**Fig.2.3 Analytical model of infill frame by Mainstone (1971)**
Where all other terms have usual meanings and the constants $A_m$ and $B_m$ are depending on material of infill and stage of loading. Values of $A_m$ and $B_m$ are represented in Table 2.1 as follows.

**Table 2.1 Mainstone’s Constants**

<table>
<thead>
<tr>
<th>Stage of Loading</th>
<th>Before first crack</th>
<th>At first crack</th>
<th>At ultimate stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infill material</td>
<td>$h$</td>
<td>$A_m$</td>
<td>$B_m$</td>
</tr>
<tr>
<td>Brickwork &lt; 5</td>
<td>0.175</td>
<td>0.400</td>
<td>0.170</td>
</tr>
<tr>
<td>Concrete &lt; 5</td>
<td>0.115</td>
<td>0.400</td>
<td>0.225</td>
</tr>
<tr>
<td>Brickwork &gt; 5</td>
<td>0.160</td>
<td>0.300</td>
<td>0.150</td>
</tr>
<tr>
<td>Concrete &gt; 5</td>
<td>0.110</td>
<td>0.300</td>
<td>0.220</td>
</tr>
</tbody>
</table>

The approaches suggested by Smith (1962-78) and Mainstone (1971) can approximately simulate the behavior of infilled frame with solid infills only.

**Mallick and Liauw** (1977) have studied both experimentally and analytically the non linear behavior of integral infilled frames. They investigated the entire range of load deflection behavior. The study revealed that the use of interface connectors increased the initial stiffness and strength of the structure. Use of mechanical ties had little effect on prevention of major cracks but enhanced the ultimate load of infilled frames. They indicated that such systems exhibited considerable strength and ductility beyond the point at which shear cracking first developed.

**Govindan et al. (1987)** have compared the experimental behavior of a quarter size seven storey infilled reinforced frame with that of reinforced concrete frame without infill subject to lateral loads and assessed the failure mode with that of brick infill frame. They have quantified the strength, ductility and energy absorption characteristic of the infilled frame when subjected to repeat lateral cyclic loads which
exposes the ductility requirement of the brick infill in the infilled frame is to behave favorably under cyclic lateral loads.

Achintya et al. (1991) have presented through experimental approach the behavior of brick infilled RC frames subjected to lateral loads. They concluded that the strength of mortar is found to have considerable influence on the lateral stiffness and strength of infilled frames. Frames tested with reinforced brick panel have shown significant improvement in failure strength. The stiffness of the infilled frame decreases very rapidly after the initiation of cracks. Lack of fit between the infill and frame due to shrinkage of infill material is also noted.

Mehrabi and Shing (1996) conducted experimental investigations on the influence of masonry infill panels on the seismic performance of two types of RC frame specimens that were designed in accordance with ACI codal provisions. One was designed for moderate earthquake loads and the other for strong earthquake forces. Both solid and hallow concrete masonry panels, which represented strong and weak infill, were considered. In addition, the influence of the frame aspect ratio and vertical load distribution on the lateral resistance of infilled frames was also considered. From experimental results, it was seen that infill panels can significantly improve the performance of RC frames. Furthermore, specimens with strong frames and strong infill panels exhibited a better performance than those with weak frames and weak panels in terms of the load resistance and energy dissipation capability. In specimens with weak frames and strong infill, brittle shear failure occurred in the columns and these specimens exhibit good energy dissipation capability, which is better than those of weak frames with a weak panel. From this study, it was concluded that strong infill panels can significantly improve the performance of RC frames.

Lee and Woo (2002) conducted experimental investigation on the effect of masonry infills on the seismic performance of two-bay three-storey 1:5 scale masonry infilled RC frame designed according to Korean practice of non-seismic detailing model. They performed a series of earthquake simulation tests and a pushover test and compared the test results with bare frame. It was shown that the masonry infills contribute to the large increase in the stiffness and the strength of the global structure. The failure mode of the masonry infill frame was that of shear failure due to the bed joint sliding of the masonry infills while that of bare frame appeared to be the soft
storey plastic mechanism at the first storey. It was concluded that masonry infills can be beneficial to the seismic performance of the structure since the amount of increase in the strength appears to be greater than that induced by earthquake inertia force while the deformation capacity of the global structure remains almost same regardless of the presence of masonry infills.

2.3 Methods Based on Analytical Studies

Existing analysis and design methods that have been suggested by various investigators may be classified into three categories -

- **I category**: Based on the concept of Equivalent Diagonal Strut (EDS) initially as suggested by Polyakov (1960) and later expanded by Stafford Smith (1966) and Mainstone (1971).

- **II category**: Based on the theory of plasticity, which relies on observed failure mechanisms which in turn are used in the derivation of ultimate loads of related infill frames.

- **III category**: Based on the use of Numerical methods such as Finite Difference or Finite Element analyses to investigate all the aspects of the behavior of infill.

2.3.1 Methods Based on Equivalent Diagonal Strut

The equivalent strut concept was originally introduced by Polyakov in 1960. Subsequent to Polyakov’s investigations, a great deal of similar experimental work was carried out both on full-scale tests and on model tests by Holmes (1961), Stafford-Smith and Carter (1962, 1966, 1967a, 1969), Mainstone (1971) and Liauw and Lee (1977). All these studies advocate the use of a diagonal strut approach for predicting the behavior of infill multi-storey frames subjected to in-plane lateral loads. The frame members remained elastic up to the failure load. It was found that the initial failure was by cracking around the perimeter of the openings or near the loaded compression diagonal, the main challenge of this extended approach was to determine the geometrical properties of the diagonal strut. The thickness of the equivalent strut
was taken as that of the infill, its width was related to the relative stiffness of the column and infill through curves derived from experiments. Due to the complexity of the problem and variables involved, theoretical predictions were far from experimental results (Stafford Smith, 1966). Various equivalent widths have been suggested ranging from $d/20$ (Mainstone and Weeks, 1970) to $d/3$ (Holmes, 1961) in which $d$ is the length of the infill diagonal. Barua and Mallick (1977) and Mehrabi et al. (1994) reported that this method overestimated both the strength and the stiffness of the test specimens. It is important to mention that all the formulations were mainly derived from tests performed on small scale steel frames infill either with masonry blocks or with concrete blocks.

### 2.3.2 Methods Based on Plasticity and Collapse Design Approach

**Wood** (1978) used rigid plastic theory to determine the collapse load of rectangular frames. The modes of failure are shear, shear rotation, diagonal compression, and corner crushing failure. All of them depends on the relative strength of the frames to the infill defined by a parameter, $m$. This parameter was defined as the ratio of the column bending strength to the compression strength of the infill. Since the masonry walls did not exhibit a perfect plastic behavior, he suggested the use of an empirical penalty factor, 7, for artificially reducing the effective Crushing strength of the infill. This was initially derived for steel frames, later modified to reinforced concrete frames, bearing in mind that the RC frames were more likely to fail in shear than steel frames.

**Liauw** (1977) extended the plastic theory concept to multi-bay, multistorey infill frames taking into consideration the redistribution of stress during collapse. They accounted for stress redistribution due to the development of cracks or crushing of the composite system at the collapse state. In addition, the shear strength at the panel-to-frame interface which might be developed by connectors was taken into account. Four modes of failure suggested were -

- a) Composite shear mode (when the frame is very strong compared to weak infill),
- b) Shear rotation mode (when infill is of medium strength),

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c) Diagonal shear mode (in case where weak frame surrounds strong infill),

d) Corner crushing mode (strong infill is bounded by relatively weaker frame).

Fig.2.4 Idealized plastic failure modes by Wood (1958)

According to them the Composite action of collapse involves bending, wall cracking and wall crushing. The first two of these suit plastic theories ideally. Simple design rules have been recommended for normal infill frames.

May (1981) has extended the Woods method to square panels with centrally placed openings. The infill was assumed to have the square yield criterion originally proposed by Nielson and used by Wood (1978). Yield lines in tension, compression and shear were determined assuming the infill to be a rigid-plastic with no tensile capacity. These were used in the ultimate analysis of infill frame and comparison was made with values obtained by Wood (1978) for various collapse modes proposed by him. The method was extended to obtain upper bound solution for square panels with centrally located square openings and lower bound solutions using discontinuous stress fields. May (1981) claims that the method has better edge over Wood’s (1978) approach since better agreements with collapse modes were obtained and the method is applicable to panels with central openings.
Liauw and Kwan (1983) proposed a plastic theory based on finite element analysis and again recognized three modes of failure for non integral infill frames as -

a) Corner crushing mode with failure in column (weak column and strong infill),

b) Corner crushing mode with failure in beam (strong infill and weak beam) and

c) Diagonal crushing mode (strong frame and weak infill).

They proposed that mode of failure of infill frames under lateral load depends on the panel proportion and relative strength of frame elements. Their method took into account shear distribution. The friction was neglected for strength reserve. The various modes and distribution of stress were obtained using their non-linear finite element analysis. Contact length and ultimate horizontal loads were obtained for the modes mentioned earlier and lowest of these was found to govern the collapse. This method, however, cannot be extended to cover infill frame with openings.

Fig.2.5 Modes of failure by Liauw and Kwan (1983)
2.3.3 Numerical Methods (Finite Element Methods)

In recent years, Finite Element Method has been successfully used to solve various engineering problems. Karamanski (1967) analyzed masonry structures by discretizing masonry components into triangular elements to model the infill. Since then, the finite element method has been extensively used in both static analyses of masonry structures (Page, 1978) and dynamic analyses (Dawe and Dukuze, 1992, Dawe et al. 1992) and infill frames in particular (Dhanasekar and Page, 1986).

Despite abundant work in this area, most models previously reported, did not attempt to include various aspects of the infill behavior such as modeling the interface between the walls and encasing frame, progressive cracking and expansion of the infills in case of reinforced concrete frames, shear and moment failure of the frame members. Recent developments in these areas have been reported by Saneinejad (1990) Mehrabi et al. (1994), Lourenco (1996) and Seah (1998).

Klinger and Bertero (1978) developed a mathematical model to predict the essential feature of the cyclic load deflection characteristics of RC frames infilled with reinforced concrete, clay block and concrete block masonry. The macroscopic model basically replaced each infill with strut so that infilled frame was idealized as braced frame. The macroscopic model offered efficiency in nonlinear dynamic analysis.

Riddington (1984) carried out the analytical and experimental investigation on the influence of gaps at the interface of the frame and infill on the behavior of the structure. The result indicated the relative small gap used in the tests significantly affected the structural behavior and conclude that initial gaps should be avoided.

Saneinejad and Hobbs (1995) proposed a method for analysis and design of steel frames with concrete or masonry infill walls subjected to in-plane forces, taking into account elastic and plastic behavior of infill frames and considering the limited ductility of infill materials, to determine the strength and stiffness of infill frames as well as the infill diagonal cracking load. In this method, practical imperfections such as lack of fit and shrinkage of the infill were also considered. The method further developed to model multistorey infill frames as braced frames, replacing the infills by equivalent diagonal struts.
Andreaus (1996) had developed a method to determine the failure criteria of masonry panels under in-plane loading. A suitable strength criterion was used to represent each of the three failure modes. The modified Mohr-Coulomb friction law was associated with slipping of mortar joints, slipping of bed joints and splitting and slipping of bed joints which accounts for the shear strength depending nonlinearly on normal stress. The Saint Venant criteria (the maximum tensile strain criterion) has been associated with the collapse mode characterized by the splitting of bricks and slipping of mortar joints, splitting of bricks and head joints, splitting of bed joints, splitting and slipping of mortar and biaxial deformation. Navier criterion (maximum compressive stress) was used for middle plane spalling. The results were validated with experimental as well as two-dimensional FEM model and were directly used to carry out the limit analysis of masonry walls, modeled by a discrete number of panels of finite size.

Gambarotta and Lagomarsino (1997) proposed a continuum model for brick masonry shear walls by considering the contribution of brick damage, which considers both the strength of the masonry to compressive stresses and the shear strength of the bricks. The model has been implemented in a finite element procedure for the analysis of large scale brick masonry walls with openings and in this model, both damage and friction mechanisms coexist. The coupling effect of ductility and brittleness of masonry walls under the horizontal seismic loads was described. The analytical results were compared with tests that were conducted on full-scale two-storey masonry building. Both the results were in good agreement in terms of stiffness, strength and dissipative behavior and the damage distribution.

Magenes and Calvi (1997) were given a simplified approach to evaluate the strength, deformability and energy dissipation capacity of un-reinforced brick masonry walls subjected to in-plane loading, within the context of seismic assessment of existing buildings on the basis of experimental and Finite Element Procedures and formulae for assessment were proposed to evaluate the strength of the masonry and the three failure modes: (diagonal shear cracking failure, flexural failure and sliding failure) were considered.

2.3.4 Seismic Evaluation Method
Mehrabi and Shing et al. (1996) conducted experimental investigations on the influence of masonry infill panels on the seismic performance of two types of RC frame specimens that were designed in accordance with current code provisions. One was designed for moderate earthquake loads and the other for strong earthquake forces. Both solid and hallow concrete masonry panels, which represented strong and weak infills were considered. In addition, the influence of the frame aspect ratio and vertical load distribution on the lateral resistance of infill frames was also considered. From experimental results, it was seen that infill panels can significantly improve the performance of RC frames. Furthermore, specimens with strong frames and strong infill panels exhibited a better performance than those with weak frames and weak panels in terms of the load resistance and energy dissipation capability. In specimens with weak frames and strong infills, brittle shear failure occurred in the columns and these specimens exhibit good energy dissipation capability, which is better than those of weak frames with a weak panel.

Madan and Reinhorn et al. (1997) proposed an analytical macro model based on an equivalent strut approach with a smooth hysteretic model for representing masonry infill panels in nonlinear analysis of frame structures. The hysteretic model used degrading control parameters for stiffness and strength degradation and slip pinching resulting from opening and closing of masonry gaps that can be implemented to replicate a wide range of hysteretic force-displacement behavior resulting from different design and geometry. The formulation used a time rate-dependent model. The equivalent strut with the hysteretic model was implemented in the computer program IDARC Version 4.0, for static monotonic analysis, quasi-static cyclic analysis in displacement or force control as well as dynamic analysis under earthquake excitations. In this macro modeling, the entire infill was considered as a single unit and takes in to account only the equivalent global behavior of the infill in the analysis. But, this approach does not permit study of local effects such as frame-infill interaction within the individual infill frame subassemblies failure in the brick units and or head joints or by splitting in the bed joints. Mathematical expression has been developed to express stress envelope.

Chaker and Cherifati (1999) studied analytically the influence of hollow clay brick masonry infill panels on the vibration and stiffness characteristics of two adjacent,
three-storey RC frames. Eigen value analysis was performed to obtain the vibration frequencies for the different models. The fundamental period of the infill frame building was much smaller than that of the frame buildings. Using shear beam lumped mass models and the vibration data; the actual lateral stiffness of both buildings was evaluated. The lateral stiffness of the infill frame buildings was found to be seven times that of bare frame building. In numerical modeling, the infill panels were modeled by one of three commonly used equivalent diagonal trusses or by plane stress finite elements and compared with experimental results. Based on experimental results, it was concluded that plane stress finite elements provided a better representation of the in-plane initial stiffness of the infill panels than the bare frame.

Arlekar and Jain (1997) studied the open storey concept which is mostly adopted in multistorey constructions in India. The RC moment resisting frame with open first storey and brick infill walls in the upper storeys was considered for the analysis. Non linear analysis for five different models of the building was carried out using ETABS. After doing this they concluded RC framed buildings with open first storeys are known to perform poorly during strong earthquake shaking. The drift and the strength demands in the first storey columns are very large for buildings with soft ground storeys.

Dolsek and Fajfar (2002) proposed a technique based on pseudo-dynamic results for the development of a mathematical model for the global non-linear seismic response of three-storey RC frame building with masonry infill in the bottom two storeys, which was tested at ELSA in Ispra. This proved to be effective and led to a fairly accurate structural model. From the results of analysis, the global non-linear seismic response of RC frames with masonry infills can be adequately simulated by a relatively simple mathematical model, which combines beam elements with concentrated plasticity, simple connection elements and equivalent strut elements representing the infill walls, provided the infill does not fail out of plane.

Ghosh and Amde (2002) verified the design of infill frames to resist lateral loads on buildings in terms of their failure modes, failure loads and initial stiffness using procedures proposed by previous authors. Verification was made by comparing the results of the analytical procedures of the previous authors with those of a new finite element model for infill frames and with experimental results. Non-associated
interface model was formulated using the available test data on masonry joints to model the interface between the frame and the infill and the mortar joints surrounding the block masonry. The cracking in tension and plasticity in compression of the infill have been modeled by the smeared crack model and the plasticity model respectively. From the FEM results it was found that the model gave not only the load carrying capacities but also detailed information on the failure mode, ductility and cracking, which is most important in evaluating the seismic resistance of infill frame.

Proenca et al. (2002) used a nonlinear model which was significantly modified through the introduction of diagonal struts, representing the stiffening effect of infill masonry walls, to match the experimentally determined fundamental frequencies. The analysis was carried out by means of two distinct nonlinear models, in terms of the load patterns. The subsequent second model differed from the first model by the removal of the struts that had collapsed. A sensitivity analysis was carried out by changing the strength parameters of the diagonal struts. The results show that the structure does not collapse but the high damage concentration in the intermediate storey renders the building partially inoperative. He concluded that strong masonry walls have a significant stiffening effect on structure.

Das and Murthy (2004) studied five reinforced concrete (RC) framed buildings with brick infill walls designed for the same seismic hazard in accordance with provision made according to Eurocode8, IS code, Nepal building code. In the design the EBF method was used. They concluded the Nepal building code 201 and equivalent braced frame method were found to be more economical.

Magenes and Pampin (2004) proposed a simple and analytical model, based on concentrated plasticity approach using rotational spring based model for the joint panel zone. Their analytical and experimental study highlighted the interaction between un-reinforced masonry infills and RC frame system by considering the joint non-linear behavior through pushover and non-linear time history analysis for 6 storey frame system. They proposed limit states based on inter storey drift and related to joint or infills damage level for the simple assessment evaluation of strength and sequence of damage using the suggested numerical model.
Mostafaei (2004) carried out an analytical investigation on effect of infill masonry on the seismic performance of reinforced concrete building. He carried out non linear time history analysis for the recorded strong motions of Bam earthquake. He developed an approach to model masonry infill walls with or without openings. The results of the analysis were compared to damage and residual cracks observed on the masonry infill walls and concluded that the presence of masonry walls is the main reason for the linear response.

Tuladhar and Koichi (2005) investigated the seismic performance and design of the masonry infilled Reinforced Concrete (RC) frame buildings with the soft first storey under a strong ground motion. They attempted to determine the strength increasing factor by adding infills to account for the effect of the soft storey by numerical analysis. They used six different 2D models of infill frames by using capacity spectrum method (CSM) and the non linear dynamic time history analysis. After doing all analytical part they concluded that, the effect of infill wall predominately changes the behavior of the structure and it is essential to consider infill walls for seismic evaluation of the structure, arrangement of infill wall in the frame affects the behavior of the structure and the non linear dynamic time history analysis for 2D models proved that the demand of the soft storey can be met by application of strength increasing factor.

Pandey and Faroz (2005) studied and compared the fundamental natural period (FNP) of RC concrete building considering various configuration irregularities such as plan irregularities, column irregularities, mass irregularities and geometrical irregularities given by various codes of practice namely IS: 1893-2002, IBC 2000 FEMA (368) and concluded that higher plan irregularity lead to higher FNP, the value of FNP differs significantly from code to code the base share calculated as per the FNP given by IS code is observed to be 10-30 % more than other codes. The recommendation of the IS code method leads to stiffer structure which will attract higher seismic force and uneconomic design.

Kaushik et al. (2006) reviewed and compared the analysis and design provision related to Masonry Infill RC frames in seismic design codes and identified various issues such as natural period, plan and vertical irregularities, response reduction factors, lateral displacement and inters story drift, strength of infill, effect of openings...
etc. that should be addressed by a typical model code. Seventeen National codes in regard to the inclusion of masonry infill in the design process from a seismic performance point of view was compared and listed the short comings for possible future research on Masonry Infill RC frames.

Salah and Moubarak (2007) studied the influence of high strength concrete and high strength masonry in load sharing characteristics of frames. They conducted experimental and finite element methods to study the capacity of the side columns strength of masonry infilling on the seismic lateral behavior of low, medium and high rise building.

Adedeji (2007) A hysteretic model was investigated with straw bale infill panel to determine the hysteretic parameters stiffness deterioration and strength degradation due to seismic loadings. The average design thickness, for the cement plastered straw bale stiffens the pre-stressed burnt brick frame was obtained.

Nikos and Martha (2007) conducted parametric study of six models with reference three construction practices often encountered in Greece namely examined (i) weak ground storey (ii) short column and (iii) floating or hanging column. In addition two combinations of the three constructions practices are also studied. These models are assessed with reference to their performance against three earthquake hazard level through the parametric study it was found that the performance of a multi-storey fully infilled RC building was superior to all construction practices examined. In particular the fully infill model was the only one that fulfilled the drift limit requirement for the occasional and rare hazard levels while it slightly exceeded drift limit for the very rare hazard level. In terms of the structural capacity the weak ground storey and short column design were found to 50% worst versus the fully infill design. Although these conclusions cannot be generalized it is an indication that for the test example considered the Greek national design codes.

Korkmaz et al. (2007) studied the effect of irregular configuration of masonry infill wall on the performance of structures using non-linear pushover analysis under earthquake and they suggested that structural infill wall have very important effect on structural behavior under earthquake effects with reference to displacement and drift with five different models of the structures and wall application.
Daffedar and Jagtap (2007) performed parametric investigation for the natural period of vibration of frames with and without infills by using free vibration analysis. In their study the result obtained for bare frame indicates that the IS code 1893-2002 underestimates the fundamental period of multi storey frames thus giving higher base share. However the same can be improved the modification factor and proposed the empirical equations for estimating the natural period for first three modes of vibration which are required for dynamic analysis.

Mondal and Jain (2008) At IIT Kanpur carried out finite element analysis on single bay single storey and multi bay and multi storey infill frames to examine on initial lateral stiffness of infill frames with and without openings. They suggested that lateral load deflection curve can be divided into three parts as - the initial part may be with a lack of fit between frame and infill, second part as approximately linear which represents the interaction between frame and infill and considered stiffness equal to load level of 10% of lateral strength of infill frames and in the third part lateral load deflection relationship a stiffness reduction takes place due to progressive degradation of the infill material with increasing stress. The FE model has been verified using the experimental results and proposed a reduction factor for the width of the strut with opening. The FE model is based on cracked flexural rigidity of beam and column where the flexural rigidity of beam and column in tension is taken as $0.5E_cI_g$ and that of column is taken as $0.7E_cI_g$ (ATC-40 1996).

Lagros and Geraki (2008) studied the effect of configuration of the infill panel on the seismic performance of RC frames designed according to Greek national codes. They gave comparative study of effects of infill on bare frame, frame with soft storey and fully in filled frame with respect to structural capacity and maximum inter storey drifts in three hazard levels. They concluded that performance of fully infilled masonry frames is better in terms of structural capacity compared to others.

2.4 Summary

The present review indicates that most experiments conducted to date on masonry infill frames. Most of the early research deals with small models in the order of one-tenth to one-sixth scale steel frames with mortar or concrete infills. Few studies have been conducted on reinforce concrete infill frames. It has been pointed
out that geometrical characteristics play a significant role in the infill frame behavior when subjected to in-plane static loads. The presence of opening in the infills extensively alters the performance of these composite structural systems. A limited number of investigations dealt with the effect of aspect ratio of the panel and variations in frame stiffness. There are still many aspects of masonry infill behavior which are not well understood. Therefore it is important that research be conducted on a number of variable which are thought to markedly influence the behavior of infill frames. Gaps used in the tests significantly affected the structural behavior of infill frames and that the effects were largely undesirable and concluded that initial gaps should be avoided wherever possible. There are few known full-scale tests up to destruction of infill frames. However no theory has been developed that account for all the parameters affecting the behavior of infill frames. Out of all the methods described earlier, methods based on equivalent strut approach are simpler and easier to apply in practical design; however, this method gives only an approximate predication of strength and mode of failure of infill.

Most of the infill frames are accompanied with openings in the form of windows and doors. Most of the researchers concluded that the opening in infill reduces the strength and stiffness of infill frame considerably. However, they did not consider practical size of door and window openings. Mallick and Garg (1971) recommended the provision of shear connectors to improve the behavior of infill with opening. Coull (1966) recommended provision of nominal reinforcement in wall and around the opening. The above recommendations for openings do not seem to be practical and it is still not clear whether to neglect the contribution of infill frame with opening or not.

Infill frames are often subjected to vertical loading. This is very important aspect in case of reinforced concrete frames infill with masonry. It is very difficult to analyze the effect of vertical loading accurately. This is because the divisions of vertical loads are largely dependent on the initial fit of the infills. In the present dissertation work, nonlinear pushover analysis and nonlinear time history analysis is proposed to analyze the multistorey buildings with infill frames incorporating variables like material properties, aspect-ratio of infill and strength of masonry with local bricks and complex nature of the dual system.