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Nonlinear behavior of Reinforced Concrete Infilled Frames using ATENA 2D

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ABSTRACT

To understand the complex behavior of the infilled frames, experimental or analytical studies are generally carried out. Though experimental studies are more realistic, they are expensive and require sophisticated testing facilities. Moreover, as parameters are many, it requires large number of trials. With the availability of high speed computers, analytical method have become more popular, especially when the parametric analysis is being carried out. With the present day development in finite element analysis, a number of softwares are available which are capable of modeling the nonlinear behavior of structures. Thus, the numerical methods are widely used and in the present study, the numerical analysis is carried out using popular finite element software's ATENA 2D (2003). The finite element software is used to capture the nonlinear behavior of infilled frame. The important parameters which affect the behavior of reinforced concrete infilled frames are identified by conducting nonlinear analysis. Load displacement curves, distribution of principal compressive stresses and principal tensile stresses, and cracks patterns are used to understand the behavior of infilled frames.

Key words: *Nonlinear behavior, Infilled frames, Atena, Masonry stresses.*

1. INTRODUCTION

The term "infilled frame" is used to denote a composite structure formed by the combination of a moment resisting plane frame and infill walls. The reinforced frame structure with masonry infill is the most common type of construction method practiced in India. Infill materials such as brick masonry, solid or hollow concrete block masonry, soil cement blocks, and stone masonry are generally used. The brick masonry is the most preferred and popular material used as infill in India, as it is durable, economical, and thermally efficient.

The codes of practice are generally silent on the infill material as the choice of infill material is random and it is believed to be a nonstructural component. The existing seismic code IS: 1893 (2002) considers the effect of infill only in terms of fundamental period of vibrations, which do not consider the extent of infill usage. Furthermore, it does not consider the influence of openings in infill walls. The past research has shown that there is a considerable improvement in the lateral load resisting system if the effect of infill material is considered during the analysis. The effect of infill is generally not considered in codes of practice because the interaction and failure modes are complex in nature and simplified analysis and design procedures are not available. The analysis or design of infilled frames should properly take in to account the highly nonlinear behavior of interaction of infill and bounding frame during lateral loads. In almost all the codes, due to the lack of reliable analytical models describing the behavior of infilled frames, there is a lack of information to structural engineer for the analysis and design of infilled frames. Currently, the information available for analysis and design of infilled frames is limited.

2. MODELING OF INFILLED FRAMES

Analytical modeling of infilled frames are broadly classified into two major groups namely, micro-modeling methods and macro- or simplified-modeling methods based on the complexity and details involved in modeling of infilled frames and degree of refinement used to represent the structure. Selection of the appropriate model depends on the purpose and requirements of study. The macro-modeling methods are best suited, if the global behavior of the infilled frames being investigated, on the other hand, if the study focuses on the detailed behavior of frames including the response of the infilled material then micro-modeling is employed.

The analytical modeling of infilled frames by replacing the infill by equivalent diagonal strut is termed as macro model. Based on the studies carried out by Polyakov [1]

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and others, Holmes *et al*. [2] proposed the concept of diagonal compression strut to simulate the effect of infill. Further research was carried out by Mainstone [3], Paulay and Priestly [4] and others strengthened the concept of diagonal strut and proposed various methods to calculate the width of the diagonal strut. The equivalent diagonal strut thickness is assumed to be equal to the thickness of the masonry infill. The main problem in this approach is to find the effective width of the equivalent diagonal strut. Many researchers have suggested different methods to find the width of equivalent diagonal strut. The width of the equivalent diagonal strut varies between one-third and one-tenth of the diagonal length of masonry infill.

Finite element techniques are generally used to model the infilled frames. According to these models, the bounding frame is constituted by plane or beam elements, the infill by plane elements and the contact between frame and infill by link elements or interface element are termed as micro-modeling methods.

Mallik and Garg [5] first applied the method of finite element approach to model the infilled frames. Mallik and Severn [6] suggested a method to address the problem of interface condition between the bounding frame and infill. Liauw and Kwan [7] used the simple beam element to represent infill-frame interaction capable of representing both separation and slip occurring at the interface. Asteris [8] suggested a new way of micro-modeling wherein the infill frame contact lengths and the contact stresses are estimated as an integral part of the analysis. The model is initially analyzed assuming infill are linked to the surrounding frame at two diagonal loaded corners. After each iteration, the infill model points are checked for overlapping into surrounding frame. If it overlaps, the infill at the points of overlaps are linked to the surrounding frame and analysis is carried out until there is no overlapping of infill model points into the surrounding frames.

3. NONLINEAR BEHAVIOR OF INFILLED FRAMES

In the present study, micro-modeling of infilled frames are performed using ATENA 2D V4.3.1, a nonlinear finite element analysis tool developed by Cervernka Consulting Ltd. It is a powerful finite element tool, especially due to the material models available to simulate reinforced concrete (RC) and masonry infill in the numerical model.

The material model SBETA available in ATENA 2D (2013) is capable of representing the material for nonlinear behavior in compression including hardening and softening means the abbreviation for the analysis of RC in German language – StahlBETon Analyse. The crack initiation and propagation of material in tension are governed by nonlinear fracture mechanics. The SBETA model has a provision for reduction in compression strength of material and shear stiffness after cracking and has incorporated tension stiffening effect. The bond between concrete and reinforcement is assumed to be in perfect bond. SBETA model uses smeared approach to model the infilled frames. The model considers material to be isotropic until the uncracked stage where the principal direction of the stress and strains are identical and anisotropic in the cracked stage where the principal direction of stress and strain are different. The nonlinear behavior of material in biaxial stress state is represented by effective stress and the equivalent uniaxial strain. The introduction of uniaxial strain eliminated the Poisson's effect in the plane stress state. The behavior of the material in tension without cracks is assumed to be linear elastic. The effective tensile strength derived from the biaxial failure function. Tension after failure are formulated using a fictitious crack model based on a crack opening law and fracture energy.

3.1. Model Description

To explore the nonlinear behavior of infilled frames, the model shown in Figure 1 and the properties shown in Table 1 are considered. The bounding frame members are of size 300 mm × 450 mm and the thickness of masonry is 200 mm. The aspect ratio of 1.0 and the relative stiffness ($\lambda h = 2.77$) are considered for the study. The relative stiffness is a dimensionless parameter denoted by λh, defined as,

$$\lambda h = \sqrt[4]{\frac{E_m t_m \sin(2\theta) h_m^3}{4E_cI_c}} \qquad \text{(Equation 1)}$$

Where, E_m is the elastic modulus of the infill, t_m is thickness of the infill, E_cI_c is the column rigidity, and h_m is the height of the infill.

3.2. Study of Effect of Infill on the Behavior of RC Frames

The effect of infill on the RC frame is studied under the following headings:

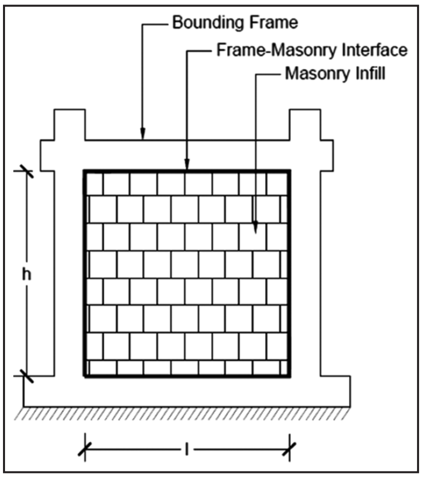

Figure 1: Model considered to study the behavior of infilled frame.

- Lateral stiffness of bare frame and solid infilled frame
- Distribution of principal compressive stress and flow of displacement vector
- Distribution of principal tensile stress and crack propagation.

3.2.1. Lateral stiffness of bare frame and solid infilled frame

Figure 2 shows the variation of lateral displacement with respect to lateral load for a bare frame and for a solid infilled frame. The ultimate load carrying capacity of RC frame is considerably enhanced by the presence of infill. The load carrying capacity of infilled frame increases by about 45% with respect to bare RC frame. The bare frame shows lesser stiffness and shows bilinear behavior. In case of solid infilled frame, the increase in the load carrying capacity is mainly due to the participation of the infill in transferring the lateral load by formation of compressive strut along the loaded diagonal. Once the diagonal strut fails, the load carrying capacity gradually decreases and reaches almost the same level as that of bare frame. It is interesting to note that after this stage, the behavior of both infill and bare frame are similar till failure. Results indicated that the infilled frame can significantly improve the performance of structure in terms of load resistance and energy dissipation. The load displacement curve of infilled frame and bare frame clearly demonstrates the energy absorption capacity of infilled frame is considerably more compared to bare frame.

Figure 3 shows the degradation of lateral stiffness under the action of lateral loading at different load steps for bare frame and solid infilled frame. The initial lateral stiffness of solid infilled frame is sufficiently large compared to the bare frame. Moreover, the stiffness of both bare frame and solid infilled frame reaches the same value after few steps. In solid infilled frames, the stiffness appears to be constant till load Step no. 5 and for further load steps, there is a drop in the stiffness. This phenomenon is due to the fact that initial cracks are observed in the infill. Further, after Step no. 11, the lateral stiffness suddenly drops down and reaches a value almost same as that of bare frame. This sudden drop may be due to the degradation of compression strut formed along loaded diagonal and resulting in the reduction of lateral stiffness and load carrying capacity.

3.2.2. Distribution of principal compressive stress and flow of displacement vector

Figure 4 shows the load levels reached at different loading steps at salient points. Each loading step corresponds to 0.5 mm of prescribed lateral displacement. The distribution of principal compressive stress and flow of displacement vector

Table 1: Parameters considered for the study of infilled frames.

Item	Parameters	Value
Concrete	Compressive strength	30 MPa
	Poisson's ratio	0.2
	Modulus of elasticity	2.739×10^4 MPa
Masonry infill	Compressive strength	5 MPa
	Poisson's ratio	0.15
	Modulus of elasticity	2.75×10^3 MPa
	Tensile Strength	0.16 MPa
Interface	Normal Stiffness	2.75×10^5 MPa
	Tangential stiffness	1.196×10^5 MPa
	Cohesion	0.2 MPa
	Frictional coefficient	0.2
Rebar	Modulus of elasticity	2.1×10^5 MPa
	Yield stress	550 MPa

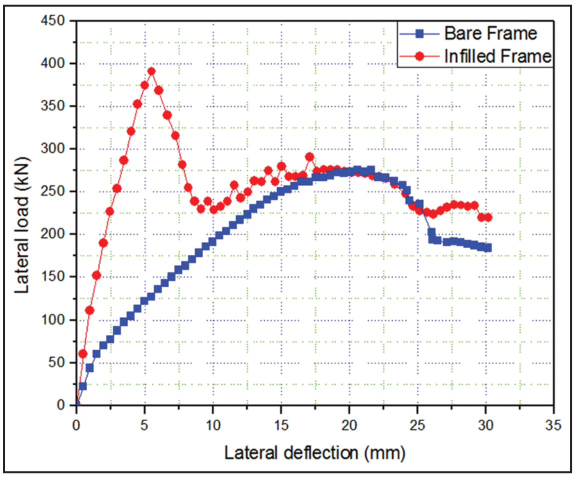

Figure 2: Load-deflection curve for bare frame and infilled frame.

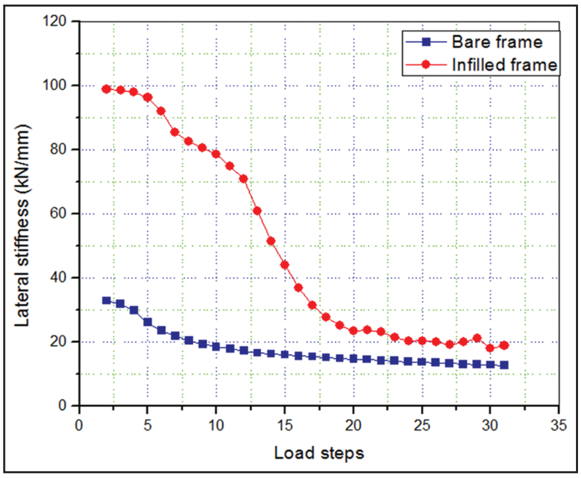

Figure 3: Lateral stiffness degradation curve for bare frame and infilled frame.

are presented at various salient loading steps and are presented in Figure 5. At load Step no. 1, the principal compressive stress contour and displacement vector corresponds to gravity load (self-weight). At load Step no. 2, the principal compressive stresses are developed along the loaded diagonal. As loading step increases, the magnitude of principal compressive stress along the loaded diagonal increases. From Figure 5a-f, it is clear that the concentration of compressive stress along the loaded diagonal explain the participation of infill in lateral load transformation.

Higher values of stresses are spread in a zone parallel to the compression diagonal or along the loaded diagonal. Thus, the infill effect can easily be represented by an equivalent diagonal strut. Load Step no. 5 corresponds to approximately 50% of the peak load. At this load, the compressive stresses neither in the frame nor in the infill panel have reached the peak value but, the tensile stresses in the infill just crosses its limit resulting in the initiation of diagonal tension cracks. Separation of the infill from the bounding frame occurs at a very early stage. Generally, this separation occurs when the load reaches to about 20-30% of the peak load. This separation is seen near the unloaded diagonal.

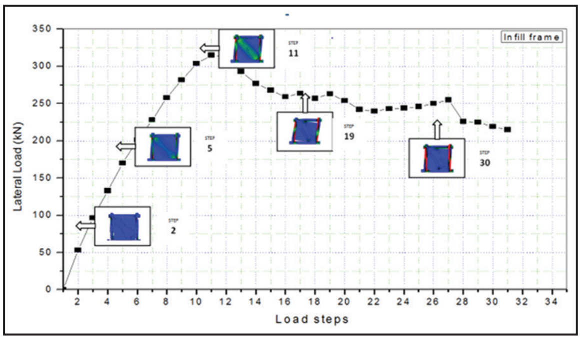

Figure 4: Behavior of solid infilled frame under the action of prescribed lateral deformation.

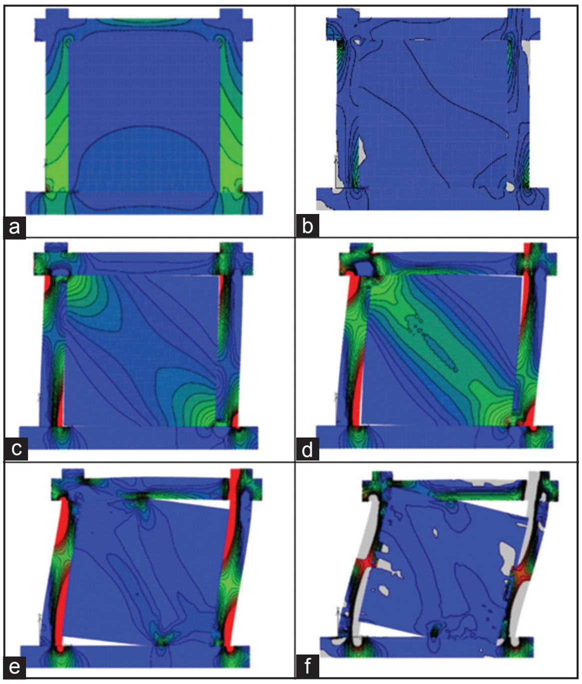

Figure 5: Variation of principal compressive stress different loading steps for solid infilled frame, (a) loading Step no. 1, (b) loading Step no. 2, (c) loading Step no. 5, (d) loading Step no. 11, (e) loading Step no. 19, (f) loading Step no. 31.

Under lateral load, the corresponding movement of the displacement vector is also horizontal. When the infilled frame reaches the peak load at load Step no. 11, the failure of infilled frame takes place when the compressive stresses in infill reaches its maximum limit. This failure is observed along the loaded diagonal and also the flow of displacement vector changes its path toward loaded diagonal corners. From loading Step no. 12 onward, the magnitude of compressive stresses suddenly reduces along the loaded diagonal indicating the ineffectiveness of the infill in transfer of lateral load. After load Step no. 19, there is a complete degradation of the stresses in the infill complementing its inability to carry any load and the behavior of infilled frames is very much similar to bare frame behavior. In the nonlinear analysis of infilled frame, two modes of failure are observed. The first mode of failure, developed as a crack extending from the center of the infill along the diagonal toward the loaded corners called diagonal tensile failures. Second failure mode occurs at one of the loaded corners, and the crushed region takes the shape of a quadrant.

3.2.3. Distribution of principal tensile stress and crack propagation

Figure 6a-d shows the principal tensile stress distribution and the corresponding crack propagation at different loading steps. The cracks starts developing along the loaded diagonal once the tensile stress in masonry reaches its maximum limit (load Step no. 5). Furthermore, the direction of cracks appear along the loaded diagonal and are perpendicular to principal tension trajectories. The development of principal tensile stresses is along the unloaded diagonal. As the load steps reaches no. 7, the maximum principal tensile stresses are visible near the location where separation of infill and frame takes place and the concentration of maximum tensile stresses increases at unloaded corners when the ultimate load is reached at load Step no. 11.

4. CONCLUSIONS

The following conclusions are drawn from the present numerical investigations:

- The effect of infill has a significant role in global performance of the structure as the ultimate load

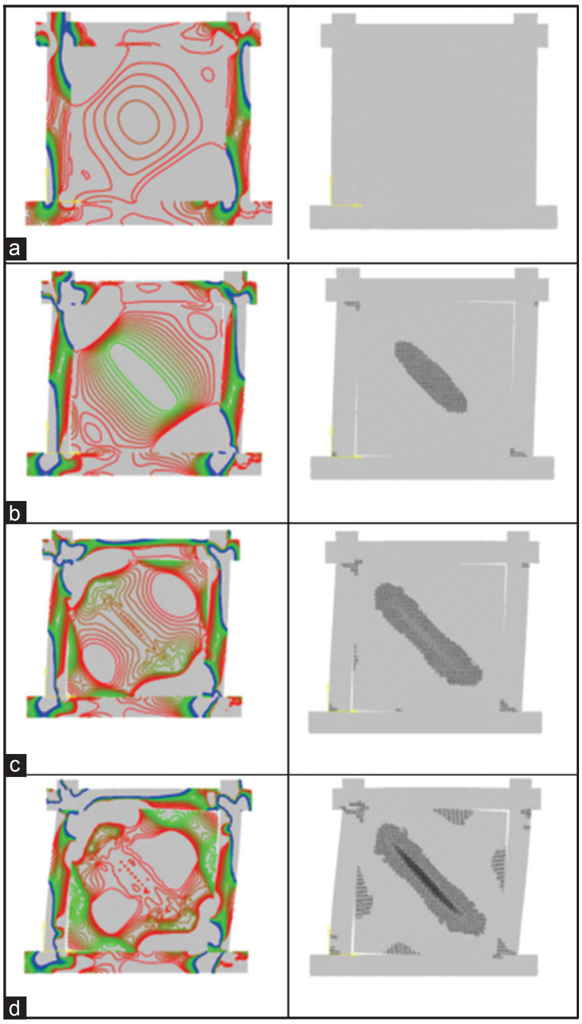

Figure 6: Variation of principal tensile stress and crack pattern at different loading steps for solid infilled frame, (a) loading Step no. 2, (b) loading Step no. 5, (c) loading Step no. 7, (d) loading Step no. 11.

carrying capacity is considerably enhanced along with the increase in lateral stiffness.

- Two modes of failures are observed in infill under lateral load. In the first failure mode, a crack extends from the center of infill along the diagonal toward the loaded corner and is called diagonal tensile failure. In the second failure mode, crack occurs at one of the loaded corners due to crushing of masonry.
- The initial lateral stiffness of the infilled frame is considerably more compared to bare frame till the peak load is reached.
- The stiffness of infilled frame suddenly reduces and takes a value almost similar to that of bare frame. This sudden drop is due to degradation of compression strut.
- The load displacement curve of infilled frame and bare frame clearly demonstrates that the energy absorption capacity of infilled frame is considerably more compared to bare frame.
- The distribution of principal compressive stresses in the infill is concentrated along the loaded diagonal indicating that the infill can be replaced by an equivalent diagonal strut. Separation of the infill from the boundary occurs at a very early stage. Generally, this separation occurs when the load reaches about 20-30% of the peak load. This separation is seen near the unloaded diagonal.
- The failure of infill frame takes place when the principal compressive stress reaches its maximum limit. This failure can be observed along the loaded diagonal and also from the flow of displacement vector which changes its path toward loaded diagonal corners.
- The crack starts developing along the loaded diagonal once the principal tensile stresses in masonry reaches the maximum limit, and also direction of crack appears along the loaded diagonal and are perpendicular to principal tensile stresses.

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***Bibliographical Sketch**

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