Seismic Vulnerability of Columns of RC Framed Buildings with Soft Ground Floor

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***Abstract*—Though multistoried buildings with open (soft) ground floor are inherently vulnerable to collapse due to earthquake load, their construction is still widespread in the developing nations. Social and functional need to provide car parking space at ground level far out-weighs the warning against such buildings from engineering community. In the present paper, an investigation has been performed to study the behavior of the columns at ground level of multistoried buildings with soft ground floor subjected to dynamic earthquake loading. The structural action of masonry infill panels of upper floors has been taken into account by modeling them as diagonal struts. Finite element models of six, nine and twelve storied buildings are subjected to earthquake load in accordance with equivalent static force method as well as response spectrum method. It has been found that when infill is incorporated in the FE model, modal analysis shows different mode shapes indicating that dynamic behavior of buildings changes when infill is incorporated in the model. Natural period of the buildings obtained from modal analysis are close to values obtained from code equations when infill is present in the model. This indicates that for better dynamic analysis of RC frame buildings with masonry walls, infill should be present in the model as well. Equivalent static force method produces same magnitude of earthquake force regardless of the infill present in the model. However, when the same buildings are subjected to response spectrum method, significant increase in column shear and moment as well as total base shear has been observed in presence of infill. In general, a two fold increase in base shear has been observed when infill is present on upper floors with ground floor open when compared to the base shear given by equivalent static force method. The study suggests that the design of the columns of the open ground floor would be safer if these are design for shear and moment twice the magnitude obtained from conventional equivalent static force method. Study of the sway characteristics also reveals significantly high demand for ductility for columns at ground floor level. Presence of infilled wall on upper floors demands significant enhancement of column capacity or ductility to cope up with increased sway or drift.**

***Keywords*—concrete, earthquake, infill, multistory, response spectrum, soft story.**

I. INTRODUCTION

Recent trend of urbanization of cities of the developing countries, especially in South Asia region, is witnessing construction of multistoried buildings with open ground floor reserved for car parking or other utility services. These buildings are generally designed as RC framed structures without regards to the structural action of the masonry infill (MI) walls present in the upper floors. However, in reality, masonry infill (MI) walls in the upper floors make those floors much stiffer against lateral load (e.g. earthquake) compared to ground floor rendering these buildings into soft story buildings. Experience of different nations with the poor and devastating performance of such buildings during earthquakes always seriously discouraged construction of such a building with a soft ground floor. Typical examples of soft story (ground floor) failures are shown in Fig.1.a and Fig.1.b.

Stiffness irregularities across floors are introduced into MIRC frames due to reduction or absence of MI in a particular story compared to adjacent stories. Various national codes can be broadly grouped in two categories of those that consider or do not consider the role of masonry infill (MI) walls while designing RC frames. A very few codes, e.g. the New Zealand [14] and Russian [20] codes, specifically recommend isolating the MI from the RC frames such that the stiffness of MI does not play any role in the overall stiffness of the frame. As a result, MI walls are not considered in the analysis and design procedure. However, construction of such a building with isolated MI wall requires high construction skill and may not be appropriate for the developing nations. Some national codes like the Indian seismic code [9] requires members of the soft story (story stiffness less than 70% of that in the story above or less than 80% of the average lateral stiffness of the three stories above) to be designed for 2.5 times the seismic story shears and moments, obtained without considering the effects of MI in any story. The factor of 2.5 is specified for all the buildings with soft stories irrespective of the extent of irregularities; and the method is quite empirical and may be too conservative and thus have further scope of improvement.

Several researchers in the past addressed the problem from different angles. Research presented in [1] highlighted the importance of explicitly recognizing the presence of the open ground story in the analysis of the complete bare frames.

Fig.1.a Soft story collapse, Los Angles, 1994 [5].

Fig.1.b Soft story failure, Bhuj 2001 [7].

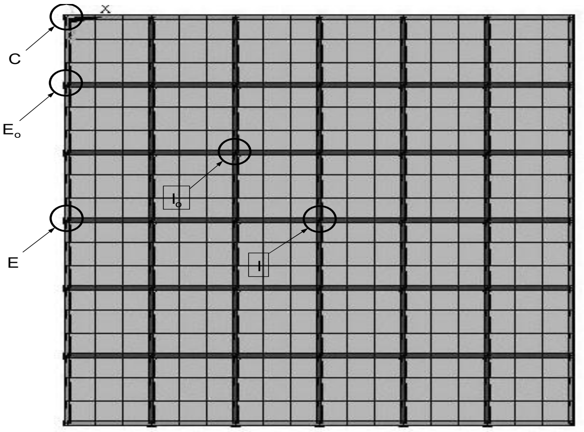

Fig.2.a FE mesh of the building in plan.

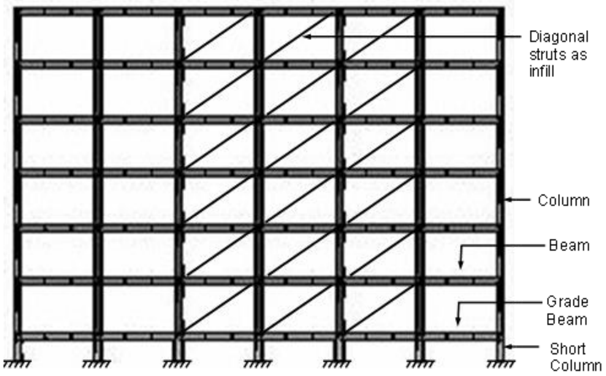

Fig.2.b FE mesh of the building in elevation.

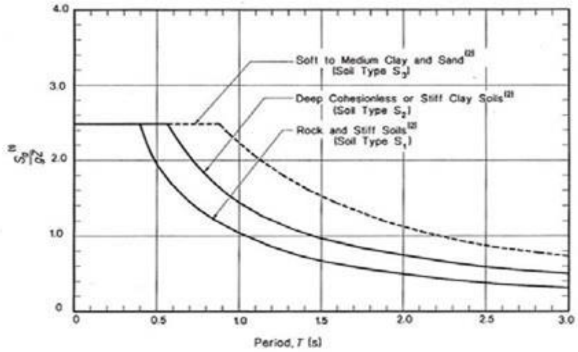

Fig.3 Normalized Response Spectra for 5% Damping Ratio [8].

neglecting the presence of infills in the upper story, is brought out through the study of an example building with different analytical models. A study of six building. The error involved in modeling such buildings as storied reinforced concrete building focussing on seismic response of the soft ground floor based on the results on dynamic response analysis is presented in [13]. Structural behavior of low-to-midrise concrete buildings of various configurations with emphases on dynamic properties, internal energy, and the magnitude and distribution of seismic load has been studied by [8]. Several idealized models were made to represent different structural configurations including pure frame, frames with fully or partially infilled panels, and frames with a soft story at the bottom level, and comparisons were made on the fundamental periods, base shear, and strain energy absorbed by the bottom level between these structures. Some research [12] illustrated that soft story is very dangerous from a seismic point of view, because the lateral response of these buildings is characterized by a large rotation ductility demand concentrated at the extreme sections of the columns of the ground floor, while the superstructure behaves like a quasi-rigid body. A solution was proposed for the preservation of a particular architectonic double soft-story configuration. Thorough numerical analyses showing the effects of masonry infills on the global seismic response of reinforced concrete structures has also been demonstrated by some researchers [5]. Response spectra of elastic SDOF frames with nonlinear infills show that, despite their apparent stiffening effect on the system, infills reduce spectral displacements and forces mainly through their high damping in the first large post-cracking excursion. In the experimental study presented in [19], two single-bay, threestory space frames, one with brick masonry infill in the second and third floors representing a soft-story frame and the other without infill were designed and their 1:3 scale models were constructed according to non-seismic detailing and the similitude law. Evaluation of the potential seismic performance of building with soft story in an area of low to moderate seismicity regions (such as Australia) by a displacement-based method involving a push-over analysis has bee reported in [17]. These past researches demonstrate the poor performance of buildings with soft ground story under seismic loading and advocates against construction of such buildings. Despite such poor performance, construction of multistoried buildings with soft ground story is being continued. It appears that the practical need of an open space to provide car parking space far overweighs the warnings issued by the engineering community and keeping provision of such an open space seems to be unavoidable. Under such circumstances attention should be directed to device some guideline or methodology readily adoptable by practicing designers which shall minimize the danger to some extent. In this paper a numerical finite element analyses have been performed to study the behavior of multistoried buildings having open ground floor with masonry infill on upper floors subjected to seismic loading. A comparative study is made between equivalent static force method (ESFM) and response spectrum

Table I: Properties of the reference RC frame model

Parameter	Values
Modulus of elasticity of concrete	2×10^4 N/mm^2
Density of concrete	2.4×10^{-9} ton/mm^3
Number of story	6, 9 and 12
Size of corner column (mm × mm)	300×300, 325×325, 350×350 for 6, 9 and 12 stories respectively.
Size of interior column (mm × mm)	425×425, 475×475, 550×550 for 6, 9 and 12 stories respectively.
Size of edge column (mm × mm)	350×350, 375×375, 425×425 for 6, 9 and 12 stories respectively.
Size of beam	400 mm × 300 mm
Height of each story	3000 mm
Number of span and bays	6× 6
Width of each bay	5000 mm
Thickness of slab	125 mm
Amount of infill (percentage)	50% of the panels
Thickness of infill	250 mm
Acceleration due to gravity	9810 mm/sec^2
Floor dead load (floor finish etc.)	1.4364×10^{-3} N/mm^2
Floor live load	1.9152×10^{-3} N/mm^2
Partition wall load	2.394×10^{-3} N/mm^2
Load on grade beam	14.61 N/mm
Equivalent strut stiffness, K_0	211000 N/mm

method (RSM). Based on the comparative study some guideline has been developed to be used in conjunction with ESFM to achieve a safer design of buildings with soft ground floor.

II. INFILL IN RC STRUCTURE

Infill of brick or stone masonry are frequently used in RC framed buildings. Although these are primarily intended to serve as partitions, their structural contribution in increasing the lateral stiffness of the frame is long recognized. There are several analytical models of infill available in the literature, which can be broadly categorized as a) continuum models such as the models proposed in [10] and [15] and b) diagonal strut models such as the model proposed in [18]. For the type of work presented in this paper the diagonal strut model of [18] has been found to be more suitable. This model has been successfully used by others [11] for static monotonic loading as well as quasi-static cyclic loading. They have also successfully verified the model by simulating experimental behavior of tested masonry infill frame sub-assemblage.

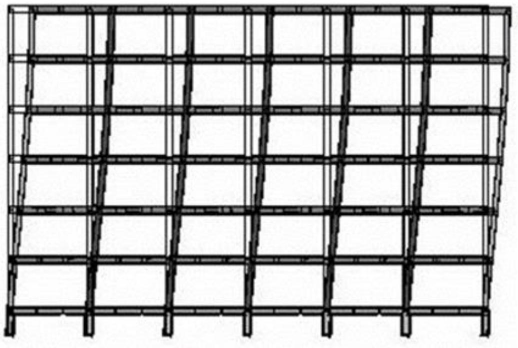

Fig.4.a.1 Mode shape 1 without infill (frequency 0.755)

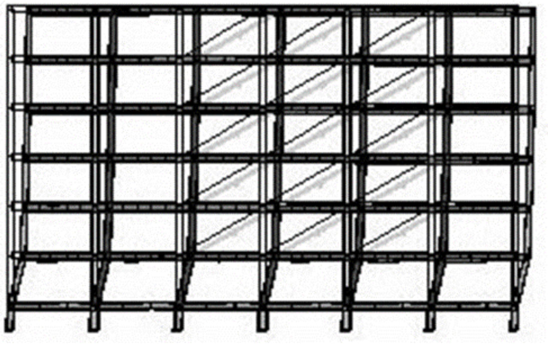

Fig.4.a.2 Mode shape 1 with 50% infill (frequency 1.278)

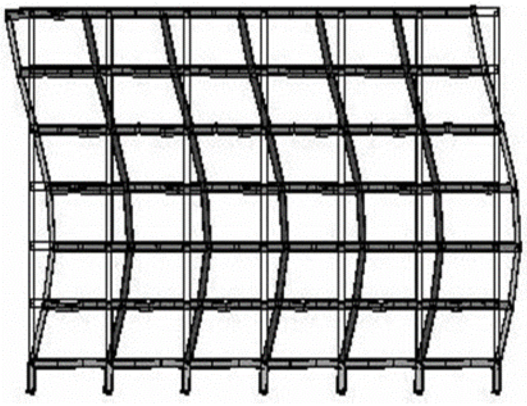

Fig.4.b.1 Mode shape 4 without infill (frequency 2.336)

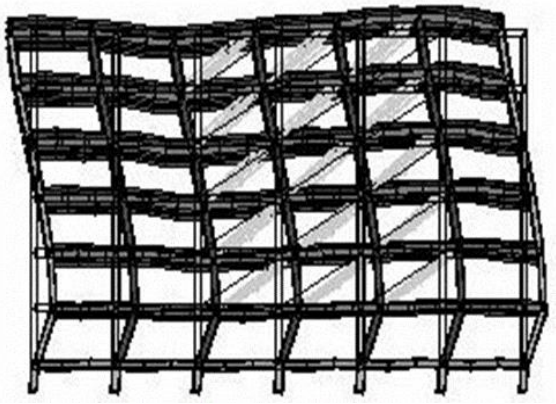

Fig.4.b.2 Mode shape 4 with 50% infill (frequency 4.807)

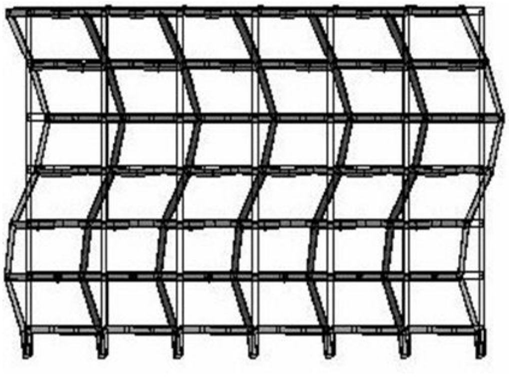

Fig.4.c.1 Mode shape 7 without infill (frequency 4.104)

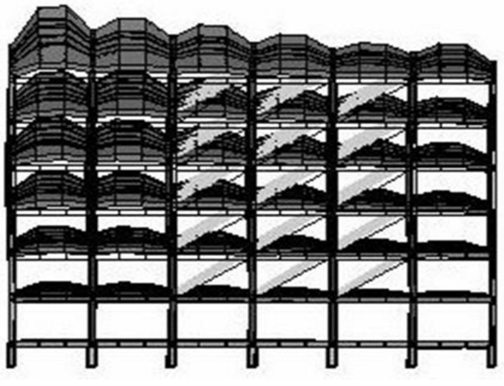

Fig.4.c.2 Mode shape 7 with 50% infill (frequency 7.438)

III. COMPUTATIONAL MODELING

A. Reference model

In this study common two noded frame elements having six degrees of freedom per node has been used for the columns. For beams, similar elements with node offset capabilities have been used to model the web of T-beams (monolithic beam and slab). The floor slab has been modeled using common four noded shell elements. Point mass elements are used torepresent the non-structural dead load like floor finish, partition walls etc. The infills are modeled as diagonal struts using two noded truss elements having only three translational degrees of freedom at node. A plan view of the building is

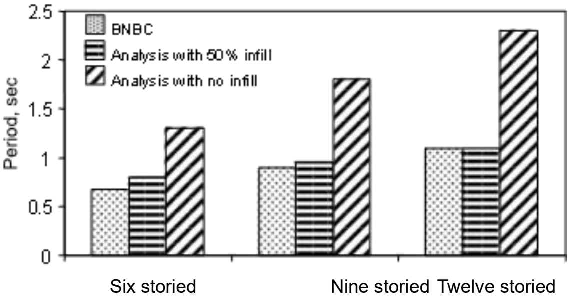

Fig.5. Natural period vs. infill percentage for buildings of different height.

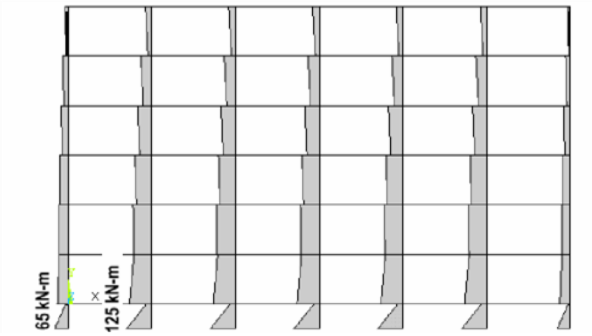

Fig. 6.a Distribution of shear force in columns due to response spectrum earthquake load for no infill condition

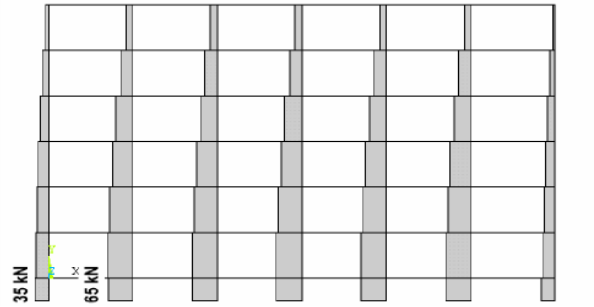

Fig. 6.b Distribution of shear force in columns due to response spectrum earthquake load for 50 percent infill condition.

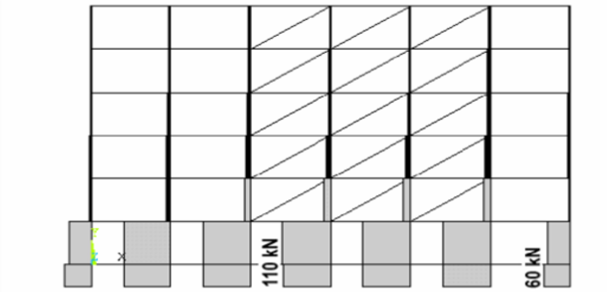

Fig. 7.a Distribution of bending moment in columns due to response spectrum earthquake load for no infill condition.

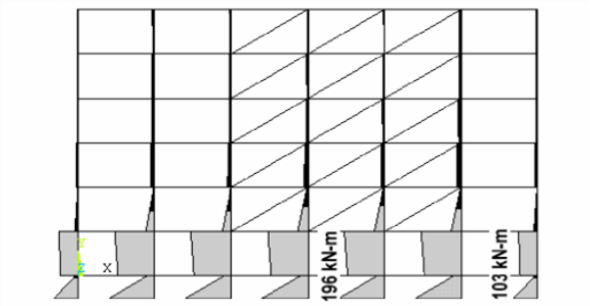

Fig. 7.b Distribution of bending moment in columns due to response spectrum earthquake load for 50 percent infill condition.

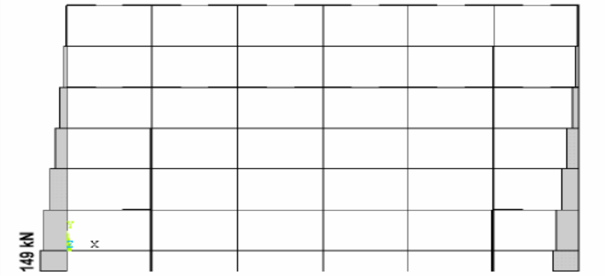

Fig. 8.a Distribution of axial force in columns due to response spectrum earthquake load for no infill condition.

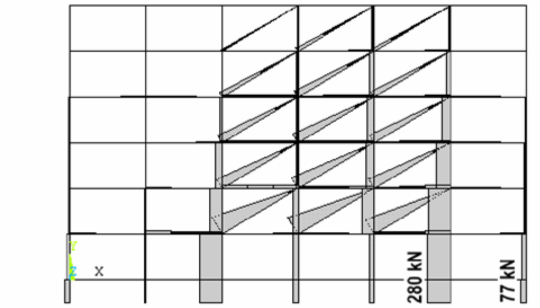

Fig. 8.b Distribution of axial force in columns due to response spectrum earthquake load for 50 percent infill condition.

shown in Fig.2.a and an elevation in Fig. 2.b. In Fig.2.a the columns where forces and moments are studied are identified. The interior columns are identified as I and Io, exterior columns are identified as E and Eo and the corner column is identified as C. The reference RC frame has the properties given in Table I.

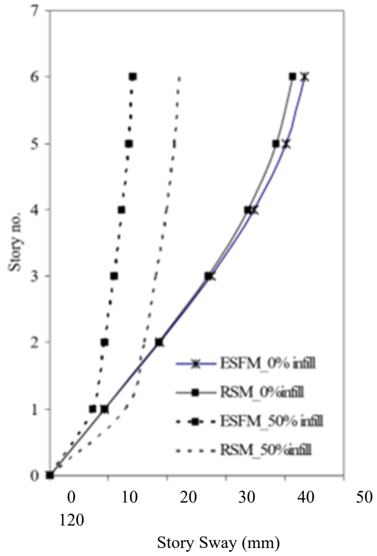

Fig. 9a. Story sway for 6 storied building for 50% infill and for no infill condition

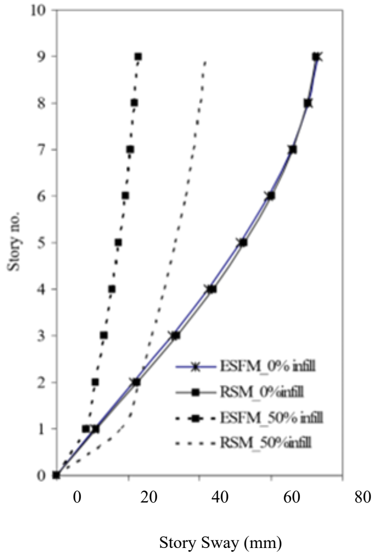

Fig. 9b. Story sway for 9 storied building for 50% infill and for no infill condition

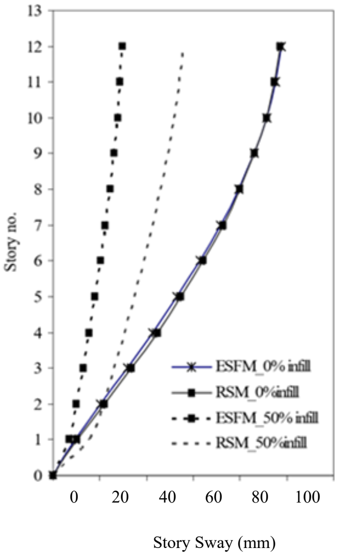

Fig. 9c. Story sway for 12 storied building for 50% infill and for no infill condition

B. Analyses Methods

Both equivalent static force method (ESFM) and response spectrum method (RSM) has been used to study and comparethe behavior of building under seismic loading. Bangladesh National Building Code [7], which is basically same as Uniform Building Code of the USA, has been used for ESFM. Modal eigenvalue analysis is a pre-requisite to response spectrum analysis. In this study, the total number of modes extracted was twice the number of floors. The normalized response spectrum of BNBC as shown in Fig.3 has been used for RSM as a generalized response spectrum. However, it may be mentioned that site specific response spectrum may be more useful to assess the vulnerability of a specific building [21]. In modal analyses, mode shapes are generally obtained in normalized form and thus the results of response spectrum method need to be properly scaled. In the present study the scaling is done as per BNBC guideline by equating the base shear obtained from ESFM to that obtained from RSM for no infill condition. For modal combination CQC (complete quadratic combination) method has been preferred to SRSS (square root of sum of squares) as suggested in [3].

C. Study Parameters

The present study is all about the effect of masonry infill in the upper floors of a building with an open ground floor subjected to seismic loading. In this study the amount of infilled panels is taken as no infill condition (zero percent infilled panels / bare frame) and 50 percent infilled panels on the upper floors. Also to see the effect of number of floors, a 9 storied and a 12 storied building is also studied in addition to a six storied building.

D. Loading Condition

In order to get an insight on the behavior of multistoried RC frames the reference RC frame building has been subjected to earthquake load (E). For earthquake load, two alternative methods, i.e. equivalent static force method and response spectrum method as stated earlier have been used.

IV. RESULTS

A. Mode shapes

As a part of the study mode shapes of different modes of vibration of the building are determined. Though higher mode shapes are more of a theoretical topic, these do indicate the dynamic characteristics of a building. Mode 1st, 4th and 7th mode of the building are visually compared in Fig.4.a.1 through Fig.4.c.2. It can be observed that when infill is present in the building, the mode shape changes significantly. Vibration frequency gets almost double when infill is present in the model. Since frequency is significantly increased, it is quite natural that earthquake force on the building would also significantly increase. Thus it can be said that presence of infill significantly changes the dynamic characteristics of a building.

B. Natural period

Effect of infill on natural period of the building has been studied for six, nine and twelve storied buildings and the results are presented in Fig.5. It has been found that when there is no infill, the period is approximately double the value predicted by code equation [8]. This indicates that FE modeling of RC framed buildings without infill may not be appropriate for dynamic analysis though such modeling may be adequate for static analysis with equivalent static loads for the purpose of reinforcement design. When infill is incorporated in the model, period shortened when the amount of infill is 50 percent of the frame panels. Code equations are generally derived on the basis of the vibration of real building frames, which invariably have infilled panels, during earthquake ground motion. Thus, it can be inferred that in real buildings, about 50 percent of the infilled panels may be structurally active. It may be mentioned here that present analysis is valid for fixed base structures. If base isolation is used in the building for earthquake resistant design then the period of the building shall be different [2]. Also, in the non.linear range, there may be shifting in the natural frequency [16].

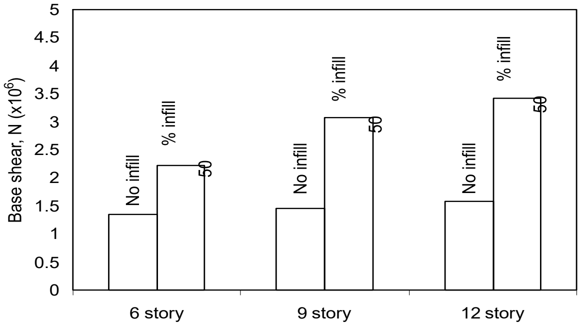

Fig.10 Comparison of base shear for different height of buildings

C. Forces and moment in column

The distribution of shear force in columns of a central frame is shown in Fig.6.a for no infill condition (or equivalent static condition) while the same for 50 percent infilled panels is shown in Fig.6.b. It can be inferred from these figures that when infill is present, column shear near ground floor (soft floor) has a sharp increase compared to the shear force of the frame without infill. The increase in shear is about twofold compared to the no infill condition or equivalent static condition. When the bare frame model is subjected to earthquake load, mass of each floor acts independently resulting each floor to drift with respect to adjacent floors. Thus the building frame behaves in a flexible manner causing distribution of horizontal shear across floors. In presence of infill, the relative drift between adjacent floors is restricted causing mass of the upper floors to act together as a single mass. In such a case, the total inertia of the all upper floors causes a significant increase in the horizontal shear at base or in the ground floor columns. Similar increase in column bending moment is observed as shown in Fig.7.a and Fig.7.b due to similar reason. The axial force of some inner columns increases when infill is present in adjacent panels as can be seen in Fig.8.b. In the present study, infill is modeled as diagonal struts which develop axial force while resisting the relative lateral drift across floors. The vertical component of this axial force gives rise to axial force in interior columns.

D. Effect of variation of infill amount on story sway Sway is plotted for the buildings for different percentage of infill (0% and 50%) of both equivalent static force method and response spectrum method in Fig. 9a, 9b and 9c. The infill act as equivalent diagonal strut which is responsible to increases the story stiffness. Both for ESFM and RSM lateral sway is the highest for frame with 0% infill and it reduces with the increase of infill due to increased stiffness of the story for the presence of infill. Displacement profiles for both ESFM and RSM have a sudden change of slope at first floor level. The inter-story drift demand is largest in the ground story for all the models for both ESFM and RSM. The abrupt changes in the slope of the profile are due to the stiffness irregularity between the ground floor and upper floors. For ESFM, lateral sway is almost same for first soft story irrespective of presence of structurally active infill in the upper stories. In the case of RSM lateral sway of ground soft story increases with the increase in infill percentage in the upper stories; on the other hand, sway in upper stories decreases with increase of infill. The whole building sways like an inverted pendulum with maximum sway concentrated in the soft ground story. The ground story columns act as the pendulum rod while the rest of the building acts as a rigid pendulum mass. As a consequence, large movements occur locally in the ground story alone, thereby inducing large damage in the columns during an earthquake. As RSM considers dynamic inertia force so this pendulum effect is considered here, this is reflected in the nature of the graph. And from this graphs it is also observed that ESFM can not reflect the soft story effect at the ground floor as it shows the same sway for different percentage of infill in the upper floor.

E. Comparison of base shear

Base shear is a very important parameter for earthquake resistant design of buildings. In the present study, shear developed at the base of the building due to response spectrum load for no infill condition and 50% infill condition has been evaluated and compared for six, nine and twelve storied building. The results are shown in Fig.10. Although the result is based on response spectrum analysis, the *no-infill* results also correspond to equivalent static force method. This means that in presence of infill, there is a significant increase in total base shear. For six storied building base shear increases by about 65 percent. For nine and twelve storied building this figure is approximately 113% in both cases. It can thus be said that equivalent static force method is incapable of predicting the magnification of base shear due to the presence of infill in upper floors of the buildings which gives rise to soft story mechanism at open ground floor.

V. CONCLUSION

Earthquake vulnerability of buildings with open ground floors is well known around the world. However, under the present socio economic context of developing nations like Bangladesh, construction of such buildings is unavoidable. In such a situation, an investigation has been performed to study the behavior of such buildings subjected to earthquake load so that some guideline could be developed to minimize the risk involved in such type of buildings. It has been found that code provisions [8] do not provide any guideline in this regard. Present study reveals that such types of buildings should not be treated as ordinary RC framed buildings. It has been found that calculation of earthquake forces by treating them as ordinary frames results in an underestimation of base shear. Calculation shows that, when RC framed buildings having brick masonry infill on upper floor with soft ground floor is subjected to earthquake loading, base shear can be more than twice to that predicted by equivalent earthquake force method with or without infill or even by response spectrum method when no infill in the analysis model. Since response spectrum method is seldom used in practice for the design of such buildings, it can be suggested that the base shear calculated by equivalent static method may at least be doubled for the safer design of the columns of soft ground floor.

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