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Strength and drift demand of columns of RC framed buildings with soft ground story

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Abstract

Earthquakes occurred in recent days reveals the fact that soft storied masonry infilled RC frame buildings are more fragile. In this paper an extensive computational study has been conducted to find out the behavior of such buildings as well as their seismic vulnerability. Finite element models of a few typical multistoried buildings have been subjected to response spectrum as well as equivalent static earthquake loading. Infills on upper floors have been modeled as diagonal struts keeping the ground floor free of infill. Response spectrum analysis shows that the total base shear in buildings as well as design column shear and moments on open ground floor are significantly magnified in presence of infill on upper floors. Study of the sway characteristics shows that the columns of open ground floor demand significantly higher flexibility and ductility. Conventional equivalent static force method is incapable of predicting these behaviors resulting in significant under-design of the columns of open ground floor which led to the collapse of many such buildings in the past earthquakes. Findings of the present study shall lead us to better understanding of the behavior of buildings with open ground floor and safer design of such buildings.

Keywords: RC framed building, infill, response spectrum analysis

1. Introduction

Masonry infill (MI) walls confined by reinforced concrete (RC) frames on all four sides play a vital role in resisting the lateral seismic loads on buildings. The behavior of masonry infilled frames has been extensively studied (Smith and Coul, 1991); (Murty and Jain, 2000); (Moghaddam and Dowling, 1987) etc. in attempts to develop a rational approach for design of such frames. It has been shown experimentally that MI walls have a very high initial lateral stiffness and low deformability (Moghaddam and Dowling, 1987). Thus, introduction of MI in RC frames changes the lateral-load transfer mechanism of the structure from predominant frame action to predominant truss action

(Murty and Jain, 2000), which is responsible for reduction in bending moments and increase in axial forces in the frame members in floors having infill.

In developing countries, especially in South Asia region, construction of multistoried buildings with open ground floor reserved for car parking or other utility services is very commonplace. 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. A typical example of soft story (ground floor) failure is shown in Fig. 1.

Fig. 1. Soft-story collapse

Various national codes can be broadly grouped in two categories - those that consider or do not consider the role of masonry infill (MI) walls while designing RC frames. A very few codes specifically recommend isolating the MI from the RC frames such that the stiffness of MI does not play any role on the overall stiffness of the frame (Standards New Zealand NZS-3101, Russian SNIP-II-7-81). 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 (IS 1893) 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. Arlekar, Jain and Murty (1997) highlighted the importance of explicitly recognizing the presence of the open ground story in the analysis of the building. The error involved in modeling such buildings as complete bare frames, neglecting the presence of infills in the upper story, is brought out through the study of an example building with different analytical models. Mezzi (2004) 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 and 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. Fardis and Panagiotakos (1997) studied, through numerical analyses, the effects of masonry infills on the global seismic response of reinforced concrete structures. 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. Rodsin (1998) evaluated 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.

Table 1.
Properties of the reference RC frame model

Parameter	Values
Concrete modulus of elasticity	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**	300×300, 325×325, 350×350*
Size of interior column**	425×425, 475×475, 550×550*
Size of edge column**	350×350, 375×375, 425×425*
Size of beam**	400 × 300
Height of each story	3000 mm
Number of span and bays	6× 6
Width of each bay	5000 mm
Thickness of slab	125 mm
Thickness of infill	250 mm
Floor dead load	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

*for six, nine and twelve story respectively, **(mm × mm)

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 facility far overweighs the warnings issued by the engineering community and 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 method (RSM). Based on the comparative study some indications have been given to achieve a safer design of buildings with soft ground floor using conventional method.

2. Infill in RC structures

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 by Lourenco *et al.* (1997) and b) diagonal strut models such as the model proposed by Saneinejad and Hobbs (1995). For the type of work presented in this paper the diagonal strut model of Saneinejad and Hobbs (1995) has been found to be more suitable. In this paper, common clay brick infill of about 130mm thickness has been considered in the analysis of model buildings.

3. Computational modeling

3.1 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 to represent the non-structural dead load like floor finish, partition walls etc. The infills are modeled as diagonal strut using two noded truss elements having only three translational degrees of freedom at node. A plan view of the building is shown in Figure 2.a. The elevation of building with various infill percentages are shown in Figures 2.c through 2.f. The reference RC frame has the properties given in Table 1. The Normalized Response Spectra for 5% Damping Ratio is shown in Fig. 2.b.from BNBC (2006).

3.2 Analyses methods

Both equivalent static force method (ESFM) and response spectrum method (RSM) have been used to study and compare the behavior of buildings under seismic loading. 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. 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 used.

3.3 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. The number of panels with infill is varied from bare frame condition (zero percent infilled panels) and 10, 30, 50 and 70 percent of panels with infill on the upper floors. Also, to see the effect of number of floors, a 6 storied and a 12 storied building are also studied in addition to a nine storied building.

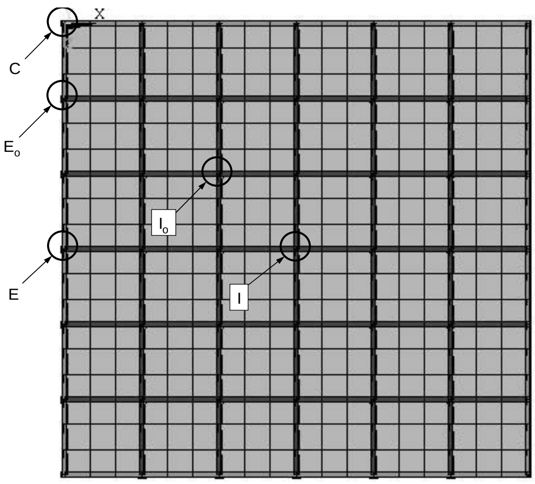


Fig.2.a FE mesh of the building in plan.

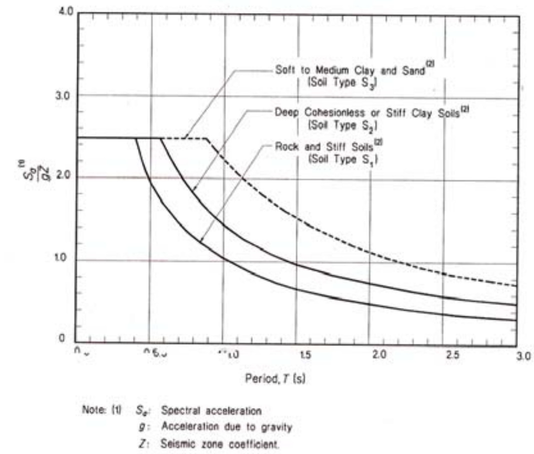


Fig.2.b Normalized Response Spectra for 5% Damping Ratio (BNBC, 2006)

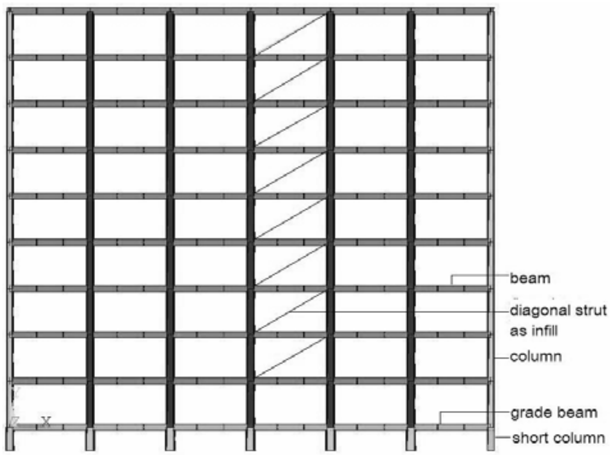


Fig.2.c FE mesh of the building in elevation with 10% infill

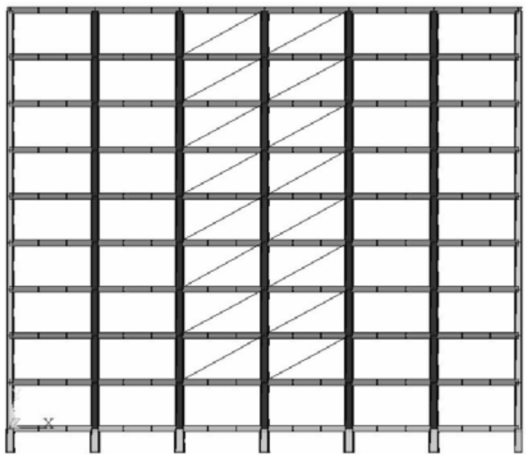


Fig.2.d FE mesh of the building in elevation with 30% infill

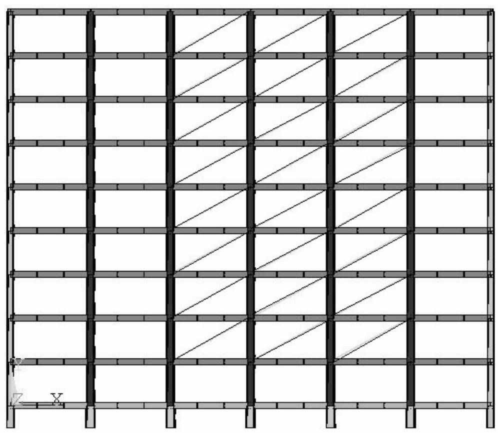


Fig.2.e FE mesh of the building in elevation with 50% infill

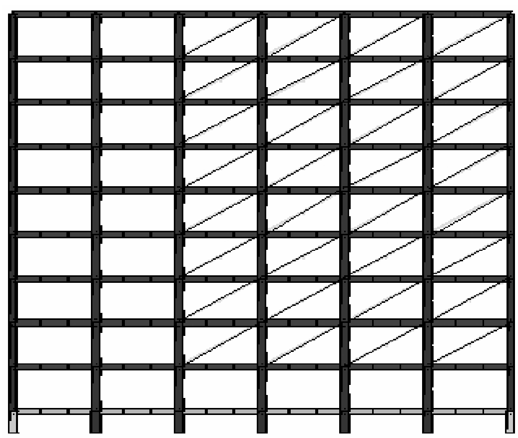


Fig.2.f FE mesh of the building in elevation with 70% infill

4. Results

4.1 Comparison of base shear

Total base shear is a very important parameter for earthquake resistant design of buildings. Total base shear for no infill and also for different amount infill has been evaluated and compared for six, nine and twelve storied building. The results are shown in Fig. 3. Since equivalent static force method is incapable of considering the effect of infill, base shear predicted by this method is approximately same regardless of the amount of infilled panel present on the upper floors of the buildings and the magnitude approximately corresponds to the base shear predicted by response spectrum method for no infill condition. Base shear by ESFM slightly increases as the amount of infilled panels are increased due to the added weight of the infills. However, compared to the total self weight of the building which also includes weight of non-structural infills, the added weight due to increasing number of structurally active infilled panel does not cause significant increase in the base shear by ESFM. On the other hand, in response spectrum method of analysis, as more and more infill is added to the upper floors of the building frames, those floors become more and more stiffer against lateral load giving rise to higher inertia force which ultimately magnifies the base shear. From Fig. 3 it is observed that as percent of infilled panels is inceased from 10% to 70%, base shear increases by about 27% (2.49×10^6 to 2.94×10^6 kN) to 66% (2.49×10^6 to 4.15×10^6 kN) for the six storied building. For nine storied building this magnification of base shear is in the range of 23% to 122%. Similarly, for the twelve storied building the magnification of total base shear is between 20% to 126%. Based on previous study (Amanat and Hoque, 2006), it is logical to assume that in most cases, the amount of infill generally present in the multistoried buildings is about 50% of the panels. For this much amount of infill, the magnification of base shear, when compared to ESFM, is 65%, 107% and 108% for six, nine and twelve storied buildings respectively. Thus, in general, it can be said that base shear is approximately doubled for RC framed buildings with open ground floor. There is no reason why such a building would withstand a moderate earthquake load.

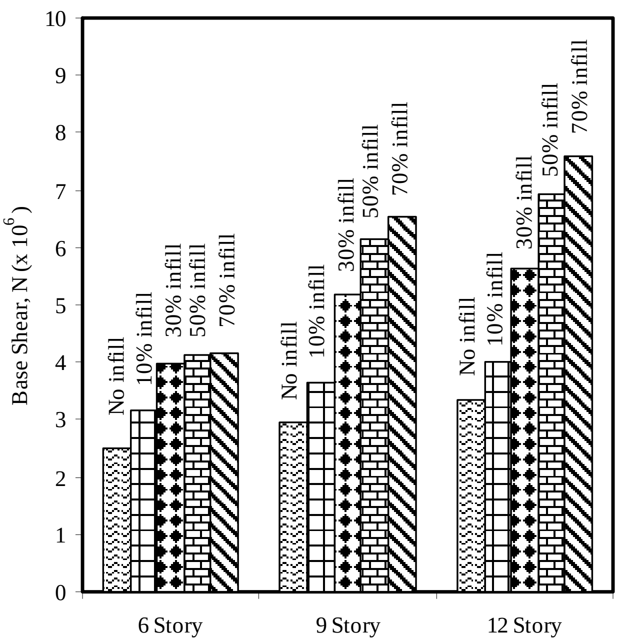


Fig. 3. Comparison of base shear for 6, 9 and 12 storied buildings for different amount of infill.

4.2 Effect of variation of number of infilled panels on story sway

Sway of the buildings is studied for different numbers of infilled panels (0%, 10%, 30%, 50%, 70% and 90% of frame panels) obtained from both equivalent static force method and response spectrum method. The infill act as equivalent diagonal strut which is responsible for increasing the story stiffness and reducing the story sway and drift. Both for ESFM and RSM lateral sway is the highest for frame with 0% infill (model without infill) and it reduces with the increase of infill due to increased stiffness of the story due to 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 at 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 significant difference of stiffness 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 soft ground story increases with the increase in the number of infilled panels in the upper stories. Sway in upper stories decreases with increase of infilled panels due to increased stiffness of those floors. For the six story model, the drift demand increases up to 45% (11mm for no infill condition to 16mm for 70% infilled condition) for ground floor columns as can be seen by comparing Fig. 4.a with Fig. 4.d. For nine storied model, the increase in drift demand is about 77% (11mm for no infill condition to 19.5mm for 70% infill condition) as can be seen from Fig. 4.b and 4.e. Similarly, from Fig. 4.c and 4.f it can be shown that for twelve storied building the drift demand is increased by about 75%. All such results are obtained through dynamic response spectrum anslysis. In presence 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 the 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. The sway characteristics as revealed by response spectrum method clearly shows that the drift demand of columns of open ground floor are much higher than that predicted by conventional equivalent static force method. Thus, the reinforcement design and detailing of such columns must accommodate high ductility to safeguard against collapse.

4.3 Effect of variation of infill percentage on force and bending moment

Four basic loads (like dead load, live load, wind and earthquake load) and their appropriate combined load cases have been considered in the analysis. Envelops for axial force, shear force and bending moment for six storied buildings in both directions are plotted in Fig. 5. These envelops are plotted for both equivalent static force method and response spectrum method with 0% and 50% infill; from which the nature of envelop for other percentages of infill can be predicted.

In case of frame without effective infill, force envelop (bending moment and shear force) decreases gradually from ground story to top story. In this type of frame shear force and bending moment envelop gives almost same value for both static equivalent method and response spectrum method. This justifies the acceptability of equivalent static method for design of earthquake when there is no infill (structurally active) in the structure as conventionally done in the design of buildings.

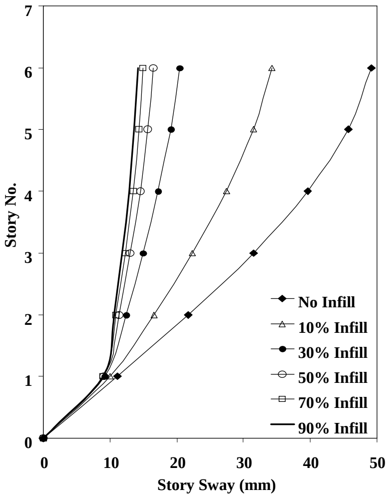


Fig. 4a. Sway of 6 storied building in ESFM

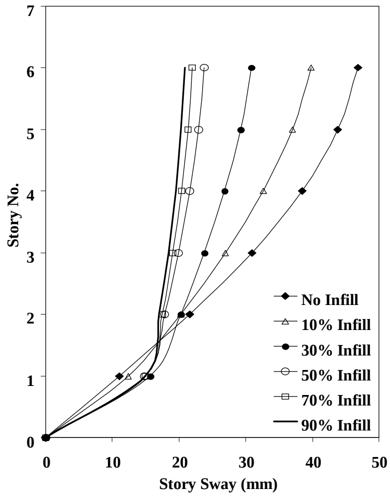


Fig 4d. Sway of 6 storied building in RSM

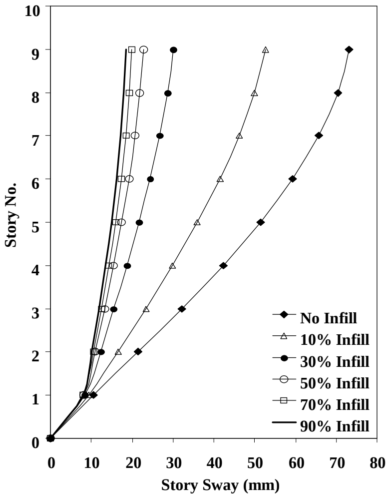


Fig. 4b. Sway of 9 storied building in ESFM

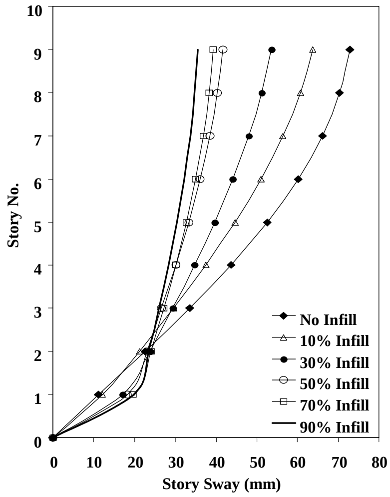


Fig 4e. Sway of 9 storied building in RSM

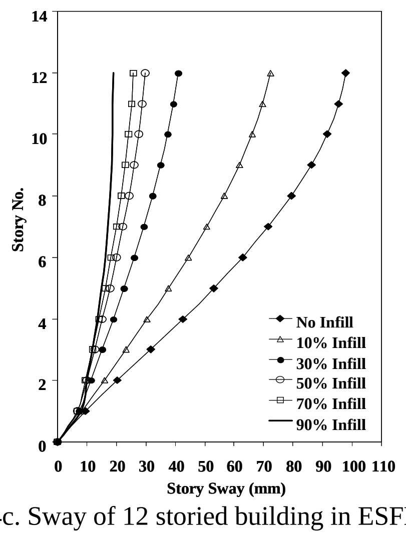


Fig. 4c. Sway of 12 storied building in ESFM

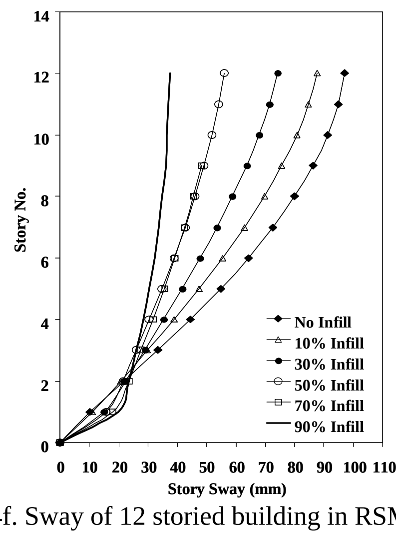
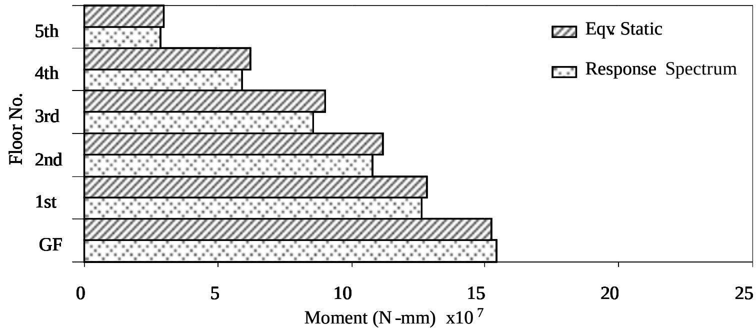
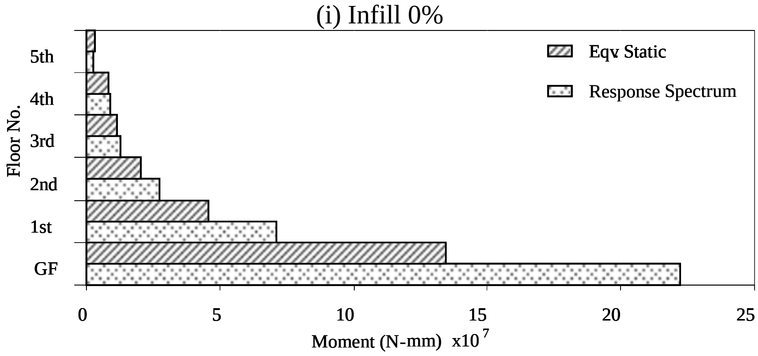


Fig. 4f. Sway of 12 storied building in RSM

As infill is applied to the model, forces (bending moment and shear force) reduces drastically from 1st floor to top floor both in equivalent static analysis and response spectrum analysis. As an example, in first floor of column i (interior, Fig. 2a.) reduction of bending moment is almost 40% after applying 50% infill than in bare infill frame in RSM method for six storied building. The introduction of walls in the upper stories increases the stiffness of the stories against lateral deformation. Consequently forces are carried mostly by strut/truss action through the diagonal struts and shear in columns is reduced. As the force is distributed in proportion to the stiffness of the members, the force in the columns of the upper story, for all the models (except frame with no infill), are significantly reduced due to the presence of brick walls. The infill act as diagonal strut takes care of most of the shear force. As a result the shear force and bending moment decreases in the upper stories due to presence of infill. This is also the reason to decrease the force envelop as infill is applied to the model.

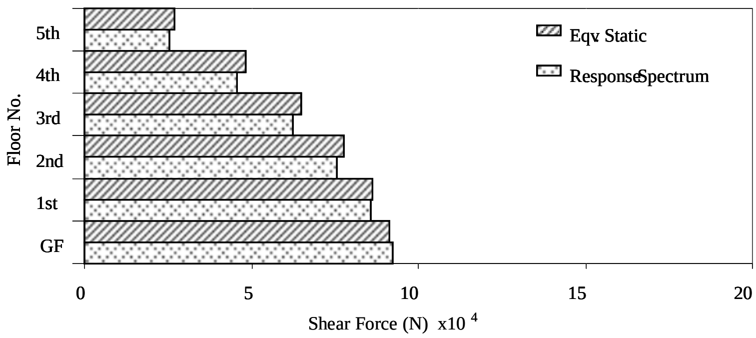


(i) Infill 0%

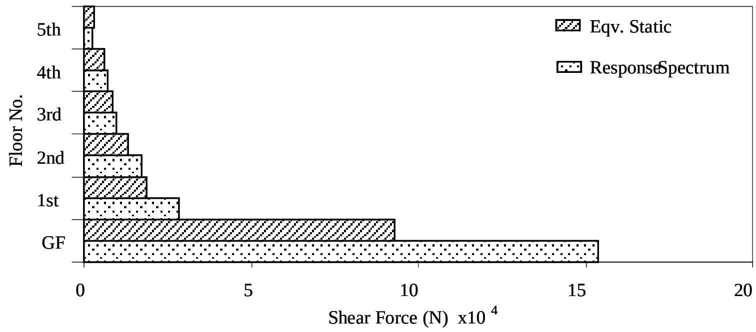


(ii) Infill 50%

Fig. 5a. Design moment envelop *(m_z)* of column *i* for 6 storied building

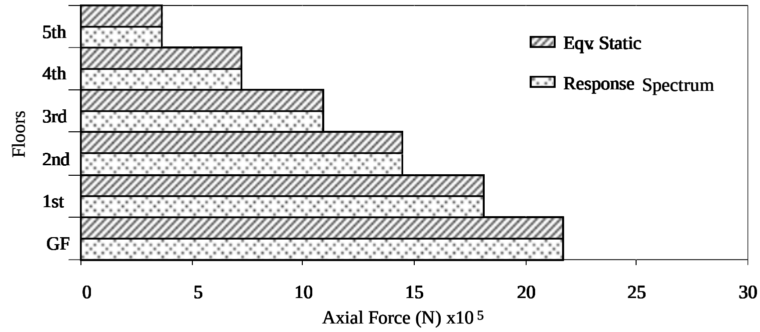


(i) Infill 0%

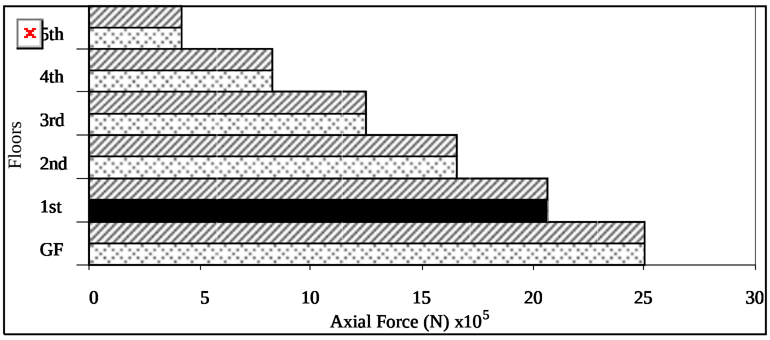


(ii) Infill 50%

Fig. 5b. Design shear force envelop (f_x) of column i for 6 storied building



(i) Infill 0%



(ii) Infill 50%

Fig. 5c. Design axial force envelop of column i for 6 storied building

The bending moment and shear force (strength) demands are severely higher for ground story columns, in case of the soft ground floor buildings. As found in the sway pattern of the buildings major deflection is concentrated in the ground story. So accordingly the bending moment is higher as well as the shear force. If the condition of 50% infilled frames is compared with bare frame the soft ground floor gives 48% higher value of shear and moment in response spectrum method for an interior column of six storied building.

As ground floor shear force and moments become higher and these values are lowered in first floor due to presence of infill so the difference of interstory moment and forces are very large. As an example for case of 6 storied building, at 50% infill condition (see Fig. 2a.), response spectrum gives shear force and bending moment almost three times higher in soft ground floor than in first floor for an interior column.

The axial force envelops are shown in Fig. 6c. which shows that design axial force decreases gradually from ground story to top story. Slight increase in the design axial force for 50% infill condition is observed which is due to the added weight of infill panels. However, no difference is observed between ESFM and RSM results in both the cases. This is due to that fact that load combination case 1.4D+1.7L governs the design axial load envelop. That is why there is no *apparent* effect of infill on axial force envelop. All the five columns of all model buildings considered, shows the similar pattern of axial force envelop. So it may be inferred that infill has no effect on design value of axial force.

5. Conclusions

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. It is, therefore, essential to develop some guideline to safeguard such buildings as much as possible from fatal collapse. It has been found that code provisions such as BNBC or UBC 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. Study of the sway characteristics of RC framed buildings with open ground floor reveals that the columns of open ground floor demands much higher allowance for drift. Drift demand of these columns are, in general, about 75% higher than that predicted by conventional equivalent static force method. Thus special detailing of reinforcement, based on designing the building as special moment resisting frame, may be adopted to meet that high ductility demand of the ground floor columns. However, the authors feel that more research in this area is need,

It has been found that calculation of earthquake forces by treating the common RC framed buildings with open ground floor as ordinary frames results in an underestimation of design force and moment for ground floor columns. 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 design shear and moment 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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