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A rational estimation of earthquake base shear for buildings with soft ground floor

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Abstract
One of the common forms of residential building in South-East Asian Region is reinforced concrete (RC) framed building with parking facility at ground level which is created by not providing any infill masonry at parking floor level. Keeping the ground level free of infill and while providing infill wall on upper floors induces the characteristics of soft floor at parking level, which is vulnerable to seismic load. Generally, structural designers follow the equivalent static force method (ESFM) to calculate the base shear related to earthquake design. ESFM is incapable of considering the structural effect of masonry infill on upper floors and the base shear calculated is generally underestimated. Such underestimation of base shear has resulted collapse of many buildings at parking level in past events of earthquake in many cities around the world. In the present study, randomly positioned structural infill as equivalent diagonal struts have been placed on the upper floors of a building frame, keeping the ground floor free of infill, and the building is then subjected to earthquake load following equivalent static force method as well as response spectrum method. Then the variation in the magnitude of obtained base shear is studied and compared. The effect of variation of different parameters like total amount of infill panels in the building, number of floors, number of spans etc. on the magnitude of base shear has been studied. Results of the study shows that it is the total number of infill panels that affects the base shear, randomness in the distribution of infill panels on the upper floors does not show any significant effect. In presence of infill on upper floors, the base shear obtained from dynamic analysis is found to be magnified when compared with same obtained from static analysis. This magnification is higher for higher number infill panels as well as when the number of floors in the building increases. However, the number of spans does not show any appreciable effect on the magnitude of base shear. Based on the results of the study, base shear magnification factors are suggested so that correct base shear can be estimated for such soft storied buildings following equivalent static force method.

Keywords: Earthquake, seismic, soft story, base shear, infill

1. Introduction

Buildings are classified as having a ‘soft story’ if that level is less than 70% as stiff as the floor immediately above it, or less than 80% as stiff as the average stiffness of the three floors above it. Presence of masonry infill on building floors makes them stiffer causing rigid body movement under seismic vibration. If such buildings have no or little infill at ground level to facilitate car parking or such other functional needs, that floor becomes ‘soft’. The columns at such a floor, not being strong enough, have a good possibility to get damaged to collapse under horizontal vibration due to earthquake.

In RC frame system, the confined masonry infill walls contribute a vital part in resisting lateral seismic loads. In soft story buildings vertical discontinuity occurs due to the application of infill on upper floors keeping the ground floor open. This causes the discontinuity of strength and stiffness between upper floors and the ground floor. The inadequately-braced ground level is relatively less resistant than surrounding floors to lateral earthquake motion. Such soft story buildings are vulnerable to collapse in a manner known as soft story collapse. In reality, the design is done assuming no infill contribution in most of the cases because of the absence of adaptable ideal procedures to account the effect of infill on frame structure. As a result many structures have been collapsed (Fig.1) in many past events of earthquakes.

To develop a logical approach of designing such RC frames the behavior of masonry infill is closely investigated (Moghaddam and Dowling 1987, Smith and Coul 1991, Murty and Jain 2000). Klingner and Bertero (1983) as well as Mehrabi et al. (1996) have concluded that the proper and careful use of infill can significantly increase the strength and stiffness of structure subjected to seismic excitations. To ensure the adequate safety of buildings, the selection of infill location must be such that the torsional and soft story effect is minimized under architectural restrictions. In considering the structural effect of infill in building design, various national codes can be broadly grouped into two categories- those that consider the role of masonry infill (MI) walls while designing RC frames and those that do not consider. 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). Some national codes the Indian Seismic Code (IS 1893) requires members of the soft story to be designed for 2.5 times the seismic story shears.

Many researches in the past were carried out to sort out the problems related to soft ground story. 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. 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. Mezzi (2004) illustrated soft story to be very dangerous from seismic viewpoint as 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 floors, while the superstructure behaves like a quasi-rigid body. A solution was proposed for the preservation of a particular architectonic double soft story configuration. Haque and Amanat (2008, 2009) studied the effect of infill on upper floors of RC framed buildings keeping the ground floor open and suggested some magnification factor for the base shear obtained from equivalent static force method.

Fig.1 Soft story collapse of a building

However in their study, the infill panels were placed on the floors in a regular pattern. In this paper a numerical study based on finite element modeling and analysis has been performed to study the effect of randomly distributed infilled panels on the upper floors, with the ground level having little or no infill. Both equivalent static force method and response spectrum method has been followed to analyze the buildings. Based on the results of the study, an attempt has been made to correctly estimate the base shear of soft ground storied buildings so that practicing design engineers may continue using equivalent static force method but can rationally account for the increased base shear.

2. Modeling of infill in RC structure

Different types of modeling approach were attempted for featuring infill characteristics in RC frame. The first published research on modeling of infill panel as an equivalent diagonal strut method was applied by Holmesh (1961). He assumed that the infill wall acts as diagonal compression strut. Saneinejad and Hobbs (1995) developed a method based on the equivalent diagonal strut approach for the analysis and design of steel or concrete frames with concrete or masonry infill walls subjected to in-plane forces. This method of modeling is being used in this study.

3. Computational Modeling

3.1 Reference model

For beams and columns, common 3D frame element is used having 2 nodes with6 degrees of freedom at each node. For slab, common shell element is used having 4 nodes with 6 degrees of freedom per node. For infills as diagonal struts, common 3D truss element is used having 2 nodes with 3 degrees of freedom per node. The diagonal struts were weightless. To account for the weight of the infill walls as well as other dead loads in the dynamic analysis, mass element is used. A 3D view of the model is shown in Fig.2.1. Normalized response spectrum for 5% damping ratio as per BNBC is shown in Fig.2.2 which has been followed for response spectrum analysis. In the present study, infilled panels were placed in a random pattern. Therefore, to get average results, several different random distribution of infilled panels has been considered and analyzed. The elevation of the central frame of a six storied model for different random application of infill on upper floors and no infill on ground floor is shown in Fig.3.

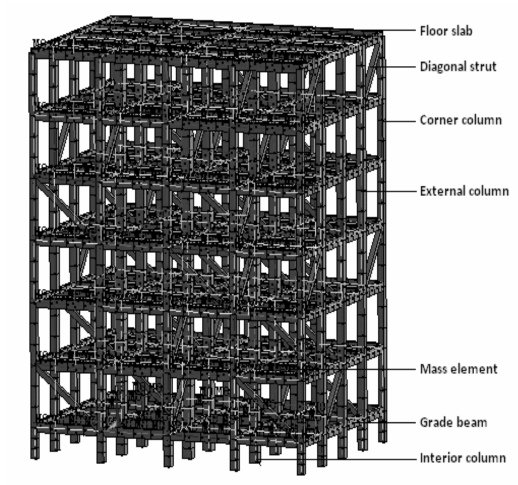


Fig. 2.1 Finite Element modeling of total structure

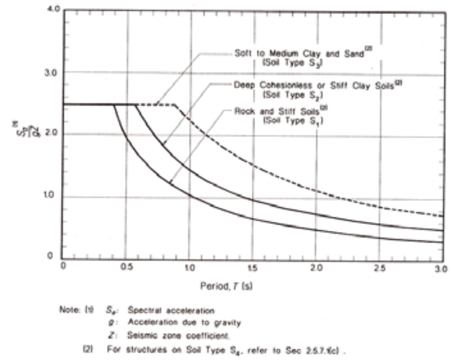


Fig.2.2 Normalized response spectra for 5% damping ratio.

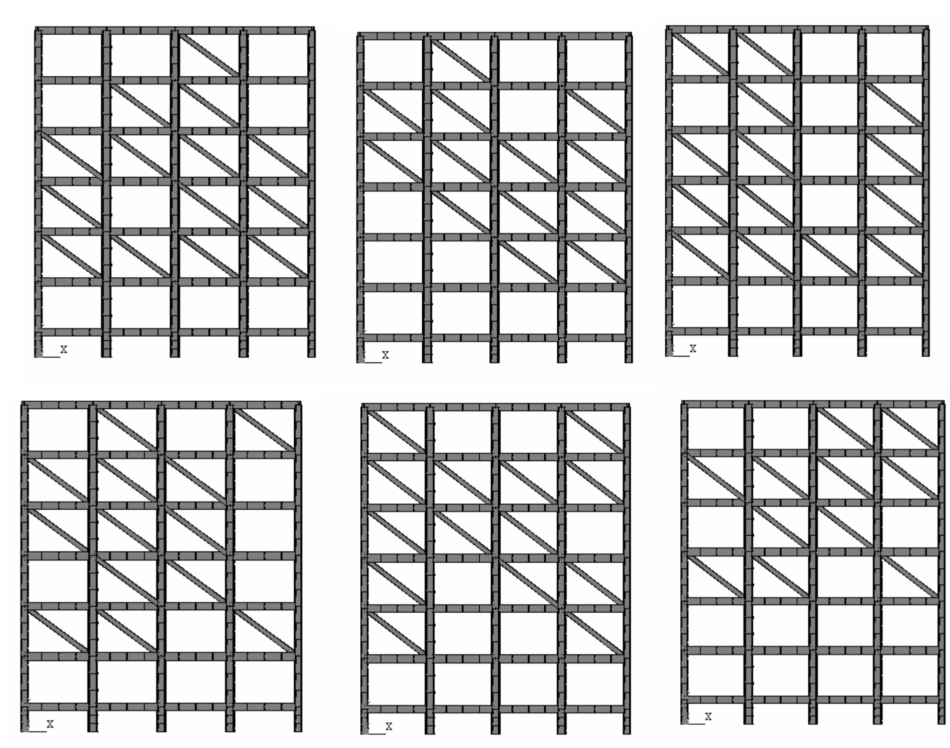


Fig. 3 Different patterns of random infill application (6 storied building)

3.2 Analysis methods

Two methods have been used to compare the results of seismic load: equivalent static force method (ESFM) and dynamic response spectrum method (RSM). Modal analysis is a pre-requisite to RSM analysis. Modal analysis is performed to identify mode shapes while the response for the particular mode has been assessed from the response spectrum. For modal combination, CQC (complete quadratic combination) method has been used.

Table 1
Properties of the reference RC frame model

Parameter	Value/Dimension
Span length	6000 mm
Number of span × bay	4×4
Bay width	5000 mm
Base height	1500mm
Floor height	3000 mm
Number of story	6,8,10 and 12
Slab thickness	150 mm
Floor finish	1.437×10^{-3} N/mm^2
Live load	2.395×10^{-3} N/mm^2
Beam Width	250mm
Beam Height	span/14 (min. 300mm)
Column	as per design requirement (min. 300×300 mm^2)
Gravitational acceleration	9810 mm/sec^2
Concrete properties	
Modulus of elasticity	20000 N/mm^2
Poisson's ratio	0.13
Density	2.4×10^{-9} Ton/mm^3
Unit weight	2.36×10^{-5} N/mm^3
Infill properties	
Density	1.92×10^{-9} Ton/mm^3
Thickness	130mm
Initial strain	150000 mm/mm

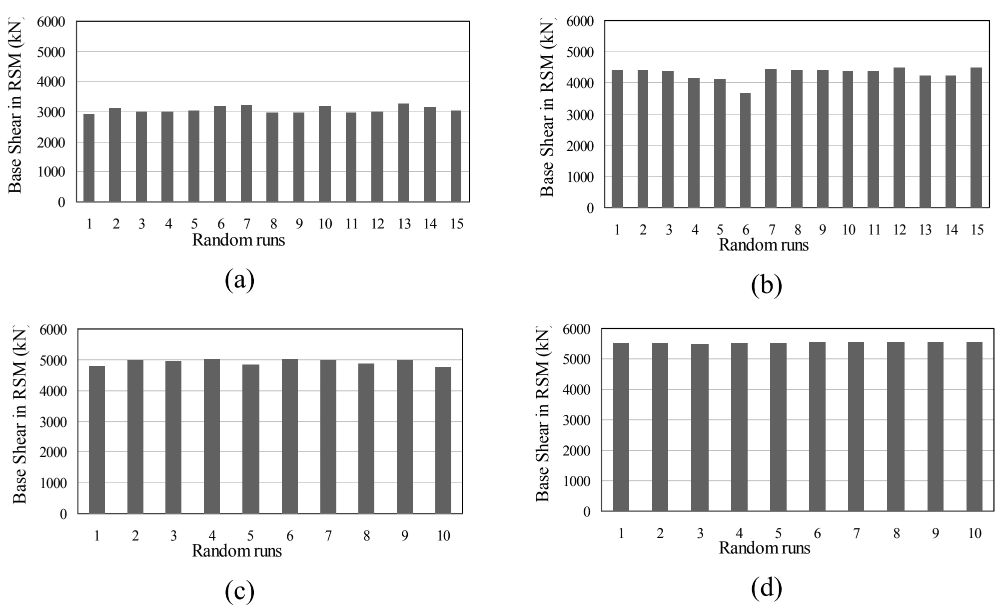


Fig. 4 Variation in base shear value (RSM) of 12 storied building (EQ load in X-dir) for random infill pattern with no infill on Ground floor and (a) 20%, (b) 40%, (c) 60%, (d) 80% infill on upper floors.

3.3 Parametric study

On upper floors, 20, 40, 60 and 80% infill has been applied randomly. The random effect of infill on upper floors has been studied for 6,8,10 and 12 storied buildings with open ground floor and 20% infill on ground floor. To determine the effect of span number and length, span length of 2000, 4000, 6000 and 8000mm is being use with 3, 4, 5 and 6number of spans. Parameters for a reference modeling are provided in Table 1.

4. Results

Seismic characteristics of masonry infilled RC frame with soft ground story have been analyzed using both ESFM and RSM and the results are examined and compared.

4.1 Comparison of base shear

Infill was applied randomly on upper floors with a percentage of 20, 40, 60 and 80. Effect of variation of these parameters on base shear has been studied for 6,8,10 and 12 storied buildings with open ground floor and 20% infill on ground floor. The effect of number of span on base shear has been investigated for similar building systems. Figure 4.a shows base shear obtained for different random distribution of 20% total amount of infill on upper floors of a 12 storied building. Similarly, Figs. 4.b, 4.c and 4.d show random variation of base shear for 40%, 60% and 80% total amount of infill. From these results, it can be observed that for lower amount of infill (20% and 40%) there are some variations of base shears among the different random distribution for a particular amount of infill. For higher amount of infill (60% and 80%) variation on obtained base shear among different random runs for a particular total amount of infill is insignificant. From these figures, it can be said that, for buildings having 50% or more infilled panel, it is the total amount of infill that matters in controlling the magnitude of base shear, the effect of randomness in the distribution of infilled panels is not significant and can be neglected.

In Fig.5, the base shear determined by ESFM is compared with the maximum and minimum base shear determined by RSM for 40% total infilled panels for buildings with different numbers of floors. It is observed that the base shear by ESFM is always underestimated even than the minimum value of base shear by RSM.

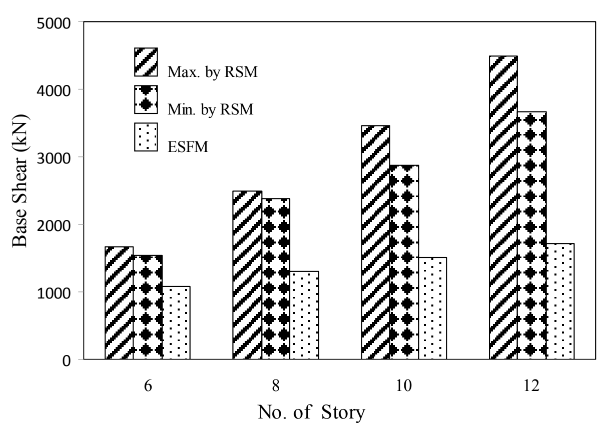
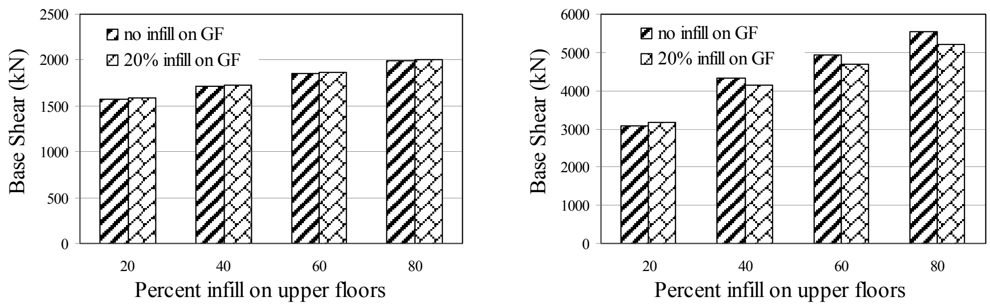


Fig. 5 Comparison of static and dynamic base shear for 40% infill on upper floors and no infill on ground floor.

Figure 6 shows the relative variation of base shear obtained from analysis by ESFM (Fig.6.a) and from analysis by RSM (Fig.6b) for 20% infill and no infill at ground floor (soft floor) level and 20% to 80% infill on upper floor level. It can be observed from the figures that ESFM is incapable of differentiating the effect of the presence of 20% infill at ground floor level when compared to no infill condition as seen from Fig.6.a. When the same building configurations are analyzed using RSM, it is observed that the presence of some infill at soft story level decreases the base shear by about 10% to 15% (Fig.6b).



(a) Static analysis (b) Dynamic analysis

Fig. 6. Comparison of base shear for no infill and 20% infill at ground floor level.

5. Magnification of base shear

From the preceding discussion it is observed that when dynamic analysis is carried out, the structural effect of infill becomes apparent. When compared with the results from the analysis by ESFM, it is observed that the base shear gets magnified. The amount of magnification depends upon the total amount of infill on the upper floors of the building. Randomness in the distribution of infilled panels on the upper floor does not have any appreciable effect on the magnitude of base shear. Let us denote a parameter called *base shear ratio*, β_o, as the ratio of the base shear obtained from dynamic analysis (RSM) to that obtained from static method (ESFM). Thus, $\beta_o = V_d/V_s$ where, V_d is the average base shear by RSM and V_s is the base shear by static analysis (ESFM). For V_d the averaging is done for different random distribution for the same building and for same total percent amount of infill. Here different percent amount of infill panels on upper floors for 6, 8, 10 and 12 storied buildings have been analyzed keeping the ground floor free of infill. The case of 20% infill on ground floor is not considered since this does not cause significant change to base shear by dynamic analysis.

5.1 Effect of number of spans and span length

Results show that (Fig.7) the base shear ratio remains almost constant for 40% infill on upper floors for various number of spans and span lengths for a six storied building. So it isapparent that there is no significant effect of number of span on seismic base shear modification for soft story.As the span length changes, the base shear ratio, β_o, changes by an small amount. This is because of the fact that a change in span length causes a change in the mass of the building without proportionate change in the stiffness of the ground floor against lateral sway since the number of columns remain unchanged making the ground floor little softer or stiffer. This ultimately causes a change in the base shear obtained by dynamic analysis resulting in slightly different values of β_o for different span lengths. Similar results are obtained for 60% and 80% infill condition for 8, 10 and 12 storied buildings which are not presented here for brevity. Thus it can be inferred that the effect of variation of span length as well as number of spans on variation of β_o is not very significant.

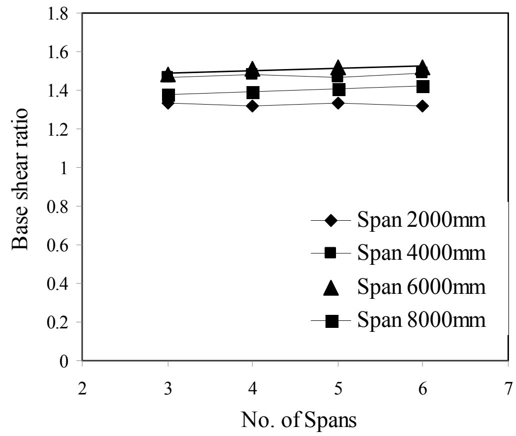


Fig. 7. Base shear ratio for different number of spans for a 6 storied building with 40% infill on upper stories and no infill on GF

5.2 Effect of amount of infill on upper floors

Figure 8 shows the variation of base shear ratio, β_o, for different amount of infill on upper floors for 6, 8, 10 and 12 storied buildings. Except for 20% infill on upper floors, it can be observed that in all other cases the relation between β_o and number of floors is almost a linear one. It is also observed that for 40%, 60% and 80% amount of infill, the relationship between β_o and number of floors remains in a narrow band. From practical experience as well as indicated by other researchers (Amanat and Hoque, 2006), the most probable percent amount of structurally active infill in a real RC framed building shall be between 40% to 60%. Therefore, we can derive an average relationship between base shear ratio, β_o, and number of floors. A simple linear regression suggests that,

Base shear ratio, $\beta_o = 0.175\ N_f\ + 0.5$ where N_f is the number of floor ($6 \leq\ N_f\ \leq 12$).

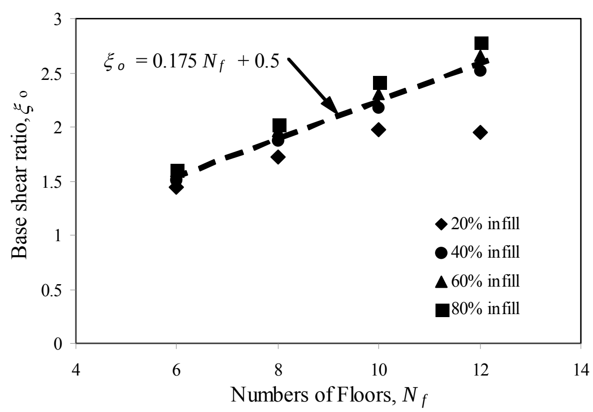


Fig. 8 Base shear ratio, β_o, as a function of number of floors and percent amount of infill

The above simplified expression for base shear ratio, β_o, as a function of only the number of floors of a building, N_f(where $6 \leq\ N_f\ \leq 12$), shall enable a designer to rationally estimate the appropriate base shear for commonly occurring RC framed buildings with open (soft) ground floor using the conventional static force method (ESFM) by simply multiplying the obtained base shear (using ESFM) with base shear ratio, β_o, obtained from the above equation. Thus β_o may be considered as a magnification factor to be applied to the base shear obtained from equivalent static force method to get a reasonable estimate of the correct base shear. This shall lead to a safer design of the columns of buildings with soft ground floor.

5. Conclusions

The general output of the investigation indicates a different characteristic behavior of infilled RC frame with open (soft) ground floor when the structural effect of infill is incorporated in the model and dynamic analysis is performed. The summary of the findings can be tabulated as follows;

1. Static analysis (ESFM) is incapable of capturing the true structural effect of infill in a RC building frame subjected to earthquake force.

2. It is the total amount of infill that affects the base shear obtained from dynamic analysis. Random (irregular) distribution of infill does not cause any significant variation in base shear for commonly occurring range of infill percentage on upper floors (40% and above).

3. Placing an small amount of infill (maximum 20%) on ground floor normally causes not-so-significant reduction on base shear value when compared with the same obtained for fully open ground floor.

4. Base shear ratio does not very significantly with the span number or length. It mainly depends on the number of floors.

A simple expression for base shear ratio as a function of the number of floors has been suggested which may be used a base shear magnifier. The base shear obtained from equivalent static method may be magnified with the suggested base shear multiplier (base shear ratio) to obtain a rational estimation of the base shear for RC framed building with soft ground floor subjected to seismic loading. It is expected that this rational estimation of base shear shall ultimately lead to a safer design of building with soft ground floor.

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