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Investigation of Column Capacity of Soft Storey Building by Pushover Analysis

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Abstract: High-rise buildings with open ground storey have stiffness irregularities as visualized during earthquakes. This paper has carried out an extensive numerical investigation to find out the column capacity of soft storey as well as their seismic vulnerability. Few finite element (FE) models of multistoreyed buildings have been developed and analyzed under equivalent static earthquake loading. Infills on upper storeys have been modeled as equivalent diagonal strut while ground storey is free of infill. Linear and nonlinear analyses are carried on FE models to investigate and compare the column capacity of open ground storey. Pushover analysis shows that the total moment and shear of open ground storey columns are significantly higher than their capabilities. This indicates that the soft ground storey columns are over stressed due to moment and shear magnification in presence of infills on upper storeys. Conventional equivalent static force method (ESFM) is incapable of predicting these behaviors resulting in significant under-design of the columns of open ground storey which led to the collapse of many such buildings in the past earthquakes. Thus, unexpected soft storey failure occurs before reaching to its desired drift. Recently few codes have suggested to magnify moment and shear of columns of soft ground storey by 2.5 times the moment and shear of same column as obtained by conventional ESFM. Finding of this study shall lead us to better understanding of the behavior of high-rise buildings with open ground storey and safer design of such buildings.

Keywords: RC framed building, infill, soft storey, pushover analysis

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1. Introduction

Soft storey configuration is known in architectural term as the open storey. The origin of soft storey configuration is mainly derived from an architecture manifesto named as “Five points for a new architecture” published by Swiss-French architect Le Corbusier, 1926 (Guevara and Perez, 2012). A soft storey is the one in which the lateral stiffness is less than 70% of that in the storey above or less than 80% of the average stiffness of the three storeys above (ASCE 7-16, 2016). This type of building has masonry infill (MI) in the upper storeys whereas ground storey is kept open for services like car parking, lobby, reception corner, etc. Consciously or unconsciously, designers have been encouraged to use the open ground storey in reinforced concrete (RC) frame buildings. In 20th century, this building configuration is exposed to seismic vulnerability.

Masonry infill (MI) is used extensively as infill wall panel of RC buildings. Lack of knowledge on its performance under seismic loading has discouraged engineers from relying on the interaction of infill with the enclosing structural system. MI walls confined by RC frames on all four sides play a vital role in resisting the lateral seismic loads on buildings. In South Asia region, construction of high-rise building with open ground storey designated for car parking and other utility services is very common. Many buildings of Dhaka city generally possess open ground storey with MI in upper storeys as shown in Figure1. These buildings are designed as RC frame building neglecting the effect of MI walls in the upper storeys. Introduction of MI in RC frames changes the lateral-load transfer mechanism of the structure from predominant frame action to predominant truss action (Murty & Jain, 2000).

Figure 1: Imperial Country Services Building, El Centro, California (U.S. Geologic Survey)

Figure 2: Crushed columns at base of Imperial Country Services Building (U.S. Geologic Survey)

Open ground-storey buildings have consistently performed inadequate during earthquakes across the world, for example, during El Centro 1940, San Fernando 1971, Turkey 1999, Taiwan 1999, Bhuj (India) 2001, and Algeria 2003 earthquakes. A significant number of buildings with soft storey have collapsed; for example, as shown in Figure 2, the crushed columns at the base of the Imperial Country Services Building were caused by the 1979 Imperial Valley earthquake in California. Alarming amount of damage to the buildings with open basements for parking has been reported during the Northridge Earthquake, 1994 as well as Great Hanshin Earthquake of Kobe 1995 (Haque, 2007). Despite such poor performance, construction of high-rise building with soft ground storey is being continued. A very few codes do consider the role of MI walls while designing RC frame buildings. Codes like NZS-3101 1995 and SNIP II-7-81 recommend isolation of MI from the RC frame to avoid the effect on overall stiffness of the frame. The Indian seismic code (IS-1893:2002) requires members of the soft storey to be designed for 2.5 times the seismic storey shears and moments as obtained without considering the effects of MI in any storey. The factor of 2.5 is specified for all the buildings with soft storeys irrespective of the extent of irregularities. This method is quite empirical. All these guidelines are too conservative thus need further improvement.

Researchers in the past studied the problem from different angles. Smith and Coal (1999) recognized that the infill wall contributes to the lateral load resisting mechanism of the building. Arlekar et al. (1997) highlighted the importance of explicitly recognizing the presence of the open ground storey in the analysis of the building. The error exists in modeling of such building as complete bare frame thus neglecting the influence of infills in the upper storeys. Mezzi (2004) explained that the soft storey is very dangerous from seismic point of view because the lateral force of the building mostly concentrates at the soft storey columns. Haque and Amanat (2009) studied the strength and drift demand of columns of RC buildings with soft ground storey and illustrated that the bending moment and shear force of ground storey columns are severely high. Rodsin (2007) evaluated the potential seismic performance of building with soft storey in area of low to moderate seismic region by displacement-based method by pushover analysis. Shaiful and Amanat (2007) carried out nonlinear time history analysis of RC frames with MI and suggested magnification of moment and shear of soft storey column. Taskin and Amanat (2020) have studied seismic response of randomly infilled reinforced concrete frames with soft ground floor and showed that the drift and ductility demand for the open ground floor columns are much higher in presence of infill on upper floors.

2. Masonry Infill in RC Buildings

MI is commonly used as partition wall in RC framed buildings and it contributes to the increase in lateral stiffness of the frame which is well recognized by the researchers. Several literatures are available on analytical models of MI but this paper has adopted the concept of Mainstone (1971) where MI is represented by an equivalent pin jointed diagonal strut and derived expressions on MI in-plane behavior. MI properties such as MI in-plane stiffness and strength are calculated following the guidelines of Hossein and Toshimi (2004). Hinges are introduced in the diagonal strut and their properties are calculated following the table 9-6, 9-7 and 9-12 of ATC-40, 1996. Common clay brick infill of about 130 mm thickness has been considered in the analysis of model buildings. Haque and Amanat (2009) have shown that the minimum percentage of infill that can considerably influence soft storey columns is 50%.

3. Computational Modeling

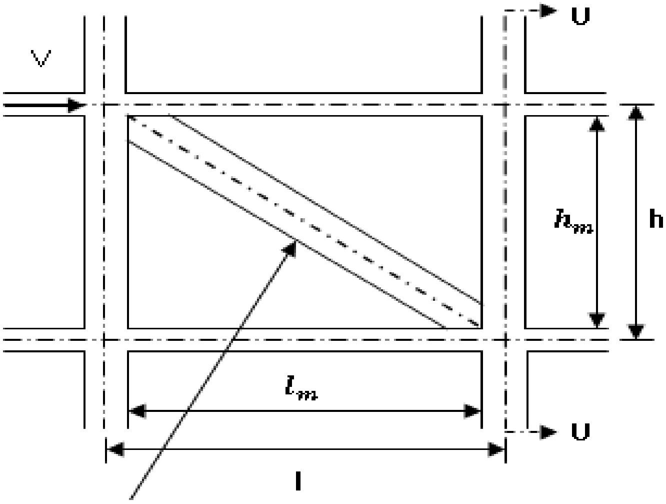
The use of inelastic procedures for design and evaluation is an attempt to help engineers in better understanding as to how buildings will behave when subjected to major earthquakes, where it is assumed that the elastic capacity of the building will be exceeded. This resolves some of uncertainties associated with code and elastic procedures. The main focus of this paper is to introduce the simplified non-linear procedure for the generation of the "pushover" or capacity curve of a structure. Pushover analysis is a simplified static nonlinear analysis method which use capacity curve and demand curve to estimate maximum displacement of a building under seismic loading. Based on this displacement, corresponding moment and shear of ground storey are derived from both bare frame and soft storey frame. These moment and shear force are compared with the designed moment of the same column as obtained by ESFM. Based on the comparative study, some guidelines have been given to conduct safer design of RC building with soft ground storey by conventional method.

3.1 Reference Building Model

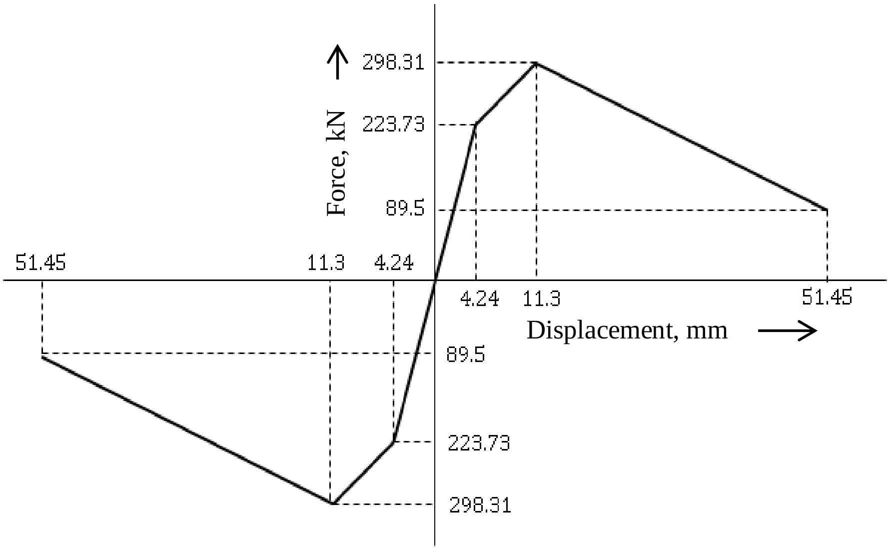
According to ACI committee 442, Special Moment Resisting Frame (SMRF) is generally efficient up to 10-15 storeys only due to their ability to provide ductility and energy dissipation. Taller moment resisting frames are undesirable for earthquake resistance as large inter-storey displacements can cause severe damage to nonstructural components. Detailed Area Plan (DAP) of Rajdhani Unnayan Katripakkha (RAJUK) of Dhaka has proposed to limiting the height of residential buildings within Dhaka city to eight storeys, aiming to manage the population density and enhance urban livability. On the other hand, Taskin and Amanat (2020) has found that the effect of MI in the high rise building above 12 storeys is almost constant. Thus, this study has considered 10 storeys building as the reference building for subsequent analysis. Two-noded frame elements with six degrees of freedom per node are used to represent the columns and beams. The floor slab has been modeled using four-noded shell elements. MI is modeled as diagonal strut using two-noded truss element having three translational degrees of freedom at each node. The force vs. displacement behavior of the masonry infill walls for different percentages of infill is calculated and represented as the strength envelop of MI as shown in Figure 3. The MI wall as an equivalent diagonal strut provides a lateral load-resisting mechanism for the opposite lateral directions of loading. In this study, three types of reference model are developed namely bare frame linear (BFL), bare frame push (BFP) and soft storey frame push (SSFP). BFL is studied linearly by ESFM whereas BFP and SSFP are studied by pushover analysis method. Interior frame and interior column of the reference model are investigated for the column capacity. The elevations of building with and without infill are shown in Figure 4. A plan view of the building is shown in Figure 5. The percentage of infill is varied in terms of cross-sectional area of diagonal strut. The normalized response spectra for 5% damping ratio are considered for this study. The parameters of reference building models are given in Table 1.

Figure 3

Analytical Model and Strength Envelope for MI Walls (Hossein & Toshimi, 2004)



(a) Equivalent Diagonal Strut



(b) Force vs Displacement Graph of Equivalent Diagonal Strut

Figure 4

Elevation Views of Bare Frame and Soft Ground Storey Frame with MI

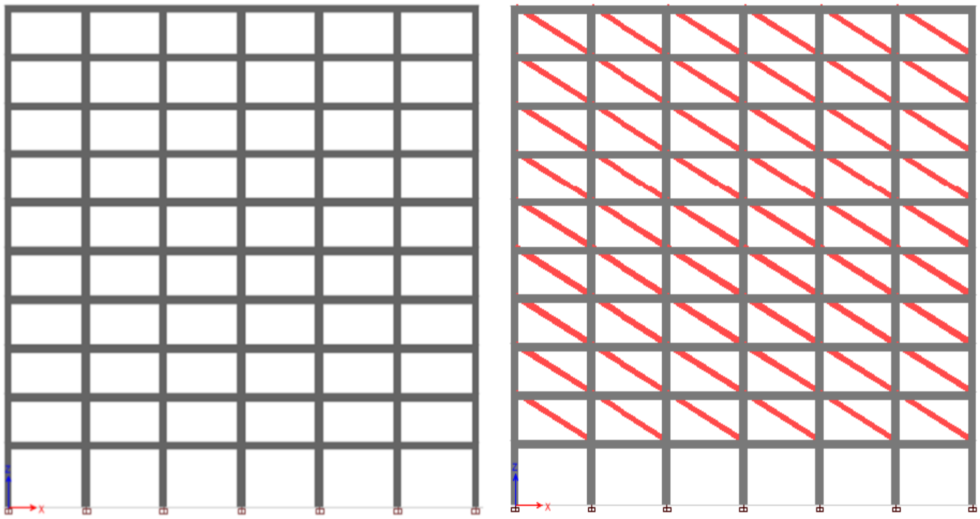


Figure 5

Plan View of the Reference Building Model

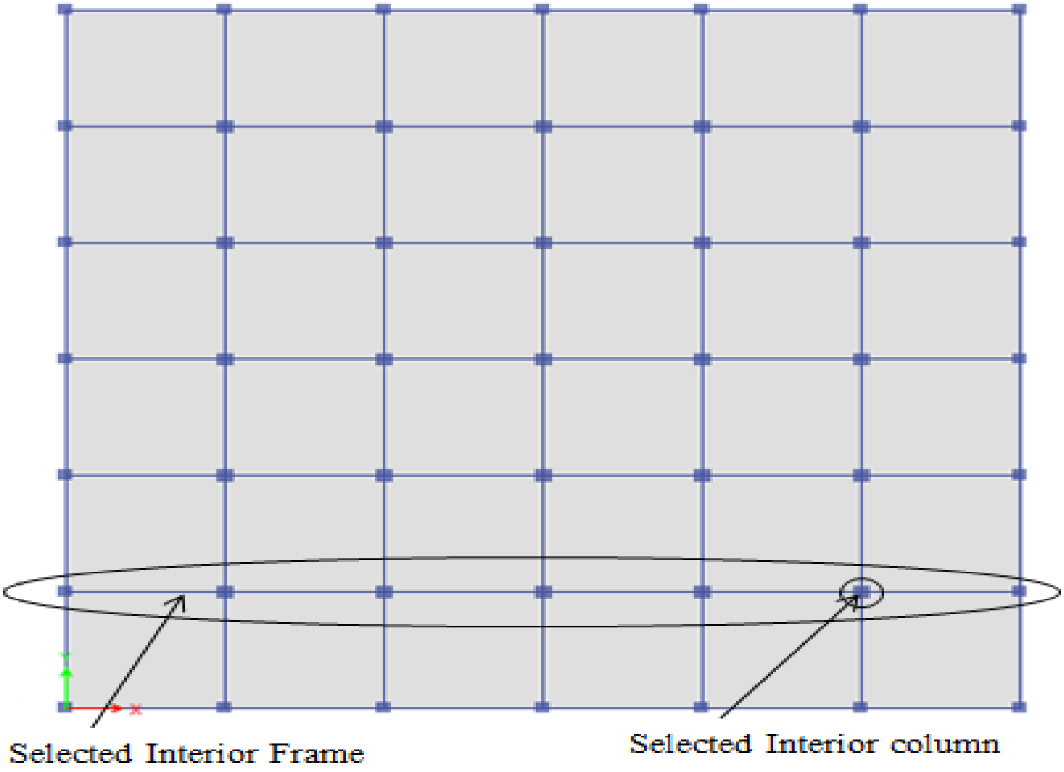


Table 1
Parameters of Reference Building Models

Parameter	**Value**
Number of storeys	10
Span Distance between columns (mm)	5500
Width of each bay (mm)	5500
Height of ground storey (mm)	4000
Height of other storeys (mm)	3000
Size of exterior beam (mm)	575 × 300
Size of interior beam (mm)	500 × 300
Size of exterior column (mm× mm)	500 ×500
Size of interior column (mm× mm)	600 × 600
Size of diagonal strut (mm× mm)	375 × 175
Slab thickness (mm)	125
Floor finish load (KN/m²)	1.437
Floor live load (KN/m²)	1.919
Partition wall load (KN/m²)	3.75
Concrete compressive strength (MPa), f_c'	28
Rebar yield strength (MPa), f_y	415
Poisson's ratio (Concrete)	0.2
Percentage of infill (%)	70
Modulus of elasticity of infill material (MPa)	9350 (BNBC, 2020)

3.2 Analyses Methods

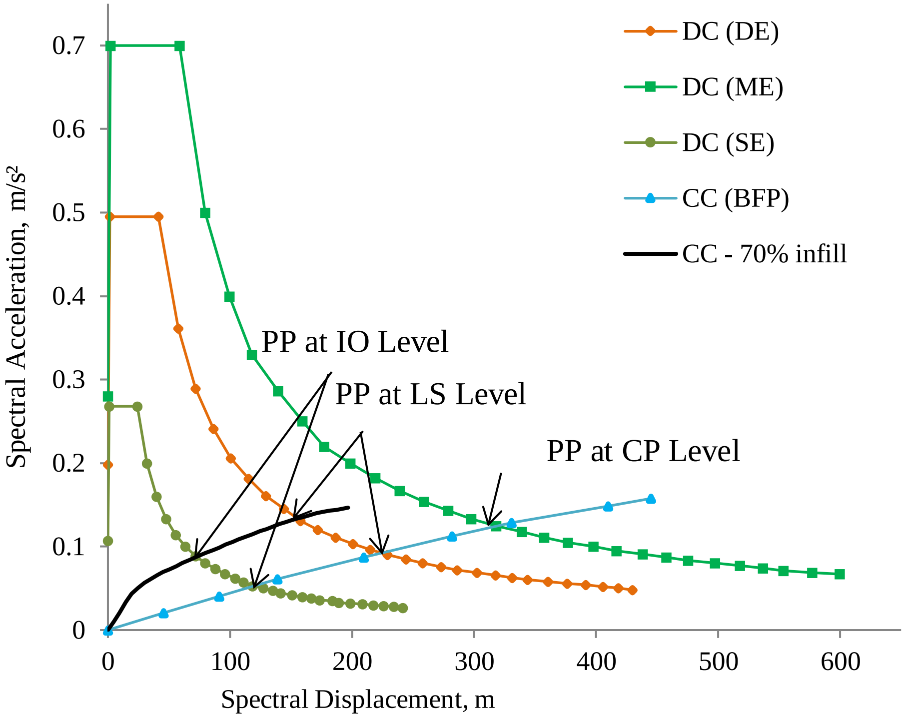
Equivalent Static Force Method (ESFM) and pushover analysis method have been utilized to study and compare the behavior of soft storey columns under seismic loading. Linear ESFM and nonlinear pushover analysis of bare frame model and soft storey model are carried out to visualize the performance of soft storey column till collapse. Linear analysis of bare frame ground storey column is carried out to determine the design capacity of building by ESFM. Nonlinear pushover analysis is carried out to investigate the column capacity of bare frame and soft storey frame.

3.3 Performance Point of Reference Building Model

Performance Point (PP) of the reference building model is derived from the intersection point of its capacity curve and seismic demand curve respectively. Demand curve is generated from the seismic response spectrum of Dhaka city as per the guidelines of ATC 40. The capacity curve of the reference building model is obtained from pushover analysis. The capacity curve of the reference building is plotted on the demand curves and three intersection points are found. The intersection point of capacity curve and demand curve of service earthquake (SE) defines the performance point (PP) of the reference building at immediate occupancy (IO) level. The intersection point of capacity curve and demand curve of design earthquake (DE) defines the PP of the same building at life safety (LS) level. Similarly, intersection point of capacity curve and demand curve of maximum earthquake (ME) defines the PP at collapse prevention (CP) level. Though three PPs are derived but PP at CP level is the most worrying factor for an engineer as it defines full collapse of the building. This study decided to selection of PP at CP level as the overall PP of all investigations. The performance points of different levels are shown in the Figure 6.

Figure 6

Determination of Performance Point for SE, DE, and ME



3.4 Study Parameters

This study focuses on the impact of column capacity of soft storey building due to the presence of MI in the upper stories. Pushover analysis is utilized to develop the capacity curve of building till collapse and decide the performance point. Demand curves are generated for three types of earthquakes namely serviceable earthquake, design earthquake and maximum earthquake. The intersection point of capacity curve and demand curve is considered as the performance point of the reference buildings. In this study percentage of infill varied from bare frame (zero percent infill frame) to 50, 60, 70, 80 and 90 percent of infill on the upper stories. Besides, number of bays and number of spans varied as 2, 4, 6, 8 and 10 to determine their impact on the column capacity of RC reference buildings.

4. Results

4.1 Moment and Shear Force Increase in Soft Ground Storey Column

The nonlinear column capacity, in terms of moment and shear force of bare frame and soft storey frame, is compared with its design capacity under different circumstances as shown in Figure 7 (a) and 7(b). It is observed that the nonlinear moment of soft storey column sharply increases in comparison to the nonlinear moment of bare frame column. Similar phenomenon is also observed for the shear force of soft storey column. On the contrary, shear force of other storey columns decreases rapidly in the upper storeys. Therefore, it is obvious that the moment and shear force of soft ground storey columns are much more higher then the corresponding values of bare frames.

Figure 7 (a)

Moment Diagram of Soft Ground Storey Interior Column for Bare Frame Linear (BFL), Bare Frame Push (BFP) and Soft Storey Frame Push (SSFP)

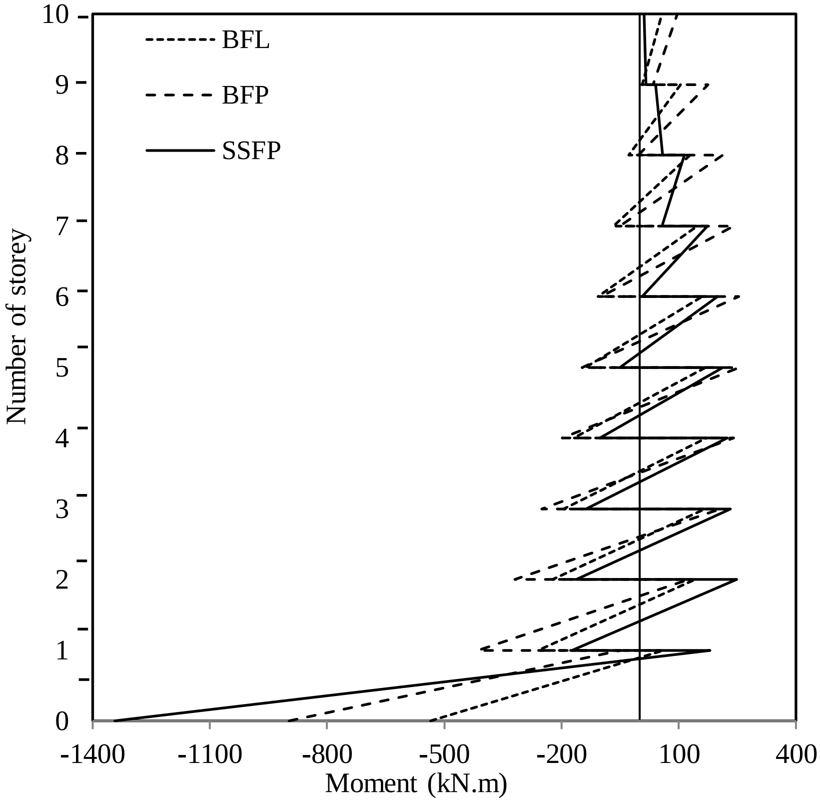
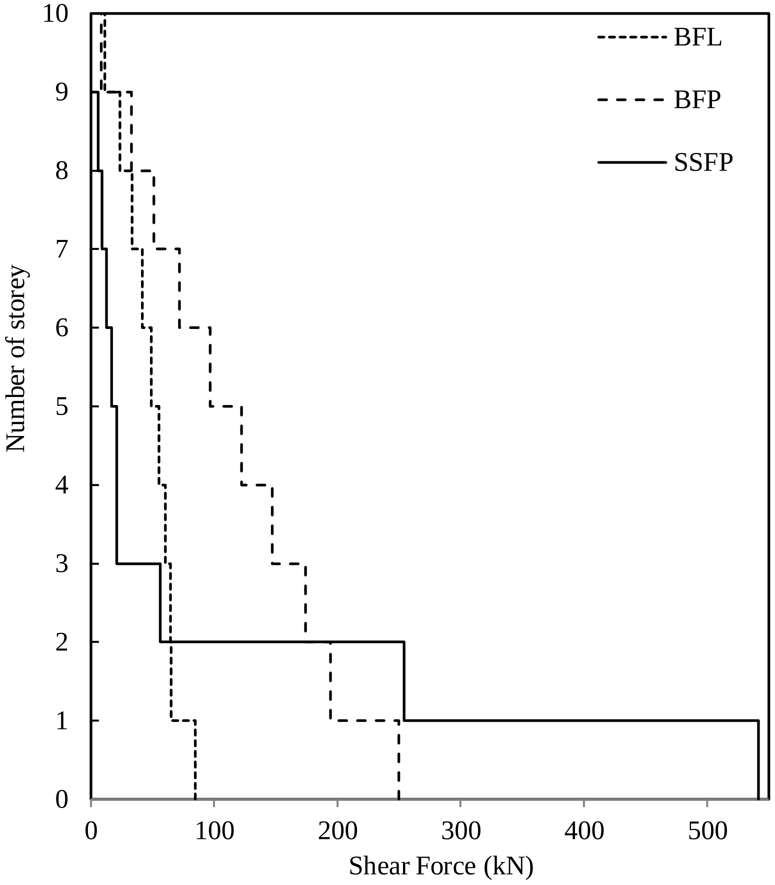


Figure 7 (b)

Shear Force Diagram of Soft Ground Storey Interior Column for Bare Frame Linear (BFL), Bare Frame Push (BFP) and Soft Storey Frame Push (SSFP)

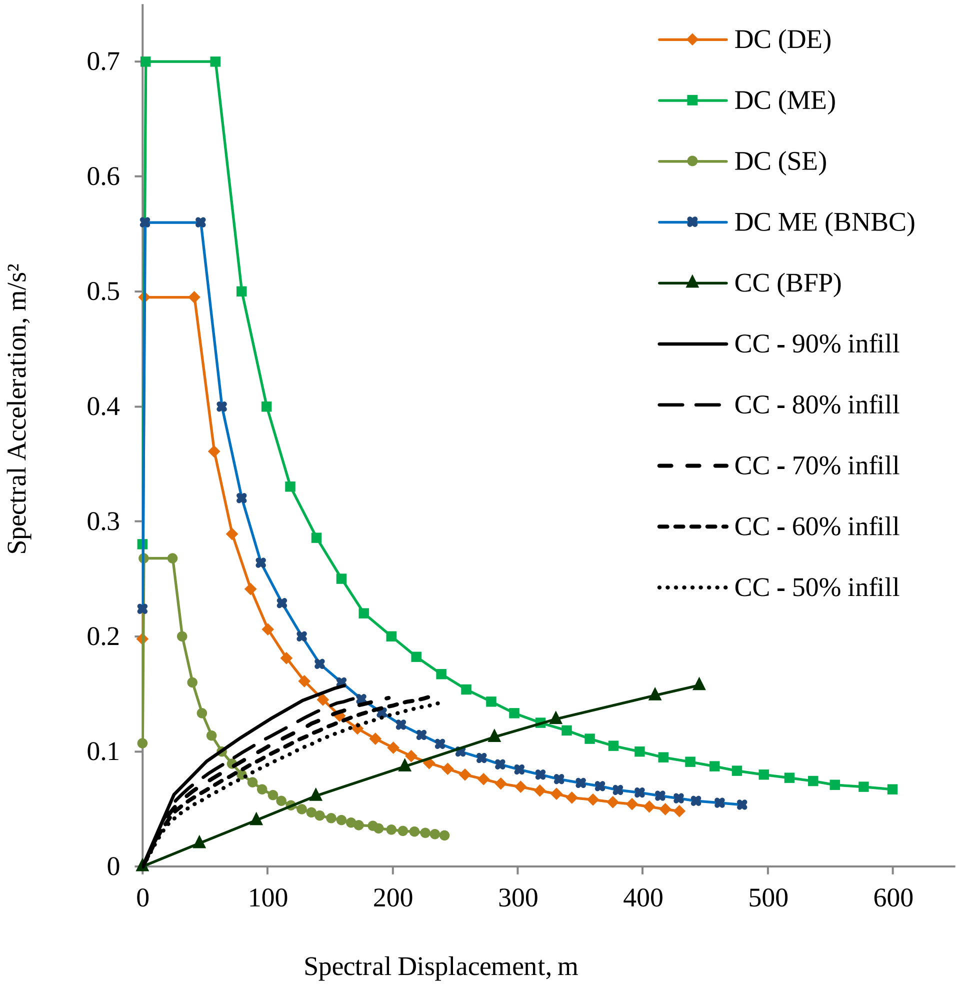


4.2 Effect of Infill on Soft Ground Storey Column

Nonlinear pushover analysis of the reference buildings is carried out for bare frame and soft storey frame with masonry infill. Infill percentages of soft storey frame are varied and pushover curve (capacity curve) is plotted as spectral displacement vs. spectral acceleration (Figure 8). The demand curves of SE, DE and ME are calculated according to the guidelines of ATC 40, 2000. It is proved that the bare frame pushover curve intersects all the demand curves, thus sustaining all types of earthquakes. Soft storey frame with different percentages of MI collapses before reaching maximum earthquake (ME). It is observed that the spectral displacement of soft storey frame decreases as the percentage of infill increases. Because MI acts as equivalent diagonal strut and increases storey stiffness thus reduces the storey sway. Therefore, soft storey buildings are vulnerable to major earthquake.

Figure 8

Pushover Curve and Demand Curve of Bare Frame and Soft Storey Frame Building



4.3 Effect of Infill on Moment and Shear of Ground Storey Column

Reference buildings are analyzed for different percentages of infill for both bare frame and soft storey frame by pushover analysis. Performance point (PP) of bare frame and soft storey frame is determined and corresponding lateral displacements are calculated. The moment and shear force of each frame is calculated for above lateral displacements. Besides, the bare frame is analyzed by ESFM and their allowable drift is calculated as per BNBC, 2020. Moment and shear force of bare frame are calculated based on total allowable drift of the building. The moment of BFL, BFP and SSP are plotted against percentage of infill (Figure 9). It is proved that the moments of BFL and BFP are constant but moment of SSFP increases with the increase of infill.

Figure 9 (a)

Percentage of Infill vs. Moment of Ground Storey Column

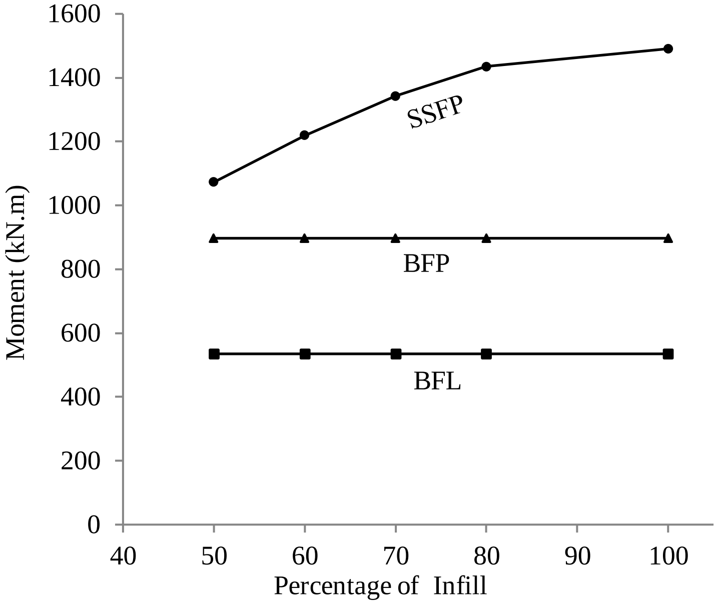
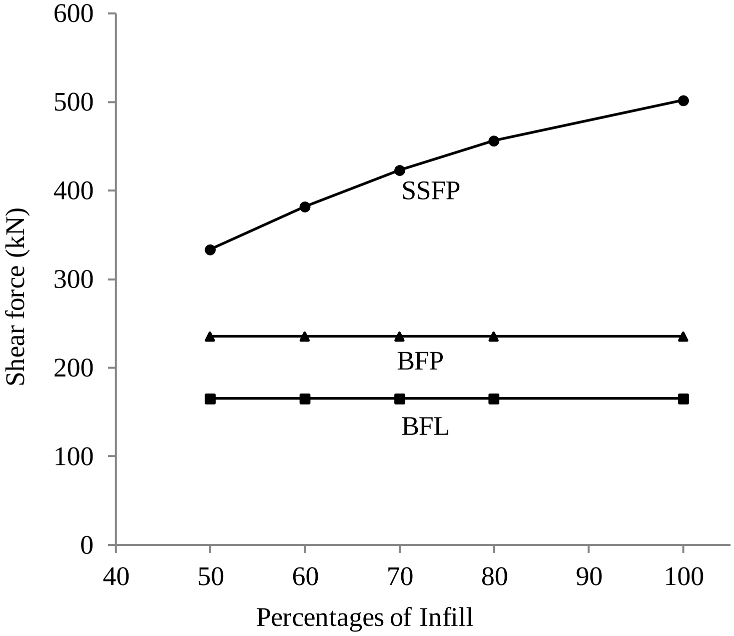


Figure 9 (b)

Percentage of Infill vs. Shear Force of Ground Storey Column



4.4 Effect of Number of Bay and Number of Span on Moment/ Shear of Soft Storey Column

Reference building models are analyzed by nonlinear pushover analysis and ESFM by varying the number of bay and number of spans. In both the cases number of bay and span varied by 2, 4, 6, 8 and 10. It is observed that the moment and shear of all the frames almost remain constant despite considerable variation of number of bay and span. Generally, lateral load of building increases with the increment of its mass but it also decreases as the frame stiffness increases. The lateral load of a symmetric building is equally distributed to each bay; thus, an increase in number of bays does not affect the moment or shear of the columns. A similar phenomenon applies to the increase in the number of spans, as shown in Figure10 and 11.

Figure 10 (a)
Number of Bay vs. Moment of Ground Storey Column

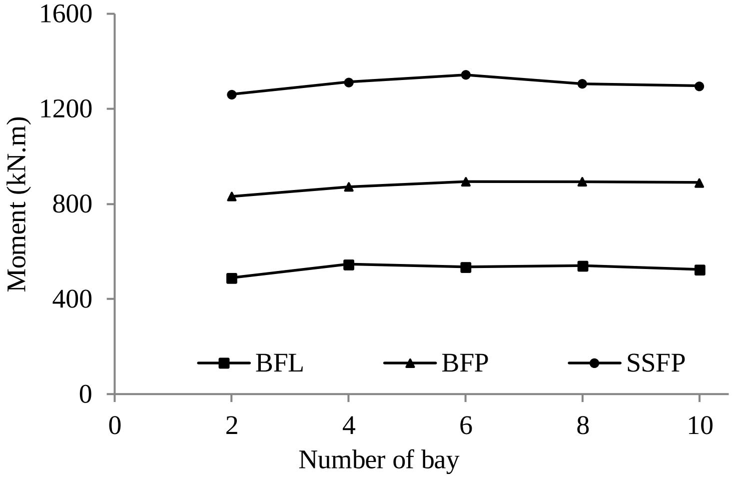


Figure 10 (b)
Number of span vs. Moment Force of Ground Storey Column

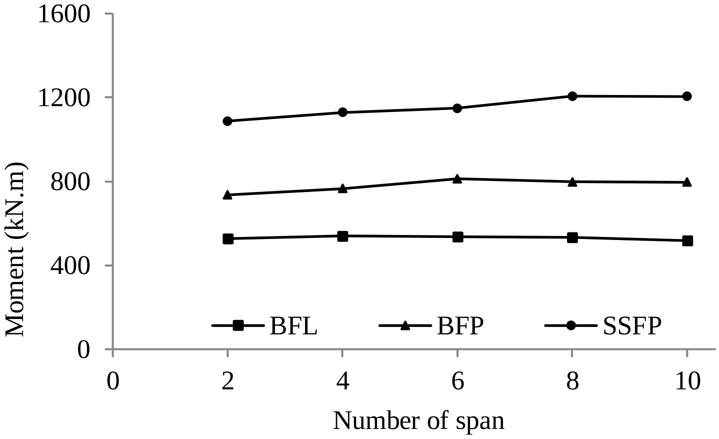


Figure 11 (a)

Number of bay vs. Shear Force of Ground Storey Column

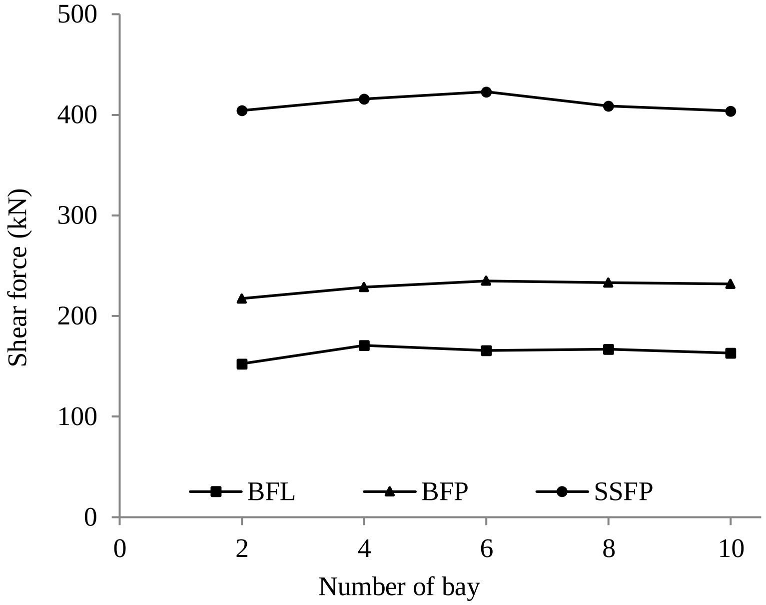
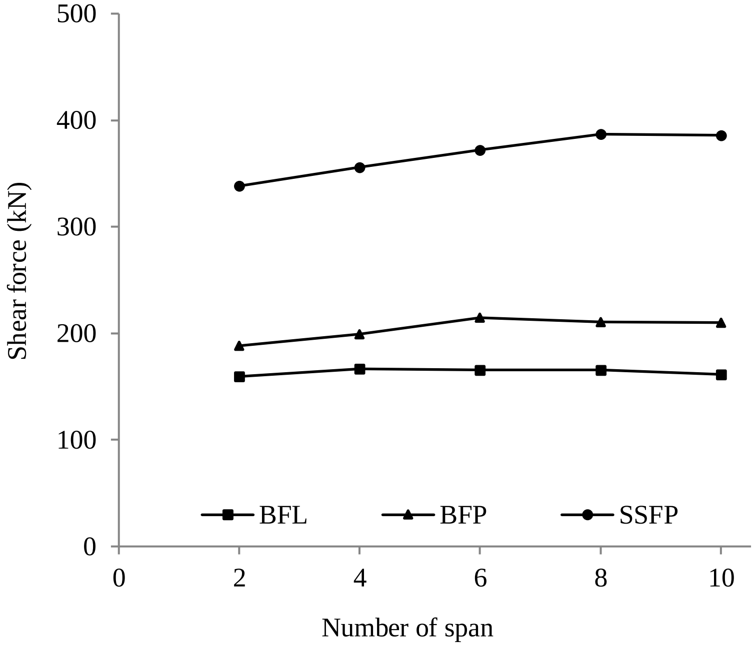


Figure 11 (b)

Number of Span vs. Shear Force of Ground Storey Column



4.5 Moment and Shear MF Due to Variation of Infill Percentage

Magnification factor (MF) of soft ground storey column is defined as the ratio between moments/ shear forces of bare frame and soft storey frame at their performance point under design earthquake. MF of moment and shear force of reference building is studied for different percentages of infill (50%, 60%, 70%, 80% and 100%) by pushover analysis method. Conventionally, buildings including soft storey are designed considering that they will perform within its elastic limit. Yet, structural engineers accept limited nonlinear performance of building during earthquake. This study showed that the bare frame of a RC building performs well despite considerable increase in the column moments. It is also found that the bare frame comfortably sustains all types of earthquakes. In case of soft storey building the situation is different.

This study observed that the soft ground storey column collapses due to development of significant moment during maximum earthquake. To address this issue, some national codes including BNBC, 2020 have incorporated an empirical MF of 2.5 on the designed moment and shear to increase the moment and shear force of soft ground storey column under any circumstances. In reality, this factor varies with the variation of MI.

Figure 12

Percentage of Infill vs. Moment/Shear Force MF of Soft Ground Storey Column

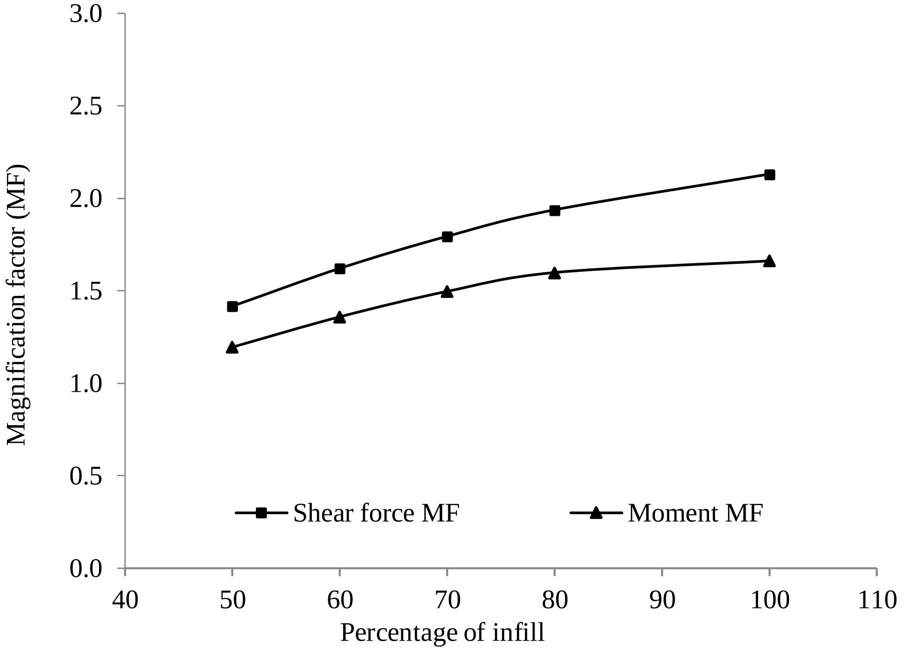


Figure12 shows the variation of MF of soft ground storey column due to variation of infill percentage of reference building models. The moment and shear force MF for soft storey column, as specified in BNBC, 2020 are also plotted in the graph to illustrate the variation. As can be seen from the graph, the moment/shear force MF of soft storey building sharply increases due to the increase of infill percentage. Initially, the rate of change of shear force MF is high, but it reduces at a later stage, while moment MF increases sharply with the increment in the percentage of infill.

MI in the beam-column panel behaves like a diagonal strut which cause increase in storey stiffness thus decreases storey drift. Drift of bare frame is found to be the highest for ESFM and pushover analysis method. In presence of MI whole building moved like an inverted pendulum rod with maximum concentration of moment and shear in the soft ground storey column. The ground storey columns act as the pendulum rod while the rest of the building acts as a rigid pendulum mass. As a result, moment and shear force of ground storey column considerably increases as shown in the Figure 12.

Generally ground storey rectangular column section carries a bending moment equal to its elastic moment of resistance where only the extreme fibers reach yield stress. If the bending moment is increased above the elastic moment of resistance, the area of the section available to resist shear is reduced until it vanishes when the plastic moment of resistance is reached. At this time, the whole section reaches its yield stress. Finally, plastic hinges are formed at both ends of the column. The plastic hinge length is defined by the region where large inelastic strains are developed. In this region, shear resistance is reduced to zero. However, the plastic shear capacity of the column is determined by following equation:

$$\mathrm{V_p} = \frac{2\mathrm{M_p}}{\mathrm{L_e}}$$

Where,

V_p = Plastic shear capacity of ground storey column

M_p = Plastic moment of ground storey column

$\mathrm{L_e}$ = Effective length of column excluding the plastic hinge lengths

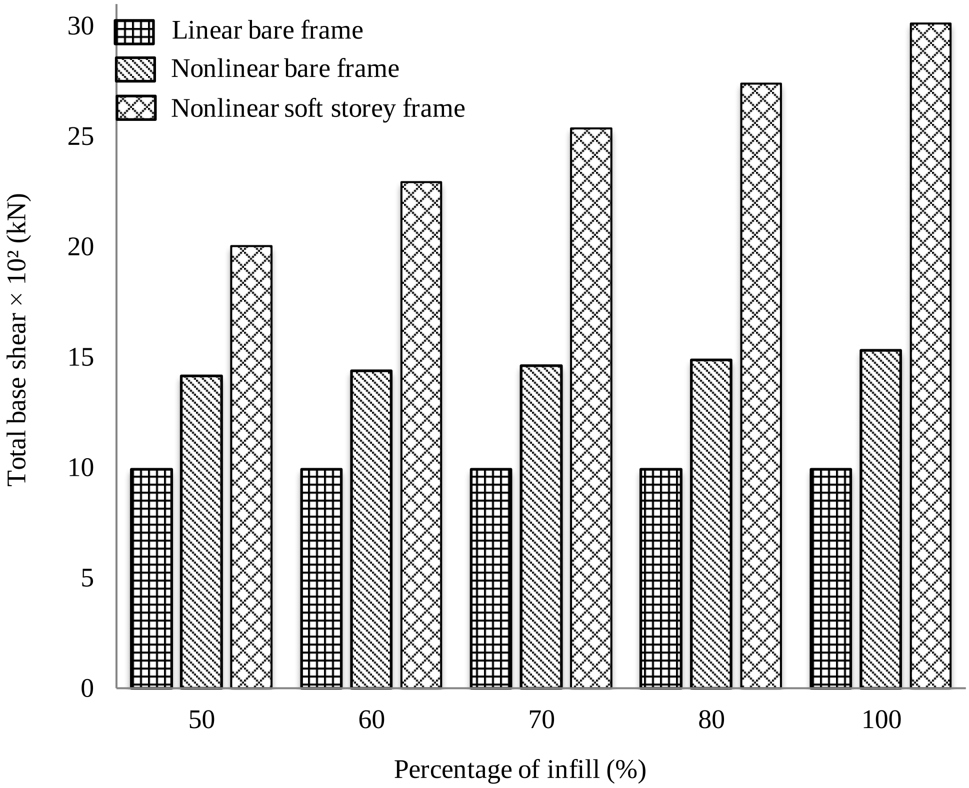
It is observed that the plastic shear capacity of ground storey column increases with the decrease of effective length of column due to the increase of plastic hinge length. Besides, increase of plastic moment of ground storey column also increases the plastic shear capacity of the same column. In Figure 12, it is clearly observed that the plastic shear capacity of ground storey column considerably increases with the increase of plastic moment.

4.5 Base Shear Comparison for Variation of Infill Percentage

The total base shear is a critical parameter for earthquake resistant design of buildings. The total base shear for bare frame (0% infill) and for different amount infill have been evaluated for the reference building. The results are shown in Figure 13. 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 presence of different amount of infill on the upper floors of the buildings. 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. Similarly, base shear of bare frame does not increase significantly due to the presence of infill as derived by pushover analysis method because the MI is added as only self-weight to the building. On the other hand, in response to soft storey building by pushover analysis method, upper storeys become more stiffer with the increase of percentage of infill in the reference building which ultimately magnifies the total base shear.

Figure 13

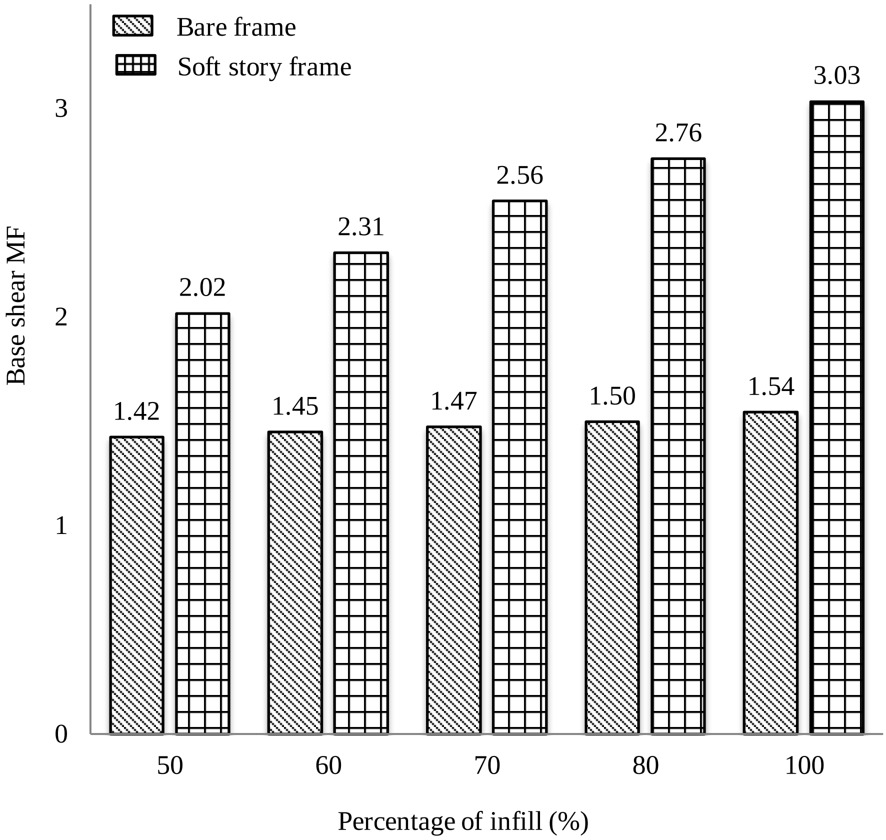
Percentage of Infill vs. Total Base Shear of Reference Building



The base shear magnification is defined by the ratio between the total base shear obtained by nonlinear pushover analysis and the total base shear obtained by ESFM. It is observed that as percentage of infill is increased from 50% to 100%, base shear increases by about 42% to 196% for the reference building as shown in Figure 14. 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 multi-storeyed buildings is about 50% of the panels. Thus, this study starts with a 50% infill percentage and varies it up to 100%. In general, it can be said that base shear of buildings increases substantially at their performance point. It is also observed that the base shear of soft storey buildings with higher percentage of infill become approximately double at their performance point which can be considered in the design practice. However, soft ground storey column of building with MI in upper storeys are significantly vulnerable to any major earthquake and likely to collapse.

Figure 14

Total Base Shear MF with Respect to the Total Base Shear Obtained by ESFM for Reference Building



5. Conclusion

An extensive numerical investigations of RC soft storey building with open ground storey has been carried out to identify their possible vulnerabilities during earthquake. The selected parameters of this study are variation of number of bays, number of spans, and percentage of infill. ESFM and nonlinear pushover analysis method are used for linear and nonlinear analyses of the buildings. Different codes guidelines are also studied and conventional building design practice is discussed. The present study supports the fact that conventional design on multistoried residential buildings with open ground storey are at risk under major earthquake. Besides, open ground storey is an important functional requirement of almost all the urban multi-storey buildings and cannot be avoided. The poor performance of such RC buildings during a strong earthquake is established by this study and remedial measures are proposed to improve their performance. These remedial measures can be applied to soft storey columns to render the building safe.

Moment magnification of soft ground storey column remains almost constant due to variation of number of bay and span as shown in the Figure12 and 13. However, moment MF of the same column varies nonlinearly due to the variation of infill percentage as shown in Figure 11. According to these figures, moment MF of RC building with soft ground storey varies between 1.2 and 1.66 for different percentage of infill. On the other hand, BNBC, 2020 specified moment MF of soft storey column as 2.5 which is much higher than the MF obtained by nonlinear pushover analysis. This paper proposes that the moment MF of soft ground storey column should be 1.5 instead of 2.5. Besides, precise calculation of moment MF can be done using Figure 11.

Shear force magnification of soft ground storey column remains almost constant due to variation of number of bay and span as shown in Figure 12 and 13. However, MF of shear force for the same column varies nonlinearly for variation of percentage of infill as shown in Figure10. Shear force MF of RC building with soft ground storey varies between 1.42 and 2.13 for different percentage of infill as shown in Figure 11. On the other hand, BNBC, 2020 specified shear force MF of soft storey columns as 2.5 which is quite higher than the MF obtained by nonlinear pushover analysis. This paper proposes that the shear force MF of soft ground storey column should be 2.0 instead of 2.5. Besides, precise calculation of shear force MF can be done using Figure11. Base shear of ground storey column of BF and SSF remains constant due to the variation of percentage of infill.

Pushover analysis demonstrates the effect of MI on moment and shear force of soft ground storey columns of any RC frame building. The moment and shear force of these columns increase moderately when they are subjected to nonlinear deformation due to earthquake. This paper has studied the said soft storey effect on these columns and proposed to increase their moment and shear force during conventional design. Designers can determine the MF of moment and shear force of ground storey column by consulting Figure 11, 12, and 13.

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