SEISMIC VULNERABILITY AND RETROFIT OF SOFT FIRST STORY RC BUILDINGS DESIGNED BY BARE FRAME ANALYSIS IN BANGLADESH

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Abstract

Reinforced Concrete (RC) buildings with open ground or soft first story had experienced severe damage during past earthquakes such as the 1995 Kobe earthquake, the 1999 Turkey earthquake, the 2003 Algeria earthquake and 2015 Nepal earthquake. It is very common in Bangladesh to use brick infill masonry as nonstructural separator element. Its usages in upper stories and keeping building's ground floor open result in lateral stiffness difference and cause soft first story state. According to the definition of proposed Bangladesh National Building Code (BNBC 2015 Draft) and American Society of Civil Engineers (ASCE7-05), when a first story has stiffness less than 70% of its upper story, is called a soft first story building. Scarcity of land in Bangladesh has compelled to construct multi storied RC buildings with open ground to be used as vehicle parking, stores or other facilities. The common practice of structural design in Bangladesh is to design the RC building without considering the effects of infill masonry. This practice of bare frame analysis leads to inappropriate estimation of structure's actual capacity and cannot address the problem of soft first stories. There was no conclusive guideline about consideration of soft story effects in the seismic design code of BNBC-1993, which is now included in the proposed seismic design code of BNBC 2015 Draft. This research intent to assess the seismic vulnerabilities of RC buildings having a soft first story but designed by only bare frame analysis, causes behind the collapse of soft first story during earthquakes, seismic performance difference with bare frames and sustainable approach to retrofit them.

In this research, a six storied RC building with open ground system located at seismic zone-III of Bangladesh (Peak Ground Acceleration 0.28g) was analyzed both for bare frame and with considering the infill masonry to represent soft first story state. Infill masonry was represented in the model by equivalent diagonal strut. Seismic performance and vulnerabilities of soft first story were assessed by the Japan Building Disaster Prevention Association (JBDPA) guidelines of seismic evaluation and nonlinear static pushover analysis. Structural performance levels defined by FEMA-356 and BNBC 2015 Draft were used to assess the structure's seismic performance. A sustainable retrofitting approach to upgrade the seismic performance of soft first story and prevent catastrophe during earthquakes was proposed.

This research found that, seismic performance, ductility demand, inter story drift pattern, damage distribution of RC buildings with a soft first story were totally different than the RC buildings designed by only bare frame analysis. Soft first story suffered huge ductility demand, extreme inter story drift change and concentrated in severe damage. Retrofitting of soft first story was found different from conventional RC buildings. A combination of RC column jacketing and adding steel bracing proved to be effective to eliminate stiffness difference and control excessive inelastic lateral drift of soft first story during earthquakes.

Keywords: soft story; lateral stiffness; nonlinear behavior; seismic vulnerability; retrofit

1. Introduction

Bangladesh with population of almost 170 million and population density of 1,145 persons per square kilometer, is one of the most densely populated countries. Scarcity of land has compelled to construct multi storied buildings with open ground to be used as vehicle parking, stores or other facilities. Like other many countries, brick masonry is used in Bangladesh as infill material due to its easy construction, local availabilities and low cost. But, using masonry infills as nonstructural element in the upper stories keeping building's ground floor open results in lateral stiffness difference. According to the definition of ASCE7-05 and BNBC 2015 Draft, when a first story has stiffness less than 70% of its upper story, is called a soft first story building.

The structural configuration with a soft first story proved to be very vulnerable and performed poorly during past earthquakes such as the 1995 Kobe earthquake, the 1999 Turkey earthquake and 2015 Nepal earthquake. Along with many natural disasters like floods, cyclones, drought, Bangladesh is under threat of moderate to strong earthquakes. It is situated in the junction of three tectonic plates known as the Indian plate, the Eurasian plate and the Burmese plate. These plate boundaries are tectonically very active and generates many earthquakes. Bangladesh has been trembled by eight devastating earthquakes having magnitude over 7.0 in the last two hundred and fifty years. Figure 1 illustrates the epicenters of earthquakes having magnitude greater than 4.0 within and near the territory of Bangladesh from the independence (16 December, 1971 to 13 July, 2018) [1].

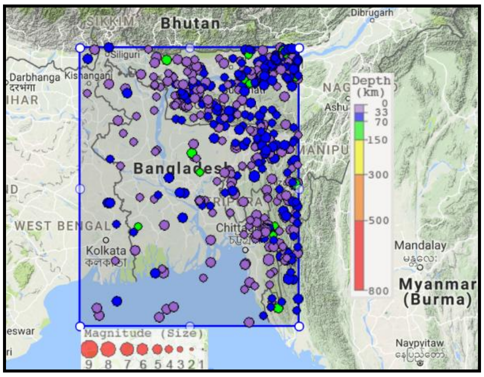


Fig. 1 – Earthquakes within or near territory of Bangladesh, 1971-2018

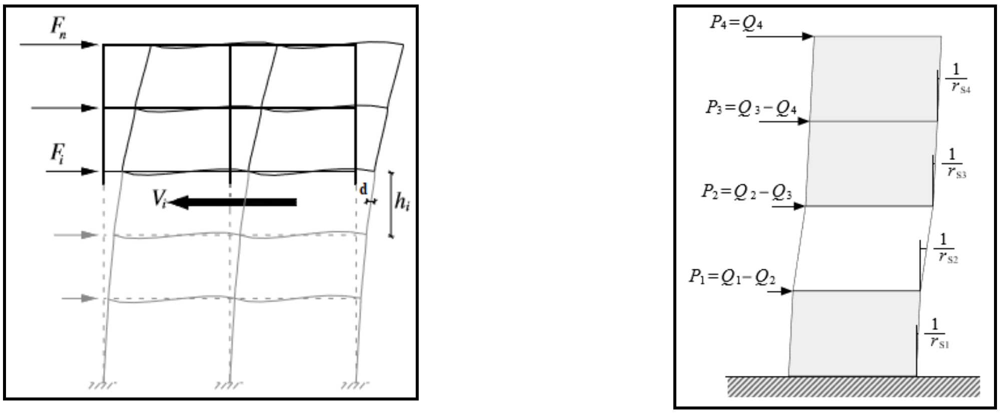
The common practice of structural design in Bangladesh is to design the RC building without considering the effects of infill masonry. This practice of bare frame analysis leads to inappropriate estimation of structure's actual capacity and cannot address the problem of soft first stories. There was no guideline about consideration of soft story effects in the seismic design code of BNBC-1993, which is now included in the new seismic design code of BNBC 2015 Draft. So, in Bangladesh most of the soft first story buildings are designed without considering the soft story effect. But, according to the new code, soft story elements need special attention during design and have to be designed for 2.5 times greater story shear than bare frame [2]. Those structures designed without considering soft story effects are under threat of severe damage or collapse during future earthquakes.

2. Theory and methodology

A six (06) storied RC building in Bangladesh having soft first story designed by only bare frame analysis following the seismic design code of BNBC-1993 (Bangladesh National Building Code) was selected. Nonlinear static pushover analysis was done to understand the progressive damage pattern and to estimate the structure's capacity by capacity spectrum method. Seismic evaluation and structural performance level checking by ATC-40 (Applied Technology Council), FEMA-356 (Federal Emergency Management Agency) and BNBC 2015 Draft were conducted. Sustainable and cost effective retrofitting methods were proposed and reevaluation was conducted to check the structural safety of soft first story. The major theory and concepts used in this research are summarized below:

2.1 Lateral stiffness and soft story

"The lateral stiffness of a story is generally defined as the ratio of story shear to story drift displacement as shown in Eq. (1). However, story drift displacement, defined as the difference in the lateral displacements of floors bounding a story, is affected by vertical distribution of lateral loads, i.e., there is a unique displaced profile for each type of lateral load distribution. Consequently, the lateral stiffness of a story is not a stationary property, but an apparent one that depends on lateral load distribution" [3]. Definition of lateral stiffness of any story is illustrated in Figure 2a (left figure). The seismic code for buildings in Japan defined lateral stiffness (r_s) as the story height divided by the story drift caused by the lateral seismic shear for a moderate earthquake motion (Figure 2b, right). This definition is expressed as Eq. (2).



a) BNBC-2015 Draft and ASCE7-05 b) Seismic code of Japan

Fig. 2 – Definition of lateral stiffness

$$\text{Lateral stiffness} = \text{Story shear (Vi) / Inter story drift displacement (di)} \qquad (1)$$

$$\text{Lateral stiffness (seismic code of Japan)} = \text{Story height / Inter story drift} \qquad (2)$$

According to the definition of BNBC 2015 Draft and ASCE7-05 (American Society of Civil Engineers), a soft story is one in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average lateral stiffness of the three stories above irregularity. An extreme soft story is defined where its lateral stiffness is less than 60% of that in the story above or less than 70% of the average lateral stiffness of the three stories above. According to the seismic design code of Japan, the ratio of lateral stiffness of each floor to mean stiffness of all floors must be equal or greater than 0.6. If the condition does not satisfy this criteria, the floor will be called as a "soft story".

2.2 Modeling parameters for non linear analysis

Seismic performance evaluation for RC structures as per displacement, seismic demand and performance criteria needs finite element modeling. As the structures behavior changes after yielding of its components, nonlinear representation of all these elements is necessary. Many computer aided structural analysis softwares are available to conduct the nonlinear analysis. In this research computer aided commercial software "ETABS-2015" developed by CSI, Berkeley, California was used for finite element modeling of RC structure. Lateral load carrying capacity of masonry infill within RC frames is dependent on lots of parameters such as masonry strength, mortar, concrete, reinforcement and properties of RC frames. It is very difficult to represent all the parameters in nonlinear finite element program. So, a simplified method known as equivalent strut method was proposed to represent the infill masonry [4]. This method was used in this research.

Equivalent struts to represent infill masonry consist of three parameters such as: depth, width and thickness of strut as shown in Figure 3. The depth of strut was calculated by Eq. (3). The thickness of strut was considered as same as the thickness of infill masonry.

The equivalent strut width, a, depends on the relative flexural stiffness of the infill to that of the columns of the confining frame. The formula presented in Eq. (4) suggested by Paulay & Priestley (1992) is used to calculate an equivalent strut width as this formula gives good results in comparison with test results.

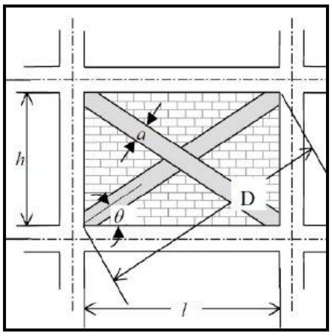


Fig. 3 – Geometry of equivalent strut.

$$D = (l^2 + h^2)^{0.5} \tag{3}$$

where, D is the total depth of strut, l and h are length and height of infill masonry within RC frame.

$$a = 0.25 \text{ x } d_m \tag{4}$$

where, a = strut width and dm= depth of the strut = D.

Two important parameters such as compressive strength of masonry prism (f’m) and modulus of elasticity (E_m) are needed to represent the infill masonry in finite element model. The compressive strength of masonry prism (f'_m) can be calculated by the equation proposed by Paulay and Priestley in 1992 as shown in Eq. (5).

$$f'_m = \{f'_{cb} (f'_{tb} + \alpha f'_j)\} / \{ U_u (f'_{tb} + \alpha f'_{cb})\} \tag{5}$$

Where, f'_{cb} = Compressive strength of the brick, f'_{tb} = tensile strength of the brick (= 0.1* f'_{cb}), f'_j = compressive strength of the mortar, h_b = height of masonry unit, U_u = stress non-uniformity coefficient (=1.5).

The maximum allowable compressive strength of a strut was calculated by multiplying compressive strength by the cross sectional area of the strut. To represent the strength reduction due to opening in the infill masonry, a reduction factor was used to consider the decreased lateral strength. Ghassan Al-Chaar et al. (2003) proposed the following reduction factor formula as shown in Eq. (6) after conducting a large scale experiment [5].

$$\lambda_{op} = 0.6*(A_o/A_p)^2 - 1.6*(A_o/A_p) + 1 \tag{6}$$

Where, λ_{op} is the opening reduction factor, A_o is the area of opening and A_p is the are total panel area.

The modulus of elasticity (E_m) of masonry prisms has been investigated by many researchers. After conducting many experiments, FEMA 273 proposed Eq. (7), Paulay and Priestley (1992) proposed Eq. (8) to calculate modulus of elasticity of masonry prisms of clay bricks.

$$\text{Clay brick, } E_m = 550 * f'_m \tag{7}$$

$$\text{Clay brick, } E_m = 750 * f'_m \tag{8}$$

BNBC 2015 Draft adopted the same formula as suggested by Paulay and Priestley (1992) in Eq. (8) with limiting value of 15,000 N/mm^2 [2].

As after yielding of the structure, the stiffness decreases due to degradation of the strength. When the stress continues to increase in the elements, after half of the ultimate stress, the proportionality of load and deformation is lost. This process of strength degradation is known as formation of plastic hinge. To represent this process in a finite element model concrete axial, shear and moment hinge were used.

2.3 Concept of nonlinear static (pushover) analysis in seismic evaluation

It is predicted that, any structure will not only perform within linear range but also in inelastic range after yielding when subjected to earthquakes. So, inelastic analysis is needed to understand the modes of failure and sequence of collapse when any structure's elastic capacity is exceeded during earthquakes. The analytical procedure of nonlinear static analysis known as "Pushover Analysis" as described by FEMA-356 and ATC-40, represents the plot of progressive lateral displacement as a function of the increasing level of force applied to the structure. By this method base shear versus roof displacement curve can be obtained, which can be converted into capacity curve (seismic acceleration versus seismic displacement). By ADRS (Acceleration Displacement Response Spectrum) format superimposing the reduced code defined response spectrum and the capacity curve, structure's performance in terms of displacement and acceleration is obtained. Seismic performance criteria of FEMA-356 [6], ATC-40, BNBC 2015 Draft were followed in this research. Demand, capacity and performance of the structure were obtained by "Capacity Spectrum Method", and ADRS format described in BNBC 2015 Draft and ATC-40. Typical capacity curve with performance criteria and normalized design acceleration response spectrum as per BNBC 2015 Draft are presented in Figure 4 and 5 respectively.

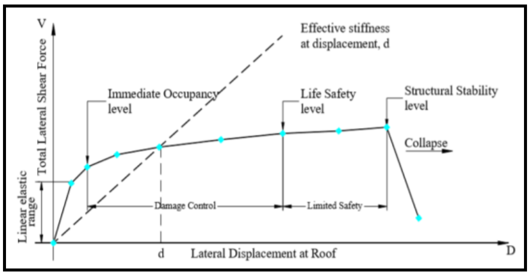


Fig. 4 – Typical capacity curve [7].

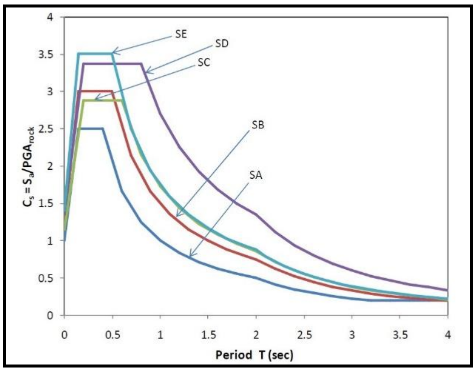


Fig. 5 – Normalized design acceleration response spectrum (BNBC 2015 Draft).

3. Outline of the analyzed building

The analyzed building is a six (06) storied RC building with soft first story located in seismic zone III (BNBC 2015 Draft) and designed by following the building design code BNBC-1993. The open ground is used for parking and brick infill masonry (250 mm thickness for periphery walls and 125 mm thickness for inner walls) with various opening is present in the upper floor. The building was designed by analyzing only bare frames. So, effects of the soft first story on RC building were neglected in this building, as there was no guideline to design soft story in BNBC-1993. Individual footings are used as foundation. Concrete strength of the structural members is 20.68 Mpa and yield strength of the used reinforcement is 415 Mpa. The soil type is SC. As, the building is an office building, its occupancy category is IV. For structural design the of the building following loads are considered: live load 2.873 KN/m^2, floor finish 1.2 KN/m^2, partition wall (typical) 3.0 KN/m^2, partition wall (roof) 1.2 KN/m^2. Architectural plan of ground floor and elevation A-A is presented in Figure 6 and Figure 7 respectively. The column schedule is presented in Table 1.

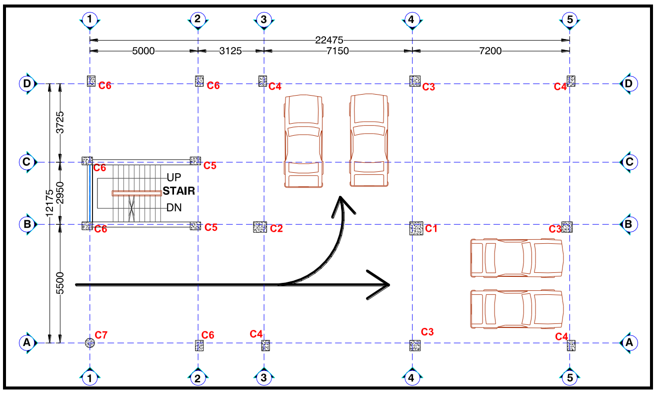


Fig. 6 – Ground floor plan.

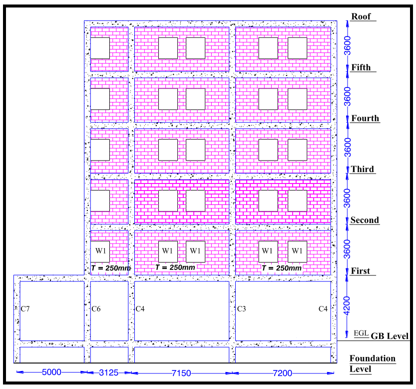


Fig. 7 – Elevation A-A.

Table 1 – Column schedule of the analyzed building.

Column ID	**Column size**		**Reinforcement of column**	
	Below G.L	**Above G.L**	**Ground to 2nd floor**	**3rd to roof**
C1	675 x 675	625 x 625	20-20mm dia	8-20mm + 8-16mm dia
C2	675 x 550	625 x 500	16-20mm dia	16-16mm dia
C3	550 x 550	500 x 500	16-20mm dia	16-16mm dia
C4	425 x 550	375 x 500	16-20mm dia	16-16mm dia
C5	425 x 550	375 x 500	14-20mm dia	4-20mm + 10-16mm dia
C6	425 x 550	375 x 500	12-20mm dia	12-16mm dia
C7	500 Dia	450 Dia	10-20mm dia	Up to porch slab

4. Identification of presence of soft story and inter story drift calculation

Lateral stiffness of any story is the ratio of story shear force to story drift displacement. This is the criteria to define a soft story. The stiffness difference with upper floors for bare frames without and with considering infills is shown in Figure 8. As per the definition of BNBC 2015 Draft and ASCE7-05, the first floor (when masonry infill in the upper floors is considered) has vertical irregularity and can be called as a "soft first story". But in case of bare frame analysis no story has experienced such lesser stiffness difference. Seismic code of Japan defines lateral stiffness as the ratio of story height to story drift. If the ratio of any story's stiffness to average of all story is less than 0.6, then vertical irregularity or soft story is present. The first floor is a soft story when infill is considered in upper floors. But no such condition was observed when bare frame analysis was done (Figure 9).

Pushover analysis was done for the target building with a soft first story up to 1/30 top drift to analyze the pattern of story displacement. Story displacement and inter story drift were calculated at the pushover step, in which a performance point was found. Similarly, an inter story drift was calculated for bare frames of the target building. Figure 10 display that in case of soft first story structure, large inelastic deformation was concentrated on soft story and exceeds the allowable drift limit (1%) as mentioned in BNBC 2015 Draft for occupancy category IV structures. So, soft first story columns are very vulnerable to earthquakes if they don't have adequate ductility and strength to meet the high ductility demand. As a sudden change of story drift occurs in soft first story, it enhances the possibility of forming non-uniform plastic hinge in soft first story columns and severe damage or even collapse during earthquakes. But in case of bare frames, uniform change of the inter story drift was observed.

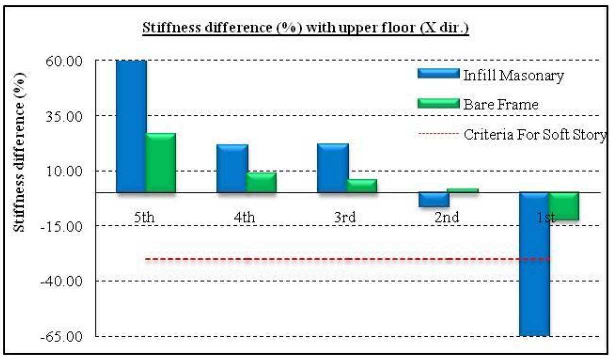


Fig. 8 – Lateral stiffness difference (BNBC 2015 Draft and ASCE 7-05)

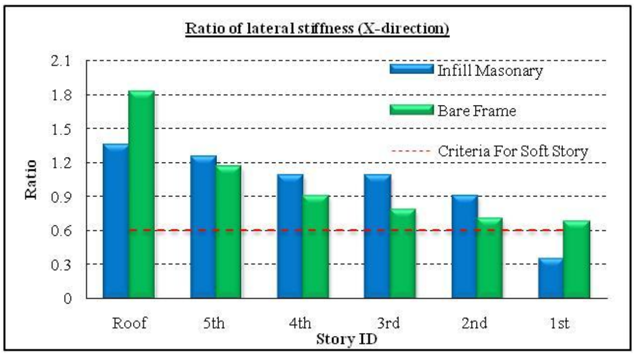


Fig. 9 – Stiffness Ratio (Seismic code of Japan)

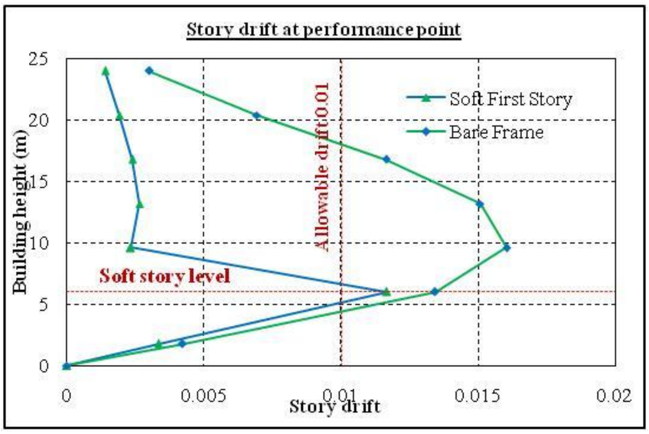


Fig. 10 – Inter story drift at performance point

5. Damage distribution and capacity curve

In Figure 11 and 12 hinge mechanisms at performance points of the analyzed building's elevation 04-04 considering soft story and bare frame are shown. It can be said that, in case of bare frames, no hinges reached collapse prevention (CP) or life safety (LS) state and damage of immediate occupancy level (IO) is distributed all through the structure. But in case of soft first story, the soft story columns suffer collapse prevention level damage and the damage is concentrated on soft story. In Table 2, the trend of hinge formation at first story columns for bare frames and soft first story are shown.

Nonlinear static pushover analysis was done for bare frames and considering soft first story. Displacement of each story for both cases was observed to understand the difference of behavior of structure during earthquakes. From Figure 13 and Figure 14, it is clear that during earthquakes soft first story undergoes large deformation beyond elastic limit and upper floors experience very small inter story displacement. But in case of bare frames, all the floors experience homogenous lateral displacement.

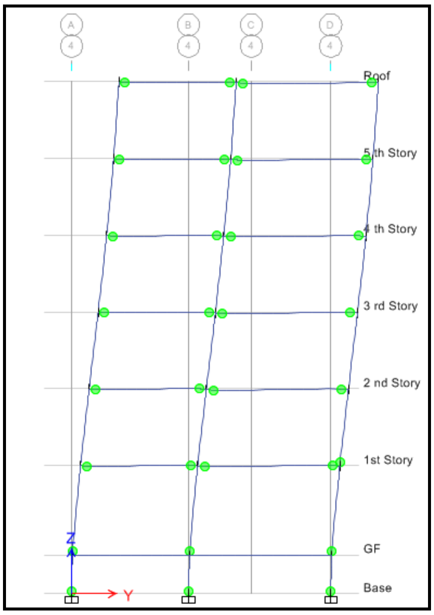


Fig. 11 – Trend of hinge formation for bare frame at performance point

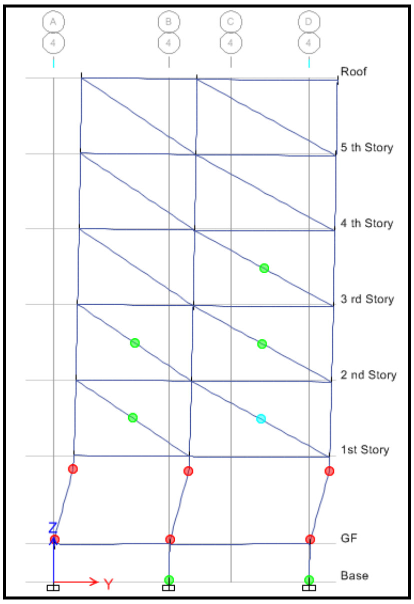


Fig. 12 – Trend of hinge formation for soft 1st story at performance point

Table 2 – Total hinges at first story column at performance point.

	IO	LS	CP
Bare frame	24	-	-
Soft first story	28	6	17

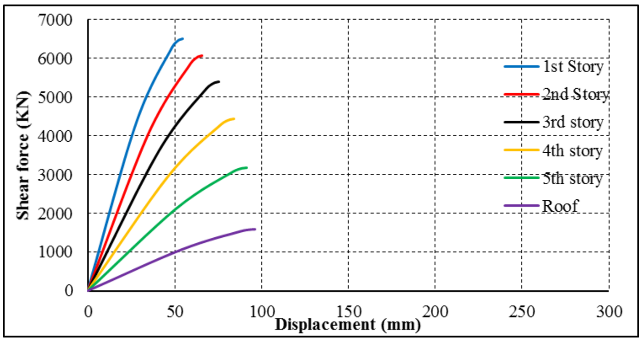


Fig. 13 – Capacity curve of each story (soft first story case).

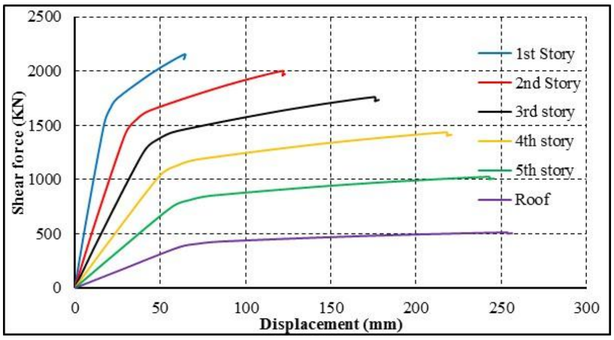


Fig. 14 – Capacity curve of each story (bare frame case).

6. Retrofit strategy for soft first story

With the advancement of research and technology, many retrofitting methods to upgrade the strength and ductility have been invented. Among them column jacketing, addition of bracing, insertion of RC shear walls, steel plate jacketing, structural slit, FRP wrapping and base isolation are popular and widely used.

Strategies of soft first story retrofitting are rather different from conventional retrofitting of RC buildings. The major objectives of soft first story retrofit are to eliminate the extreme stiffness difference and control excessive story drifts beyond elastic limit to enhance the seismic performance up to a satisfactory level. Intentions of keeping ground floor open should be kept in consideration during making plans for retrofitting. Sometimes using only one option can hamper the usage of soft first story. Using column jacketing, steel plate jacketing or FRP alone may not eliminate the extreme stiffness difference. Using only steel bracing can provide stiffness to the frame but may require a large number of bracings. So, a combination of these retrofit methods can be a sustainable and cost effective solution for retrofitting soft first story. Two retrofit options were considered and analyzed in this research. In option1, only columns which are not adjacent to steel brace system are jacketed with 100 mm thick RC, and required number of steel bracings are placed in outer frames. In option 2, column jacketing is done for columns adjacent to the steel bracing, which provides more inner spaces, performed better and recommended by this research. Retrofit plan and elevation 5-5 are presented in Figure 15 and Figure 16 respectively. Reinforcement and size of the retrofitted columns are presented in Table 3.

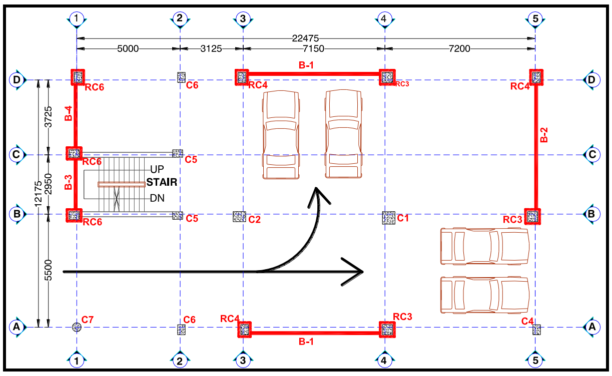


Fig. 15 – Retrofit plan for soft first story

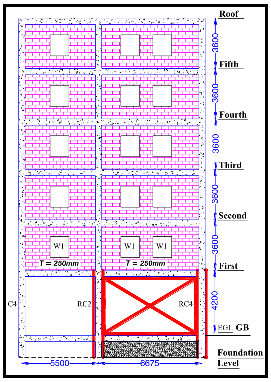
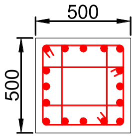
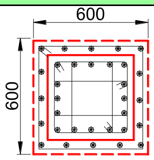
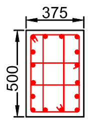
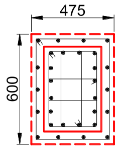
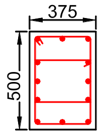
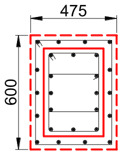


Fig. 16 – Elevation 5-5

Table 3 – Column size and reinforcement details of retrofitted column.

Column ID	Column size		Reinforcement of column	
	Previous	Jacketed	Previous (GF to 1st)	Jacketed (GF to 1st)
RC3	500 x 500	600 x 600	 16-20mmØ	 16-20mmØ + 16-16mmØ
RC4	375 x 500	475 x 600	 16-20mmØ	 16-20mmØ + 14- 16mmØ
RC6	375 x 500	475 x 600	 12-20mmØ	 12-20mmØ + 14- 16mmØ

7. Structural safety checking of the retrofitted structure

The structure's performance level and safety were checked after retrofitting with column jacketing and after addition of steel bracings by static nonlinear pushover analysis using the criteria of BNBC 2015 Draft, FEMA-356 & ATC-40. A comparison of story drift at the performance point of the structure before retrofitting and after retrofitting by in X-direction is presented in Figure 17. The Figure 17 illustrates the improvement of story drift with column jacketing and addition of steel bracing. With column jacketing, story drift at soft first story level was reduced by little margin, but addition of steel bracing provided stiffness to the frame of soft first story and controlled the story drift within safe limit as mentioned in BNBC 2015 Draft. This story drift limit also satisfies the Immediate Occupancy (IO) criteria as suggested by FEMA-356.

The major vulnerability of soft first story happens due to large inelastic deformation in the soft story. Soft first story columns are very vulnerable to earthquakes if they don't have adequate ductility and strength to meet the high ductility demand. As sudden change of story drift occurs in soft first story, it enhances the possibility of forming non-uniform plastic hinge in soft first story columns and severe damage or even collapse during earthquakes. Retrofitting with only column jacketing may not eliminate the stiffness difference which causes the soft story problem and cannot control the excessive large inelastic displacement. So, for retrofitting of soft story addition of bracing or shear walls is very necessary to eliminate stiffness difference and control the excessive drift within the allowable limit.

Figure 18 presents the performance point for bare frames of the original building having a soft first story and after retrofitting as mentioned earlier in section 6. The demand spectrum of the target building was reduced by effective damping and the performance point was obtained by Capacity Spectrum Method as described in ATC-40. The effective damping for bare frame, original building with a soft first story and retrofitted by was found from finite element modeling 16.70%, 13.54% and 11.60% respectively. The improvement of seismic capacity of the retrofitted structure can be observed from Figure 18.

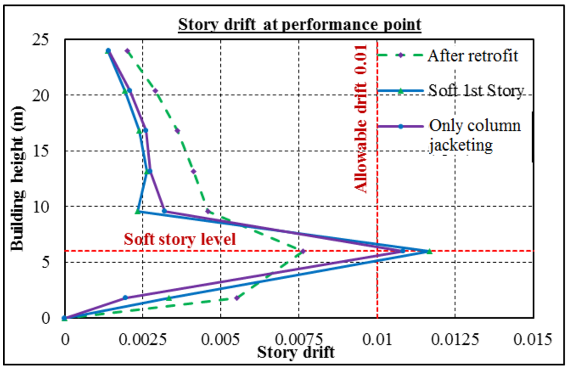


Fig. 17 – Inter story drift before and after retrofit at performance point

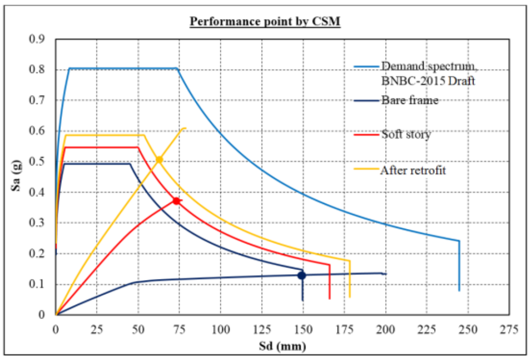


Fig. 18 – Performance point determination

The proposed retrofitting technique can eliminate the formation of collapse prevention (CP) and life safety (LS) hinges in soft first story columns. Figure 19 shows that, the frame 04-04 of the original structure suffered collapse prevention level damage at soft first story, but with retrofitting only immediate occupancy (IO) hinges formed in the soft first story columns. Some nonstructural infill walls are collapsed, but no severe damage is observed in the structural frames. The total number and type of hinges formed at soft first story columns are presented in Table 04. It can also be seen that, number of collapse prevention (CP) and life safety (LS) hinges reduced by retrofitting. This certifies the structural safety of the retrofitted soft first story structure during earthquakes.

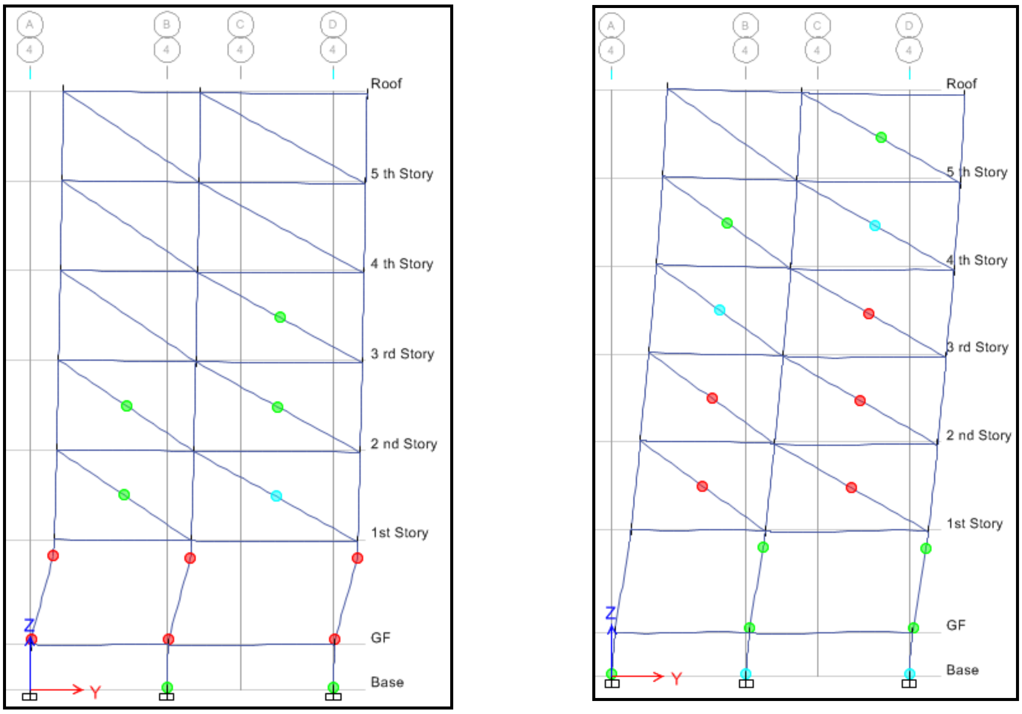


Figure 19. Hinge formation at frame 04-04 at performance point (before retrofit and after retrofit respectively).

Table 4 – Trends of hinge formation at performance point.

	IO	LS	CP
Bare frame case	24	-	-
Soft 1st story case	28	6	17
After retrofit	23	-	-

8. Conclusions

Discontinuity of masonry infills in the ground floor causes lateral stiffness difference and results in less stiff or flexible than its upper floors. The more infills with less openings in the upper floors present the more possibility that less stiff causes in the ground floor than upper floors. It was observed that, any regular RC building designed by analyzing only bare frames without considering the effects of masonry and following the seismic code of BNBC-1993 is structurally safe against earthquakes. In case of bare frames, during nonlinear static pushover analysis, homogenous story displacement, uniform change of inter story drift was witnessed. All the hinges formed in the columns were found within the immediate occupancy (IO) level and insignificant damage was observed to be distributed all over the structure. In case of nonlinear static pushover analysis considering soft story effects by infills in the upper floors except the ground floor, it was detected that enormous lateral drift concentrated in the soft first story columns and imposed high ductility demand. The soft first story experienced large deformation beyond elastic limit and the upper floors experienced very subtle inter story displacement. Collapse prevention (CP) and life safety (LS) hinges were formed and damages concentrated in the soft first story columns. The sudden extreme change of inter story drift in the soft first story which increased the possibility of forming non uniform hinges in the soft first story columns found to be the major reason behind severe damage or collapse of soft first story.

In Bangladesh, structural designs of RC buildings are generally done by analyzing bare frames and without considering the effects of masonry infill. In case of multi storied RC buildings with a soft first story, this design consideration of bare frame analysis results in extremely vulnerable structure. Seismic behavior, ductility demand, inter story drift pattern, damage distribution of structures designed by only bare frame analysis were observed totally different than soft first story RC buildings. Retrofitting strategy of soft first story multi storied RC buildings must be different from the conventional RC buildings. It was observed that retrofitting by only one method like RC column jacketing, steel plate jacketing or FRP wrapping of columns could not eliminate the stiffness difference of soft first story with upper floors and also could not control the excessive lateral drift of soft first story beyond elastic limit. Again, if only steel bracing or RC shear walls are used, it can eliminate the stiffness difference and control the excessive lateral drifts, but it will require a large number, which may hamper the usages of the open space. So, a combination of these retrofitting methods was found to be best and sustainable solution for retrofitting of soft first story and recommended by this research.

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