EFFECTS OF SOFT FIRST STORY ON SEISMIC PERFORMANCE OF RC BUILDINGS AND SUSTAINABLE APPROACH TO RETROFIT

MD. KAMRUZZAMAN* **Supervisor: Matsutaro SEKI****
MEE17712

ABSTRACT

The structural configuration with a soft first story proved to be very vulnerable and performed poorly during the past earthquakes. Like other many countries, brick infill masonry is used in Bangladesh as a nonstructural element. Its usages in upper stories and keeping building's ground floor open result in lateral stiffness difference and cause soft first story state. The scarcity of land in Bangladesh has compelled to construct multi storied RC buildings with an open ground to be used as vehicle parking, stores or other facilities. This research committed to assess the seismic vulnerabilities of RC buildings with a soft first story, causes behind the collapse of soft first story during earthquakes, seismic performance difference with bare frames and sustainable approach to retrofit them. Seismic performance and vulnerabilities of the soft first story were assessed by the JBDPA guidelines of seismic evaluation, FEMA-356, BNBC-2015 and nonlinear static pushover analysis. Flexural moment magnification at the soft first story columns during earthquakes was determined. Sustainable retrofitting approaches to upgrade seismic performance and prevent catastrophe during earthquakes were proposed with cost analysis. This research found that, seismic behavior, ductility demand, inter story drift pattern and damage distribution of RC buildings with a soft first story were totally different than the RC buildings designed by only bare frame analysis. The soft first story suffered huge ductility demand, extreme inter story drift change and concentrated in severe damage. Magnification of flexural moment at soft story columns was detected as a variable entity. 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 the excessive inelastic lateral drift.

Keywords: Soft story, Seismic performance, Nonlinear analysis, Retrofit.

1. INTRODUCTION

Bangladesh is one of the most densely populated countries. The scarcity of land has compelled to construct multi storied buildings with open ground. Using masonry infills as a nonstructural element in the upper stories keeping ground floor open results in lateral stiffness difference and cause soft story vulnerabilities. Many RC buildings with a soft first story collapsed during past earthquakes such as the 1995 Kobe earthquake, 2015 Nepal earthquake. Along with many natural disasters like floods, cyclones and droughts, Bangladesh is under threat of moderate to strong earthquakes. The three plate boundaries surrounding Bangladesh are tectonically very active and generates many earthquakes. The common practice of structural designs 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. Many multi storied RC buildings with a soft first story exist in Bangladesh, and many are under construction.

*Public Works Department, Bangladesh.
**Visiting Research Fellow, International Institute of Seismology and Earthquake Engineering, BRI, Japan.

2. THEORY AND METHODOLOGY

A six (06) storied RC building (Figure 1) in Bangladesh having soft first story designed by only bare frame analysis following the seismic design code of BNBC-1993 (Bangladesh National Building Code) is selected. Seismic evaluation and structural performance level checking by JBDPA (Japan Building Disaster Prevention Association) guidelines of seismic evaluation, ATC-40 (Applied Technology Council), FEMA-356 (Federal Emergency Management Agency) and BNBC-2015 are conducted. Nonlinear static pushover analysis is done to understand the progressive damage pattern and to estimate the structure's capacity by capacity spectrum method. Sustainable and cost effective retrofitting methods are proposed and reevaluation is conducted to check the structural safety of soft first story. The major theory and concepts used in this study are summarized below:

a) In RC frame structures, discontinuity of walls in some floors causes stiffness differences. According to the definition of BNBC-2015 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.

b) 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. Seismic performance criteria of FEMA-356, ATC-40, BNBC-2015 are followed in this research. Demand, capacity and performance of the structure are obtained by "Capacity Spectrum Method", and ADRS (Acceleration Displacement Response Spectrum) format described in BNBC-2015 and ATC-40.

c) ETABS-2015 is used in this research for nonlinear analysis. An equivalent diagonal strut is used to represent infill masonry. The equivalent strut width (a) and compressive strength (f'_m) is calculated as per the formula proposed by Pauly and Priestly. Alchaar equation is used to calculate the strength reduction due to the presence of openings in the infill masonry.

d) Seismic demand index, *Iso* which is the level of seismic capacity needed for a structure to remain safe against a certain ground motion or code defined ground motion. Seismic demand index for the RC (Reinforced Concrete) buildings in Bangladesh is calculated as per the proposal of the "Seismic Assessment Manual" prepared by CNCRP (Project for Capacity Development on Natural Disaster-Resistant Techniques of Construction and Retrofitting).

e) The seismic evaluation standard proposed by JBDPA consider only RC walls. In Bangladesh, clay bricks are used widely as the infill elements in the RC frame. Shear strength and ductility index is calculated on the basis of behavior of infill masonry within RC frame. Seki *et al.* proposed the shear strength of infill panel as 0.2 Mpa. Alwashali *et al.* proposed *R-max* (maximum drift angle) for masonry infill as 1% of story drift. Ductility index based on this proposal is calculated as 1.5.

f) The strength index and ductility index of the jacketed column by RC jacketing and FRP (Fibre Reinforced Polymer) wrapping and retrofitted by steel bracing are calculated by the guideline of JBDPA seismic evaluation. For ETABS modeling of FRP wrapped columns, "Lam and Teng's stress-strain model for FRP confined concrete" is used.

3. SEISMIC PERFORMANCE OF SOFT FIRST STORY

3.1. Outline of the target building

The target building is a six (06) storied RC building with soft first story located in seismic zone III (BNBC-2015) and designed by following the building design code BNBC-1993. The open ground is used for parking and brick infill masonry with various opening is present in the upper floor. The building is designed by analyzing only bare frames. Individual footings are used as foundation. The soil type is *SC*. Architectural plan of ground floor and elevation A-A is presented in Figure 1 and Figure 2 respectively. As, the building is an office building, its occupancy category is IV.

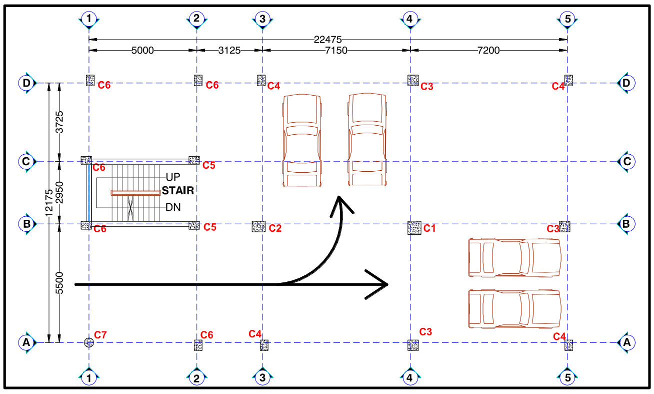

Figure 1. Ground floor plan.

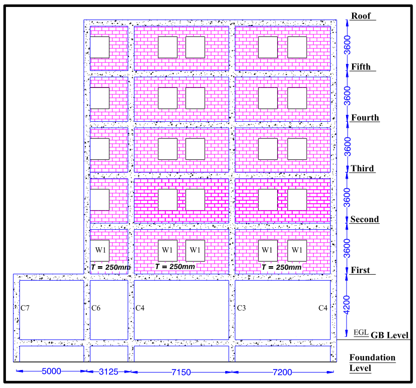

Figure 2. Elevation A-A.

3.2. Lateral stiffness

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 3. As per the definition of BNBC-2015 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 is observed when bare frame analysis is done (Figure 4).

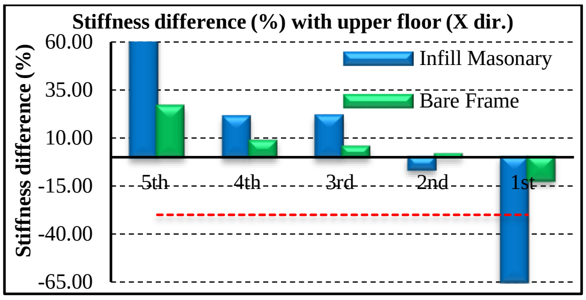

Figure 3. Stiffness difference (%).

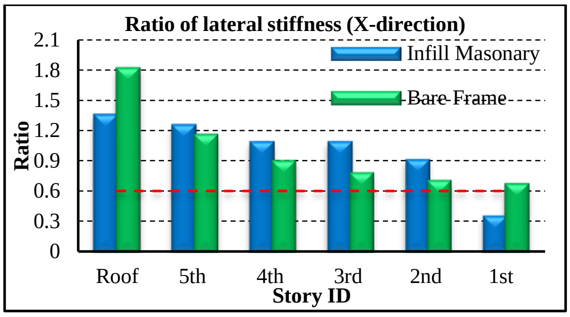

Figure 4. Stiffness ratio.

3.3. Story displacement and inter story drift

Figure 5 displays that, in the case of soft first story structures, soft first story undergoes large deformation beyond the elastic limit, and upper floors experience very subtle inter story displacement. Soft first story exceeds the allowable drift limit (1%) as mentioned in BNBC-2015 and FEMA-356 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 the soft first story, it enhances the probability of forming the 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 is observed. If a soft first story building is designed by only bare frame analysis, it may suffer severe damage or collapse during an earthquake.

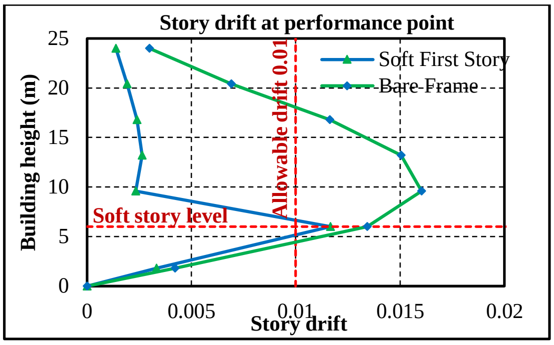

Figure 5. Inter story drift.

3.4. Hinge mechanism and damage distribution

In Figure 6 and 7, hinge mechanisms at performance points of the building's elevation 04-04 considering a soft story and bare frame are shown. The bare frame did not reach collapse prevention (*CP*) or life safety (*LS*) state, and only damage of immediate occupancy level (*IO*) is distributed all through the structure. But soft story columns suffered and concentrated in collapse prevention level damage. Total 27 *CP* and 6 *LS* hinge were formed in soft first story columns, but only 24 *IO* hinges were formed when only bare frame was considered.

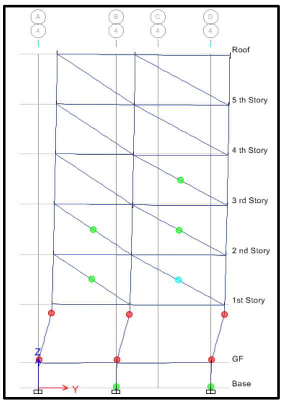

Figure 6. soft story case.

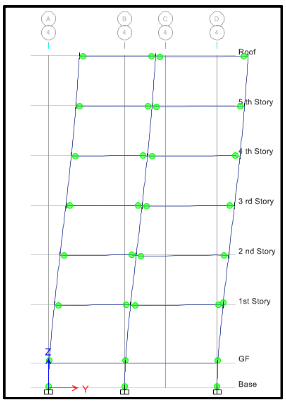

Figure 7. bare frame case.

3.5. Seismic evaluation by JBDPA standard

1st level screening for bare frame shows the lack of seismic capacity in all floors. 2nd level screening shows, when masonry is considered, all the floors except soft first story have adequate capacity.

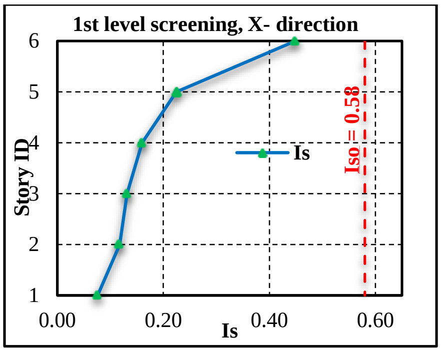

Figure 8. First level screening.

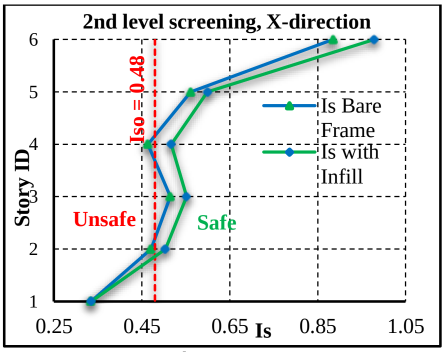

Figure 9. 2nd level screening.

4. RETROFIT OF SOFT FIRST STORY

4.1. The retrofit strategy of the soft first story

Strategies of soft first story retrofitting are rather different from conventional retrofitting of RC buildings. The major objectives of a soft first story retrofit are to eliminate the extreme stiffness difference and control excessive story drifts. 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 a soft first story. 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 study. In Figure 11 and 12, seismic index and inter story drift after retrofitting are presented which are within the allowable limit. Improvement in capacity of spectral acceleration and elimination of *CP* hinges in the retrofitted soft first story is presented in Figure 13 and 14 which ensures the structural safety.

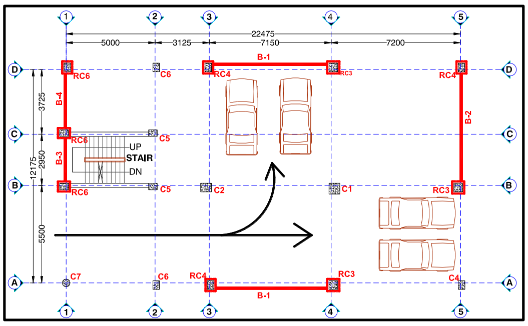

Figure 10. Retrofit option-2.

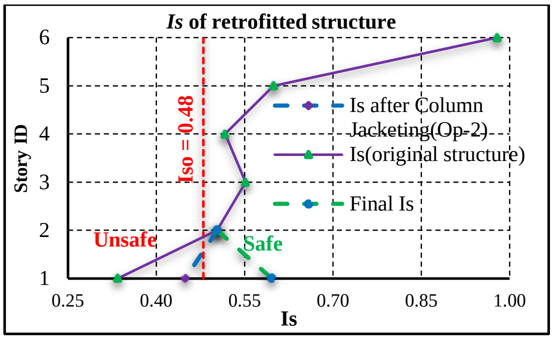

Figure 11. *Is* of retrofitted structure.

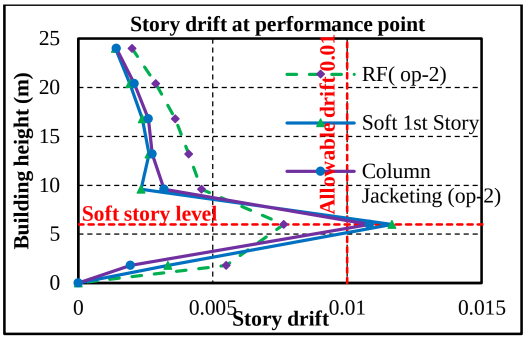

Figure 12. Inter story drift.

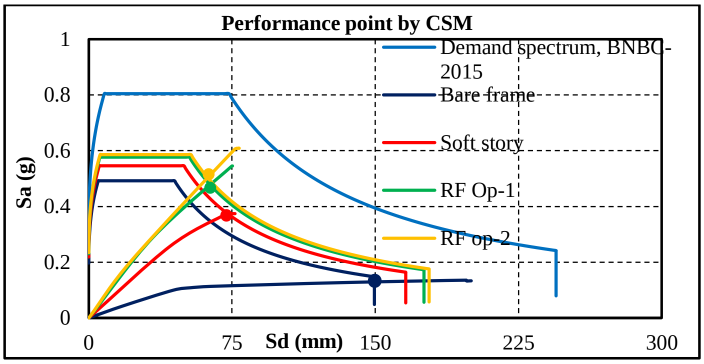

Figure 13. Performance point by CSM.

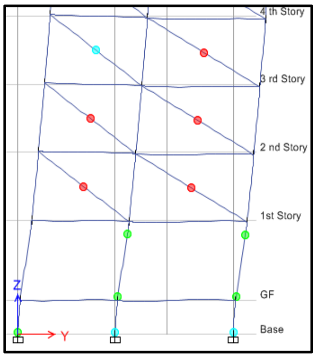

Figure 14. Hinge formation.

4.2. Retrofit with FRP and steel bracing: A-case study

FRP wrapping is an effective way to retrofit soft story because retrofitted columns have almost the same size as before, do not add any weights and strength and ductility of existing RC columns can be upgraded. FRP wrapping does not increase flexural strength much. So, the columns have shear failure mode can be retrofitted by FRP. This can alter the failure mode from shear failure to flexural failure. Shear failure is not desirable in RC structure as it causes sudden collapse without warning. The soft first story columns of the target building have flexural failure mode. For a case study, the shear reinforcement of the target building ground floor columns are considered as d-10 mm having 250 c/c spacing to ensure shear failure. Three layers of FRP having thickness 0.167 mm of each layer are used for retrofitting in this case study. The upgraded ductility index and the changed failure mode is presented in Table 1. Using Lam and Teng's model the enhanced compressive strength and strain of FRP wrapped columns are calculated and presented in Table 1.

Table 1. Enhanced of ductility index, strain and strength of FRP wrapped column.

Column ID	F (before retrofit)	Failure mode (before retrofit)	F (after retrofit)	Failure mode (after retrofit)	Enhanced strain	Enhanced strength (Mpa)
C1	1.12	Shear	2.30	Flexural	0.0102	23.79
C2	1.18	Shear	2.01	Flexural	0.0121	22.97
C4	1.03	Shear	2.95	Flexural	0.0159	23.48

4.3. Bracing connection design and cost analysis

Proper connection between steel bracing and existing RC frames is very important. RC shear walls should be constructed beneath the steel bracing to ensure safer transfer of shear force. Summary of the connection design is

Table 2. Summary of bracing connection design.

Panel ID	Bolt	Headed stud			Anchor bolt			Ladder rebar	
	Total no.	Dia (mm)	S (mm)	Total no.	Dia (mm)	S (mm)	Total no.	Spacing (mm)	Dia (mm)
A(03-04)	8	12	200	63	16	200	31	200	12
1(B-C)	8	16	150	29	16	100	21	200	12
1(C-D)	8	16	150	40	16	100	29	200	12
5(B-D)	8	12	200	60	16	200	29	200	12

presented in Table 2. By cost analysis (Table 3), it is understood that retrofitting by FRP is a costly option than other retrofit methods.

Table 3. Cost analysis.

Retrofit option-1		Retrofit option-2		FRP + bracing	
Column jacketing ($)	$3056	Column jacketing ($)	$3768	FRP ($)	$11694
Steel bracing ($)	$1149	Steel bracing ($)	$11493	Steel bracing ($)	$11493
Total cost ($)	$14550	Total cost ($)	$15262	Total Cost ($)	$23188

5. MAGNIFICATION FACTOR FOR SOFT FIRST STORY COLUMN

Magnification factor of flexural moment is the ratio of flexural moment induced at soft first story column to that of full infill column. This research suggests that, magnification factor to design soft story columns should not be any constant entity which is mentioned by BNBC and ASCE as 2.5. It should vary with the number of stories and amount of infill presents in the upper floors and stiffness difference of soft story with upper floors. Three equations are proposed by this research to calculate magnification factors of soft first story columns with two, four and six storied buildings.

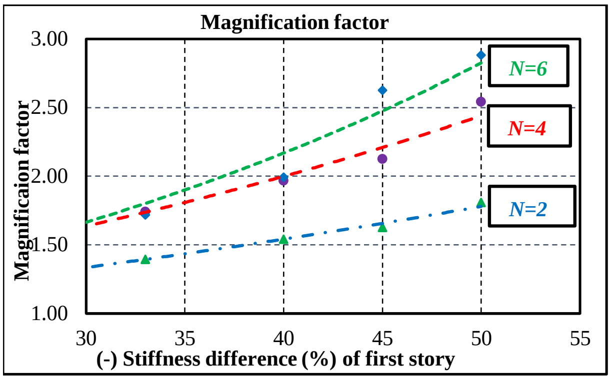

Figure 15. Flexural moment magnification factor.

6. CONCLUSIONS AND RECOMMENDATIONS

Any RC building with a soft first story will suffer severe damage even collapse if designed by only bare frame analysis. Regular RC building designed by only bare frame analysis is proved to be safe in Bangladesh. The soft story suffers large displacement during earthquake. Sudden extreme change of inter story drift is one of the main causes of soft first story damage. By retrofitting, collapse or damage of soft first story can be minimized. Combination of RC column jacketing and adding steel bracing which can eliminate stiffness difference and control excessive lateral drift is found sustainable to retrofit a soft first story. Using FRP, column failure mode can be altered, and shear failure can be prevented. The magnification factor to design soft first story column should not be a constant entity. It should vary with the number of story above soft first story and stiffness difference with the upper floors.

The exact shear strength and ductility index should be investigated for the masonry used in Bangladesh. Only diagonal compression failure of masonry infill was considered, therefore, sliding shear and out of plane failure should be incorporated in future research. To calculate flexural moment magnification factor, full building with more stories should be analyzed to determine it more precisely.

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