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SEISMIC PERFORMANCE OF RC TALL BUILDING WITH COLUMNS RESTING ON TRANSFER STOREY

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Abstract

Constructions of tall buildings with discontinuous vertical elements, such as columns and structural walls are quite common in India. Such structural form exists to cater the functional need of obstruction free large area for the purpose of vehicular parking or use it for common amenities. Many a time such structural forms are adopted to satisfy the aesthetic requirement desired by owner or architect. In order to accommodate this vertical discontinuity, vertical elements are typically supported on a transfer girder. This transfer girder has to transfer the vertical and lateral load from upper storey to storey below it. However, such feature creates abrupt change in storey stiffness leading to localised damage near transfer storey, during a major earthquake. Current comparative study is an attempt to understand the increased demand in storey drift for a reinforced concrete moment resisting-structural wall building, with and without a transfer slab. For this purpose three dimensional finite element models of two towers have been created. And the effect of transfer storey on global seismic performance of both the tower, under linear time history analysis, was observed by comparing their inter storey drift, and storey displacements. Finally, the building with a transfer slab found to be inappropriate for seismically active regions.

Keywords: Tall buildings; Vertical Irregularity; Transfer Slab; Transfer Storey; Seismic Performance

1. Introduction

Multi-storey buildings with discontinuous vertical elements are becoming popular in urban settlements of India (Fig. 1). The builder community tries to accommodate a maximum number of flats in a project constructed at the prime location of the city. The overall size of flat in such projects is designed to cater the need of a middle-class family. This leads to closely spaced supporting system. However, the bay width arrived from such planning is not feasible for accommodating obstruction-free space for assembly hall, shopping malls, indoor sports facilities, gym, parking area etc. within the same structure. In order to have obstruction-free space use of transfer slab to support the discontinuous elements came into practice. The idea is to make use of large span slabs in the lower storey of the tall buildings to have obstruction-free facilities listed above. Once the desired amount of additional facilities is accommodated at initial floor levels the typical floors with closely spaced vertical elements are constructed. The first storey of a typical floor, which needs closely spaced columns, is supported on the transfer storey provided just below it. Such storey has relatively huge depth compare to typical storey since they have to carry a large amount of axial force and bending moments transferred by floating columns or shear walls. This transfer storey has to transfer the vertical and lateral load from upper storey to storey below it. However, during major earthquakes such feature creates abrupt change in storey stiffness leading to localised damage near transfer storey. The Current comparative study is an attempt to understand the increased demand in storey drift for a reinforced concrete moment resisting-structural wall building, with and without a transfer slab (Fig. 2). For this purpose two buildings were modeled using a commercial software and the performances of the buildings subjected to three ground motions were compared.

Fig. 1 - Building with transfer storey

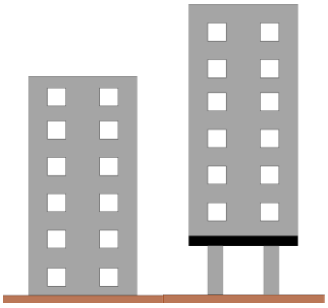


Fig. 2 - Building with and without transfer storey

2. Literature Review

It is a well known fact that discontinuity in vertical stiffness and strength leads to concentration of damage. The performance of Olive View Hospital in the 1971 San Fernando earthquake was a wakeup call for the earthquake engineering community. It has revealed the possible threats posed by buildings having a discontinuous shear wall. The olive hospital did not collapse, but two occupants in intensive care and a maintenance person working outside the building were killed. The general vertical configuration of the main building was a 'soft' two-storey layer of rigid frames on which was supported a four-storey (five, counting penthouse) shear wall-plus-frame structure (Fig. 3). The second floor extends out to form a large plaza. Severe damage occurred in the soft story portion (Fig. 4). The upper stories moved as a unit and moved so much that the columns at ground level could not accommodate such a high displacement between their bases and tops, and hence failed [1]. The largest amount by which a column was left permanently out-of-plumb was 2 feet 6 inches.

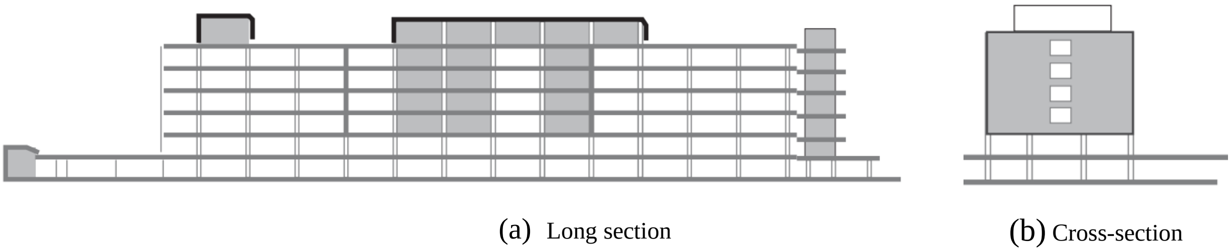

(a) Long section (b) Cross-section

Fig. 3 - Olive View Hospital [1]

Citing the words of Arnold [2] on the reason of such damage in hospital, he states “Had the columns at Olive View been more strongly reinforced, their failures would have been postponed, but it is unrealistic to think that they would have escaped damage. Thus the significant problem lies in the configuration, and not totally in the column reinforcement.” Sadly, such practices are still continued for high-rise buildings as well.


(a) Fallen stair towers and damaged basement

(b) Heavy damage to columns at the bottom storey

Fig. 4 - Damage in Olive Hospital [3]

High-rise buildings with transfer storey configuration are more popular in regions with low seismicity. And it generally suffers no/minor cracks (conventional elastic behaviour) when subject to a frequent (minor) earthquake [4]. However, severe cracking in the vicinity of the transfer floor is encountered when these buildings are subjected to rare (medium to major) earthquakes. Chinese National Standard [5] realized the gravity of the situation much before and hence limited the use of transfer structures in concrete building only in low-to-moderate seismic zones (maximum seismic intensity of VII). Whereas, Indian tall building code [6] doesn’t explicitly stop designer to provide transfer structure in reinforced concrete buildings. Truly speaking not every transfer structure automatically leads to a soft storey; however, seismic engineers are concern about the failure of transfer structure due to soft storey effect [7]. Hence, identification of soft storey in a high-rise structure becomes very important since the severity of the collapse will increase with the increasing number of stories. This is because the plastic energy accumulated at the weak story of the building increases with the increase in a number of storeys. Thus, control of the collapse mechanism in irregular buildings under earthquake excitation is needed, especially in high-rise buildings [8].

3. Codal Provisions on Transfer Storey and Vertical Stiffness Irregularity

To prevent the stiffness irregularity, Indian seismic code [9] restricts the designer to have lateral stiffness of particular storey lesser than that of the storey immediately above it (Fig. 5). Further, IS 1893 suggests prohibiting the use of floating column in buildings irrespective of their seismic zone, citing the reason that it will likely to cause concentrated damage in the structure. Especially when such members are part of primary lateral load resisting system. However, Indian Tall building code [6] which was released very recently allows designer for having stiffness difference of up to 30% between two consecutive storey, i.e. it states “lateral translational stiffness of any storey shall not be less than 70 per cent of that of the storey above". This clause had it's place in past seismic code [10] as one of the qualifying criteria for declaring building as a 'soft storey'. As mentioned under scope of IS 16700, this code should be used along with all other relevant Indian standards. But in case of any conflict IS 16700 clause will be applicable. Hence, there is high chance that all the old (Fig. 6) as well upcoming RC buildings taller than 50m have bypassed or is bypassing the stiffness irregularity clause given by latest seismic code. This is one of the major shortcoming which is knowingly or unknowingly exploited by designers for construction of tall building with transfer storey or soft storey at lower levels.

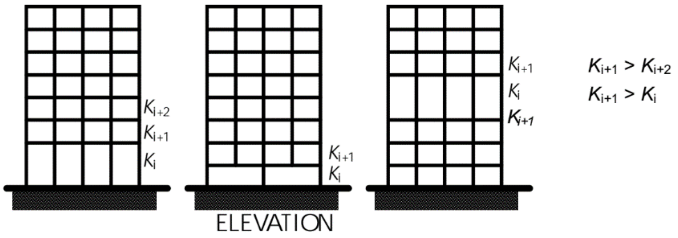


Fig. 5 – Soft storey caused due to stiffness irregularity [9]

Fig. 6 – Tall building having soft storey at lower level

ASCE7-10 [11] has separate provision for elements supporting discontinuous walls or frames, this is in addition to the basic irregularities provision of out-of-plane offset, stiffness-soft storey, stiffness-extreme soft storey, in-plane discontinuity, discontinuity in lateral strength. Code states, "The connections of such discontinuous walls or frames to the supporting members shall be adequate to transmit the forces for which the discontinuous walls or frames were required to be designed." Hence, Code outlines the additional load combinations to be used for both allowable stress and strength design of members as per Eq. (1).

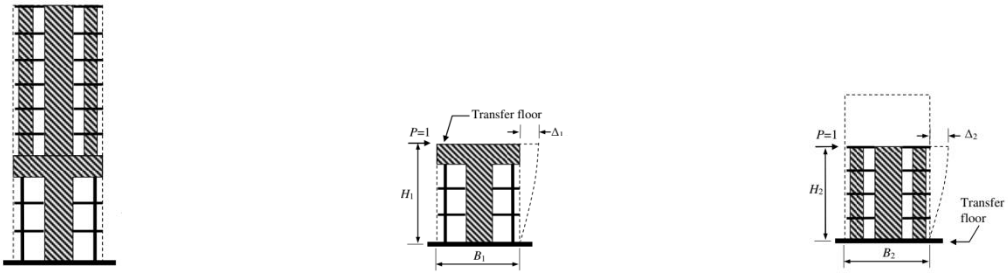
$$\begin{gathered}(1.2 + 0.2S_{DS})D + E_{mh} + L + 0.2S \\ (0.9 - 0.2S_{DS})D + E_{mh} + 1.6H\end{gathered} \tag{1}$$

Where, D, S and H are the dead load, snow load and lateral earth or water pressure, respectively. E_{mh} is the horizontal seismic forces effect including the structural over-strength factor; $E_{mh}=\Omega_o Q_E$ with Ω_o being the seismic force amplification factor ($\Omega_o=1.25$ *to* 3.0) and Q_E is the horizontal seismic forces from V or FP (equivalent lateral force procedure). S_{DS} is the design spectral response acceleration parameter at short periods. Further, LATBSDC [12] and Tall building Guideline [13] developed by PEER insist designer to consider the effect of vertical ground motion when significant discontinuities encounter in the vertical-load-resisting system. For such cases, vertical masses (based on the effective seismic weight) shall be included with sufficient model discretization to represent the primary vertical modes of vibration in the analysis model used to simulate vertical response.

In Chinese tall building code [14], an additional guideline for building with transfer structure is given based on the equivalent lateral stiffness ratio γ_e as defined in Eq. (2).

$$\gamma_e = \frac{\Delta_1}{H_1} \Big/ \frac{\Delta_2}{H_2} = \frac{\Delta_1 H_2}{\Delta_2 H_1} \tag{2}$$

As per this guideline, two models simulating the structures above and below the transfer structures as shown in Fig. 7 *b* and *c* are built, and the bases of the models are fixed. The height of the substructure below the transfer structure (as shown in model 1 in Fig. 7 *b*) is H_1, while that of the substructure above the transfer structure (similar to but not taller than H_1; see model 2 in Fig. 7 *c*) is H_2. By applying a unit horizontal load to each model, the elastic lateral deflections Δ_1 and Δ_2 of models 1 and 2 are calculated, and the equivalent lateral stiffness ratio γ_e can be evaluated accordingly. According to the JGJ3-2002, when the structures below the transfer structure are more than one storey, the ratio of the equivalent lateral stiffness ratio γ_e should not be greater than 1.3 for seismically resistant design.



(a) Full Model

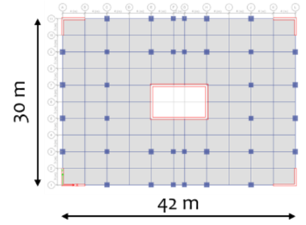
(b) Model 1: Substructure below the transfer structure

(c) Model 2: Substructure above the transfer structure

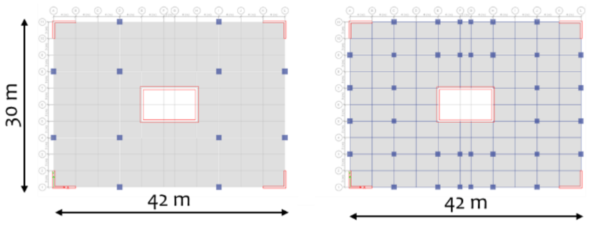
Fig. 7 - Numerical Model for calculating equivalent stiffness below and above transfer structure

4. Case study

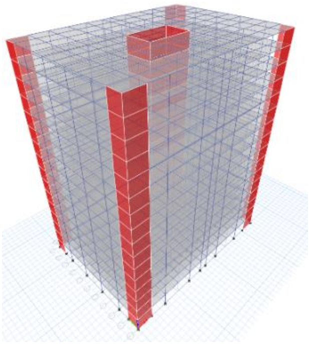
In order to compare the seismic performance of transfer storey structure, following linear time history case study was conducted. Study consists of designing the two RC buildings as per IS 456:2000 [15], IS 16700:2017 [6], IS 875:2015 [16] and IS 1893:2016 [9] for office use. First building i.e., *Model A* consists of regular RC tall building used for office. Second building i.e., *Model B* catering same need and having same floor area, however, with transfer storey in the form of 1m thick transfer slab at first floor is modeled. The basic details of both the structures are given in Table 1 and Fig. 8. Appropriate size of structural members were used to satisfy the all applicable design code requirement.



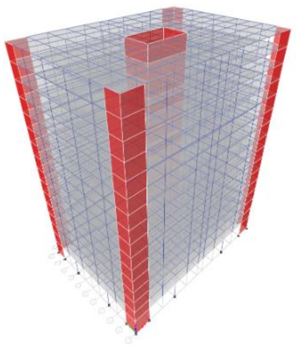
Typical Plan



Typical and Transfer Storey Plan



Elevation
(a) Model A



Elevation
(b) Model B

Fig. 8 – Plan and Elevation view of Case study Buildings

Table 1 – Building Structural Configuration Details

Particular	Building A	Building B
Length (m)	42	42
Breadth (m)	30	30
Height (m)	52.8	54
Typical Floor Height (m)	3.3	3.3
Ground Storey Floor Height (m)	3.3	4.5
Number of Floors	(G+15)	(G+15)
Transfer Slab Thickness	-	1 m

Both the buildings considered in this study are of a regular plan with no infill wall and have cladding along periphery. The buildings were modelled with slab using a commercial finite element software. While designing buildings reduced moment inertia for slabs, beams, columns and structural walls for both factored and unfactored case were used as recommend by clause 7.2 of IS 16700:2017. The details of material and loading is given in Table 2.

Table 2 -Material and Loading details

Basic material	Load property	Seismic Load Details
• Slab and Beams: M45 • Columns and Structural Walls: M60 • Steel: HYSD415	• Imposed Load(Typical floor): 4 kN/m^2 • Imposed Load(Roof): 1.5 kN/m^2 • Floor Finish:1 kN/m^2 • Cladding: 2kN/m^2 • Parapet wall: 4.6 kN/m	• Seismic Zone: IV (0.24g) • Importance factor: 1.2 • Response Reduction factor: 4 • Soil Type: Medium (Type II)

After designing the buildings linear time history analysis (LTHA) was conducted for three Indian earthquakes scaled to *0.24g* (Fig. 9). The details of earthquake and it's characteristics is given in Table 3 and Table 4.

Table 3 - Earthquake Details [17,18]

Sr No.	Earthquake	Date	Recording Station	Lat	Long	Depth (km)	Magnitude
1	Bhuj/Kachchh	January 26, 2001	Ahmedabad	23.420	70.230	16	M_b 7.0
2	Chamoli	March 28, 1999	Gopeshwar	30.512	79.403	15	M_b 6.6
3	Uttarkashi	October 19, 1991	Bhatwari	30.780	78.774	10	M_s 7.0

Table 4 – Ground Motion Characteristics

Sr No.	Ground Motion Name	Significant Ground Motion Duration (sec)	Peak Ground Acceleration (g)	Period Content (sec)
1.	Bhuj	16.97	0.24	0.75-1.20
2.	Chamoli	14.08	0.24	0.53-0.89
3.	Uttarkashi	07.78	0.24	0.48-0.60

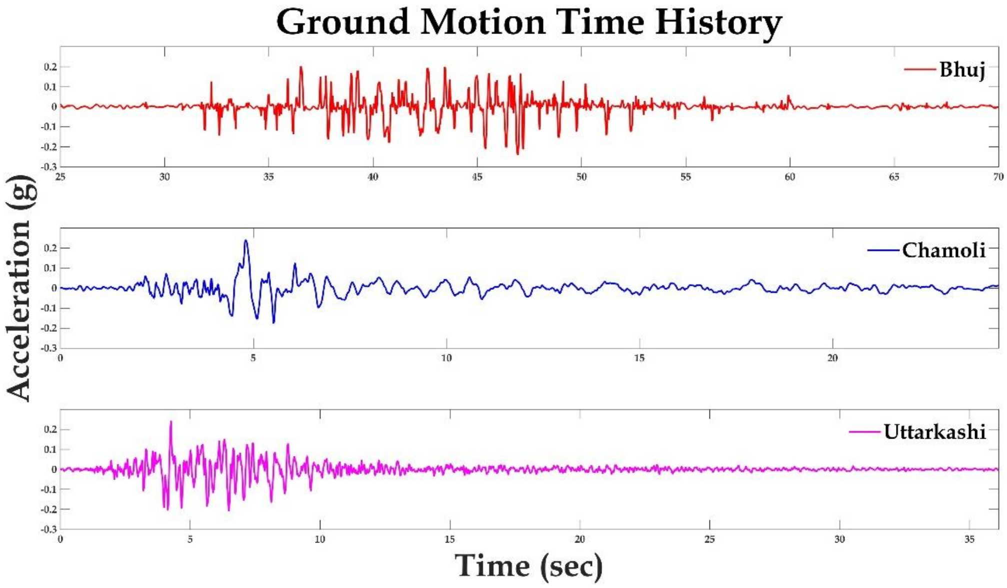


Fig. 9 – Ground motion time histories used for Linear Time History Analysis (LTHA)

5. Results and Discussions

The Indian Tall building code [6] recommends to go for two different moment of inertia of structural element for factored loads and unfactored loads. Further, this is link with wind load and seismic load. Hence, two separate models for each building were created to compute the wind and seismic load. P-Delta effect was considered in design while assessing the effect of lateral loads. Respective checks related to fundamental natural periods, inter-storey drift and inter-storey drift stability coefficient were applied in models. The final member size was proposed based on governing load case from wind or earthquake. For both the building earthquake load found to be governing over wind load case. Equivalent static analysis(ESA) and response spectrum analysis(RSA) methods were used to get the seismic loads. The base shear values for wind and earthquake load case are outlined in Table 5. It was observed that ESA is exceeding RSA design base shear values in both direction for both buildings. It is worth to note that increase in wind demand by 4% was observed for building B compared to that of building A, in both the direction. Further, for building B the ESA design base shear was also found to be increased by 12.5% and 13.5% in X and Y directions, respectively. This increase in demand can be directly linked with transfer slab configuration feature. On one side, transfer slab is increasing overall height of the building, leading to increase in surface area thereby rise in wind load and at the same time huge depth of transfer slab is increasing considerable seismic mass thereby causing increase in earthquake induced force.

Table 5 - Design Base shear for both buildings due to lateral loads

Building	**Base Shear (kN)**					
	Wind X	**Wind Y**	**ESA X**	**ESA Y**	**RSA X**	**RSA Y**
A	4338	6073	17708	12290	12678	10825
B	4511	6315	19914	13949	12906	11546

Table 6 outlines the natural periods of first three modes in each direction for both the buildings. Further, The natural period along Y direction was found to be maximum followed by X and rotational direction for both cases. In addition, Building B is found to be relatively flexible compare to that of building A. However, this flexibility is not contributing much in reducing design base shear values for seismic load.

Table 6 - Fundamental Natural Periods of buildings

Building	**T_X (sec)**			**T_Y (sec)**			**T_θ (sec)**		
	Mode 1	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 1**	**Mode 2**	**Mode 3**
A	0.891	0.224	0.144	1.056	0.282	0.134	0.817	0.245	0.128
B	0.930	0.226	0.198	1.155	0.289	0.216	0.842	0.247	0.158

After arriving at the final sizes of each structural member, using its full moment of inertia, both the buildings were subjected to three ground motion time histories in both the direction. The linear maximum base shear values generated at any point during entire duration, for each ground motion, along each direction is stated in Table 7. No specific pattern was observed here. This is due to fact that in spite of having same PGA of *0.24g*, each ground motion has different duration and having different predominant frequency range. Hence, buildings with different configuration will respond differently to each ground motion time history.

Table 7 - Base shear for all buildings due to LTHA

Building	**Base Shear (kN)**					
	Bhuj X	**Chamoli X**	**Uttarkashi X**	**Bhuj Y**	**Chamoli Y**	**Uttarkashi Y**
A	116531	82593	84795	97578	66156	69147
B	108243	79661	76683	103641	63300	70150

The inter-storey drift values is key factor in assessment of building. IS 16700 and IS 1893 recommends designer to limit the inter-storey drift value to 0.004*h*. Fig. 10 shows the maximum inter-storey drift occurring due to all ground motion in LTHA. Whereas, Table 8 outlines the only maximum value of inter-storey drift occurring at any time step in entire structure for a given direction. For all earthquake load case, except for Uttarkashi earthquake in Y direction, the inter-storey drift value for Building B was found to be more than that of Building A. In fact, for Bhuj earthquake (along Y direction) around 11 storey (Floor 5 to 15) of building B are exceeding the limit of 0.004*h* value. Overall, building B was found to be performing poorly in terms of its inter-storey drift value when compared with response of building A.

Table 8 – Maximum Inter-storey drift for LTHA

Building	**Inter-storey drift**					
	Bhuj		**Chamoli**		**Uttarkashi**	
	X	**Y**	**X**	**Y**	**X**	**Y**
A	0.0036	0.0038	0.0027	0.0030	0.0026	0.0023
B	0.0038	0.0050	0.0028	0.0033	0.0027	0.0021

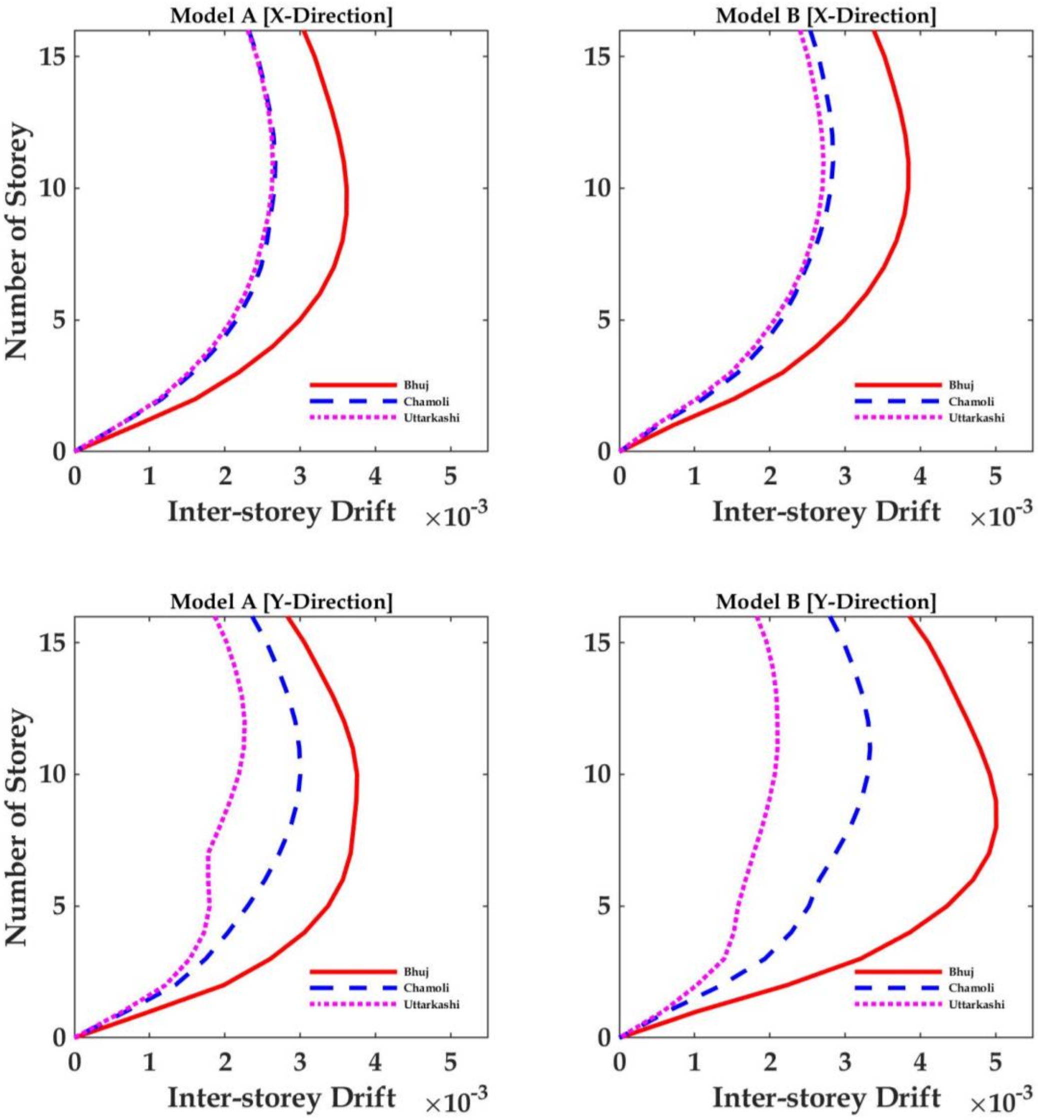


Fig. 10 - Inter-storey drift for LTHA

The same can be observed by looking at Fig. 11 where displacement profiles for both buildings are plotted. The overall displacement profile for both buildings matches with each other. However, striking difference is found for Bhuj earthquake (along Y) direction (Table 9). A difference of about 54mm was observed at the top storey in building B compared to that of building A.

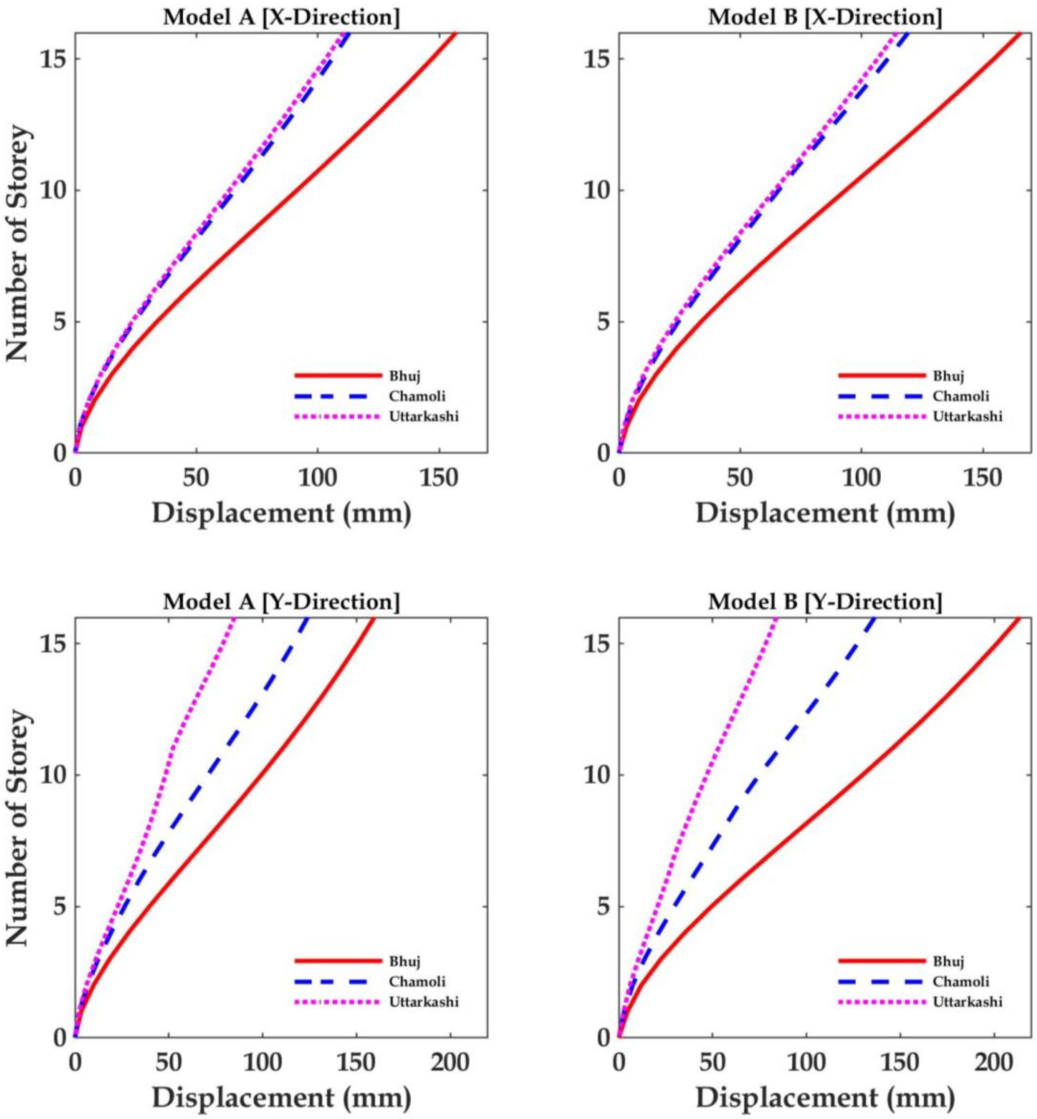


Fig. 11 – Displacement profile for LTHA

Table 9 – Maximum Displacement for both buildings

Building	**Displacement (mm)**					
	Bhuj		**Chamoli**		**Uttarkashi**	
	X	**Y**	**X**	**Y**	**X**	**Y**
A	157	160	113	124	111	85
B	166	214	119	136	114	84

Overall it is observed that performance of building with transfer slab is poor, under linear time history analysis, compared to building without transfer slab. This was reflected in terms of values of design base shears to values of inter-storey drift, and displacements. The current study can be extended by choosing more number of ground motions such that dominant periods of buildings is matching with dominant period of ground motion. Further, carrying out non-linear time history analysis will give more insights about performance of both the buildings.

6. Conclusions

The Indian seismic code is very clear about the vertical irregularity arising due to change in stiffness in successive floors. However, shortcomings in IS 16700 clause related to stiffness irregularity can lead to construction of building with transfer storey in medium to high seismic zone of country. Indian structural and earthquake engineering community should reconsider this clause in coming revision.

Linear time history analysis carried for limited number of Indian ground motion for a given case study found that building with transfer slab is performing poor. Further, majority of existing multi-story buildings designed based on previous seismic code will qualify for ‘soft storey’ as per current code. Hence, from current study it can be extrapolated that such building will also have poor seismic performance. This is true since building with transfer storey and building having soft storey will have inherent vertical stiffness irregularity in them. Therefore there is an urgent need of detailed seismic assessment followed by retrofitting of such tall buildings before next big earthquake hits.

More number of such analytical and experimental studies on scaled down models of building with transfer storey needs to be carried. This will help in benchmarking solid conclusion and thereby upgrading Indian codes by incorporating clauses specifically addressing the transfer storey configuration in tall buildings.

7. Acknowledgements

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