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Design and Cost Comparison of High-Rise Building Structural Systems Using Performance-Based Design

N. Khurram[1], M. F. Tahir[2], U. Akmal[3], M. I. U Hassan[4], U. U Sahar[5]

[1,3,4,5]*Department of Civil Engineering, University of Engineering and Technology Lahore, Pakistan*
[2]*National Engineering Services of Pakistan (NESPAK), Lahore, Pakistan*

[1]nauman@uet.edu.pk

Abstract- In this study, a computer aided analytical comparison is carried out for bundled tube structural system and moment resisting frame system for 10, 15, 20, 25 and 30 storeys buildings using *Performance-Based Design* method, under selected performance level. Seismic and wind loading are considered in addition to gravity loadings as these loadings play a predominant role in the selected tall buildings structural systems and the structure can experience inelastic state while experiencing the ultimate conditions of these loadings. Therefore, a detailed investigation of the actual behavior of the structure is carried out by performance-based design method that gives us an insight into the behavior of structure by identifying the potential weak members, failure modes and ultimate collapse of structure. At the end, structural cost for both systems is also determined. Bundle tube structural system is found to be the most efficient system in terms of performance and cost.

Keywords- Performance based design, High-rise building, Moment resisting frame system, Bundled tube system, efficient system, Performance level

I. Introduction

High-rise buildings have become the need of the time due to increasing population and availability of limited land in larger cities. The high-rise buildings serve both as economic center as well as residential purposes. High-rise buildings are usually categorized into two types of structural systems namely; Interior structures and exterior structures [1]. According to classification, an interior structure resists the lateral loads with the help of the structural system that is located within the interior of the building and, an exterior structure resists the lateral load with the help of a structural system that is located on the outer periphery of a building structure. Moment Resisting Frame System (MRFS) is classified as interior structure whereas; the Bundled Tube System (BTS) is classified as an exterior structure.

Advancement in the field of high-rise buildings has led to a few alternative structural systems and design techniques. BTS is one of the structural systems used for the high-rise buildings. Vikram and Varghese [2] analyzed the bundle-type structural system and concluded that this kind of building improves infrastructure and reduces the cost of cladding. It has also been reported that a proper proportion of beam columns size can improve shear lag behavior of reinforced concrete (RC) bundle type building [3].

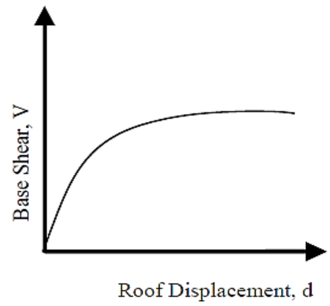
Due to unpredictability and random occurrence of seismic events, the engineering technology requires a continuous advancement to make structures safer and to reduce both life and financial losses. Overall drifting of the building can be reduced by increasing stiffness of members. Karthik and Geetha [4] compared five steel structural frameworks; regular steel structure, tube structure, bundle-tube structure, bundle-tube structure with belt truss and bundle-tube structure with belt-truss and mega-bracing. They found that bundle-tube structure with belt-truss and mega-bracing are stiffer than other four types. Chae et al, [5] has examined the lateral stiffness of associated with horizontal extension of existed bundle-type single unit skyscrapers. He also suggested that at 300-story bundle-type skyscraper to improve stiffness and lateral resistance of building effectively.

During an actual seismic event, the behavior of structure may change from elastic to inelastic. Therefore, non-linear analysis techniques must be considered to evaluate the actual structural behavior under any seismic event. Performance based design tools have become quite popular to assess the inelastic damage state of structures during earthquakes. Performance-based design gives an insight into the actual behavior of the structure by identifying the potential weak members, failure modes and the ultimate collapse of the structure and then explicitly evaluates how a building is likely to perform; given the potential hazard that it is likely to experience. For the last one-decade, nonlinear performance-based design has become quite popular and is being investigated

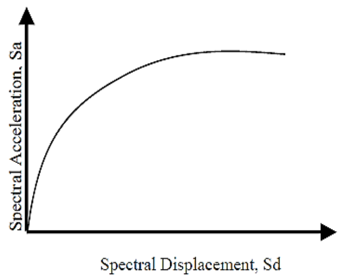
in detail to evaluate various design parameters [6-12]. In this regard, effect of irregularity and unsymmetrical in tall building have been evaluated by considering a performance based nonlinear analysis including the seismic load. [13-14].
Zhang and Tian [15] evaluated the performance based seismic design for multi-storey reinforced concrete moment frames and indicated that flexural strength and cross-sectional area can be reduced up to 30% and 26% respectively from initial strength-based design. A comparative study to check seismic performance of couple core wall building and core wall building with MRFS and performance-based design approach was followed. It was found that building with moment resisting frame showed smaller inter-storey drifts and lower repair cost [16]. Klemencic et al. [17] pointed out that factors like building height, soil type and seismic hazards should be considered carefully to make appropriate assumption of cracking for performance-based design of tall ductile concrete buildings
The goal of performance-based seismic design is to ensure that selective performance objectives are satisfied i.e., the structure will perform in a desired manner under various intensity of earthquake loading. In this regards Habibullah and Pyle [18] have explained in detail, the steps and procedure involved in performing the nonlinear static (pushover) analysis using SAP-2000 [19]. Since than many researchers have successfully used the pushover analysis to study the ductile behavior, development of hinge pattern and seismic demand of high-rise building incorporating the performance-based design approach [20-22]. Literature indicates that numerous research work has carried out using performance-based design. Whereas most of the research deals with specific aspects of MRFS. However, a limited study is available BTS using performance-based design and demands more concentration. Further, very limited work on comparison of BTS and MRFS systems in terms of both design and economy is carried out, which require more attention. Therefore, the present study is emphasized on developing a performance based non-linear analytical comparison of two structural systems, i.e., Moment Resisting Frame System (MRFS) with Bundled Tube System (BTS). The maximum forces, maximum drifts, structural behavior, hinge developments and cost are the main parameter to be compared using performance-based design method.

II. Performance Based Design

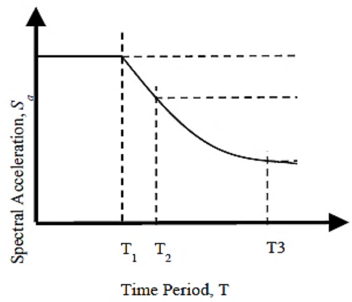
Performance based design predicts the actual behavior of structure in terms of its performance, nature, location, and pattern of hinge formation, identifying the weak members. In this design technique, performance target may be selected as displacement or any other parameters and then design of building is checked against the selected performance level, which is just the reverse of conventional design method. To target displacement level, a pushover analysis is performed, which gives values of displacements and base shear to plot the pushover curve. ATC-40 [23] and FEMA-273 [24] explain the methods to perform pushover analysis.



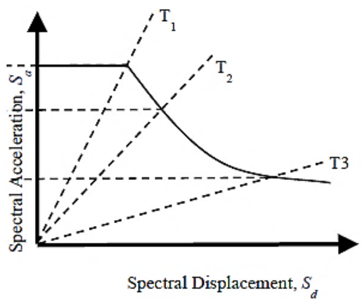
(a) Capacity Curve



(b) Capacity Spectrum



(a) Traditional Spectrum



(b) ARDS Spectrum

Figure 1. Capacity Spectrum Method

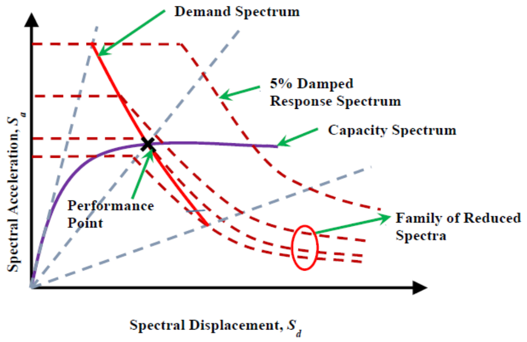


Figure 2. ADRS Capacity Spectrum Method

2.1. Capacity Spectrum Method

Capacity curve is obtained from displacement and base shear values, which is converted into capacity spectrum that is obtained from acceleration displacement response spectra (ADRS) in format of spectral acceleration and spectral displacement. By using equations (1) and (2) capacity curve is converted into capacity spectrum as shown in Fig. 1(a) and Fig. 1(b), while equations (3) and (4) are used to convert traditional spectrum to ADRS spectrum as presented in Fig.1(c) and Fig. 1(d). The final solution for the capacity spectrum method is shown in Fig. 2, various components are shown on the graph. After plotting the capacity spectrum and the demand spectrum on a single plot, the intersection of these spectrums gives the performance of the structure in terms of a performance point. At the performance point, the capacity of the structure is equal to demand which is imparted by the seismic event.

$$S_a = \frac{V/W}{\alpha 1} \quad (1)$$

$$S_d = \frac{\Delta_{roof}}{PF1 \times \phi 1_{roof}} \quad (2)$$

$$S_d = \frac{S_a T^2}{4\pi^2} \quad (3)$$

$$T = 2\pi \sqrt{\frac{S_d}{S_a}} \quad (4)$$

2.3. Building Performance Levels

Performance level are defined as a point on the scale to determine the condition of building after earthquake. FEMA-273 has defined these levels in detail. A typical force-deformation diagram for plastic hinge is shown in Fig. 3. The region between A to B depicts a linear structural behavior. The point IO, LS and CP represent the immediate occupancy, life safety and collapse prevention states, respectively. The point from C to D shows the ultimate collapse of the structure and the point from D to E corresponds to any available residual strength of structure. Immediate occupancy (IO) is the level when minor damage is imparted to structure and is safe to occupy after any seismic activity. Life safety (LS) is the level, when both structural and non-structural members are excessively damage but still building can be used after some repair works. Corresponding to collapse prevention (CP) level, the building is damaged severely and is showing permanent drift. In order to avoid any excessive damage to structure, Immediate Occupancy (IO) level is selected as a performance point in the present study *i.e.*, the building structures remain in the Immediate Occupancy range under the maximum considered earthquake. The results obtained in the present study are checked against the selected performance objective as mentioned in Table 1 and Table 2.

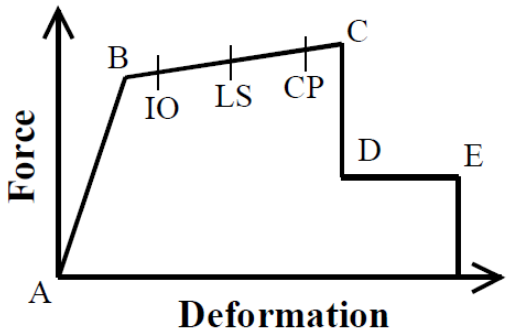


Figure 3. Force-Deformation for pushover hinge [18]

Table 1: Drift limits for concrete frame (FEMA 356, 2000)

Structural Performance level	**Drift (%)**	
Immediate Occupancy	1.0	*Transient*
Life Safety	2.0	*Transient*
	1.0	*Permanent*
Collapse prevention	4.0	*Transient **or** Permanent*

Table 2: Deformation limits for various performance level (ATC-40, 1996)

Performance level	**Inter-storey drift limits**	
	Maximum total drift	***Maximum inelastic drift***
Immediate Occupancy	0.01	0.005
Damage Control	0.01 – 0.02	0.005 – 0.015
Life Safety	0.02	No limit
Structural Stability	$0.33(v_i / p_i)$	No limit

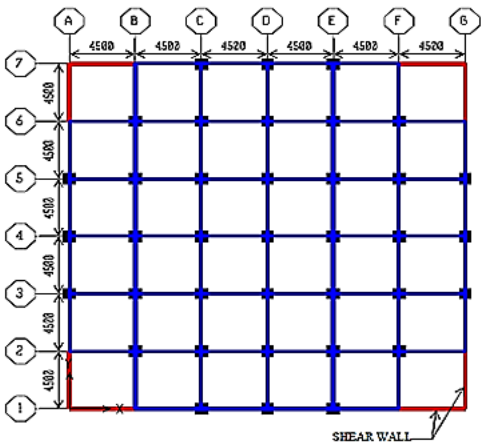
III. BUILDING DESCRIPTION

Overall, similar building configuration is adopted in both Moment Resisting Frame and Bundle Tube structural system. Whereas plan area, number of bays, and number of storeys remains same in all the cases. A brief description of both structural system is described as follows.

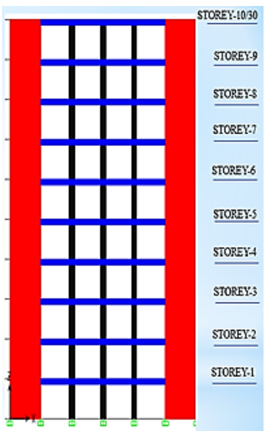
3.1. For Moment Resistant Frame System (MRFS)

Two hypothetical reinforced concrete building plans, symmetrical about both axes are used for this research work. The structural system comprises of slab supported on beams, which transfers the load to columns and from columns to the foundation system. Shear walls are provided at the corners of the buildings to resist the lateral loads from wind and earthquake. The model considered for MRFS consists of six (6) bays in both *x*- and *y*- direction as shown in Fig. 4(a) and elevation is shown in Fig. 4(b). The building is analyzed for 10, 15, 20, 25 and 30 storeys. Various geometric parameters for the building are given below.

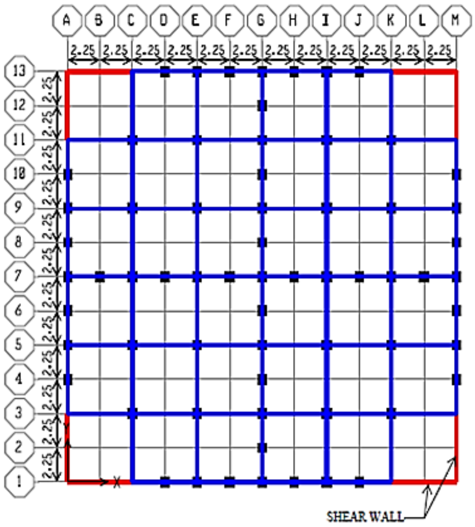
Bays in *x-d*irection = 6 @ 4.50 m c/c
Bays in *y*- direction = 6 @ 4.50 m c/c
Storey height = 3.35 m



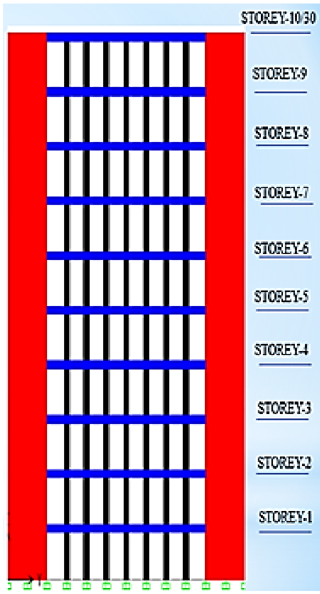
(a). Plan view



(b) Elevation
Figure 4. Plan view and elevation of moment resisting frame



(a) Plan view



(b) Elevation

Figure 5. Plan view and elevation of bundle tube system

3.2. For Bundle Tube System (BTS)

For BTS structure, six (6) bays in both x- and y- direction as shown in Fig. 5(a) and elevation is shown in Fig. 5(b). It comprises of four tubes consisting of 3 bays in each direction joined together. The columns at the outer periphery of the tubes are closely spaced and the center to center spacing between them is 2.25m. The interior columns are placed at a spacing of 4.5m center to center. The building is analyzed for 10, 15, 20, 25 and 30 storeys. Total of eight (08) shear walls are provided at the corners. Various geometric parameters for the building are as follows.

Bays in x- direction = 6 @ 4.50 m c/c
Bays in y- direction = 6 @ 4.50 m c/c
Storey height = 3.35 m

Center to center spacing between the interior columns = 4.50 m
Center to center spacing between the columns at outer periphery = 2.25 m

IV. ANALYTICAL MODELLING

An initial analysis and design of structures for both building systems is carried out as per specification of American Concrete Institute, ACI 318-08 [25], using the standard codes in SAP-2000 [19]. The loadings have been applied as per Uniform Building Code (UBC-97) [26]. Values of different loadings and material properties are shown in Table 3 and Table 4, respectively. The structural members (beams and columns) are modeled as the frame element, whereas slab and shear wall have been modeled as the shell element. For non-linear analysis, flexure (M3) hinges for beams and bi-axial flexure (P-M2-M3) hinges for columns are assigned as per FEMA-356 [27]. The hinges are assigned to each structural member at the start and at the end locations of the structural member. Two cases are defined for pushover analysis, first is a force-controlled process to apply the gravity load (pushdown) with DL+SD+0.25LL load combination and second for the lateral loads. Loading (pushover) starts from the final conditions of the gravity load case, and it is a displacement-controlled process. The pushover analysis is then carried out by using the fundamental mode (mode-1) of the structure in the global *x*-direction. The control node is defined at the roof level. After defining and assigning the plastic hinge data and the pushover load cases, a non-linear static analysis is carried out. The plastic hinges at nodes were assigned using auto hinge properties option available in SAP 2000. The performance of the structures is assessed by using Capacity Spectrum Method as defined by ATC-40. The demand spectrum for determining the performance objective is taken from UBC-97. After the analysis, the results are obtained in terms of pushover curve and the performance point from the capacity spectrum curve (ADRS capacity spectrum method). The number of hinges at each performance state are also calculated. The storey drift ratio for each storey is then calculated at the performance point.

Table 3. Different values of load

Dead Load (DL)	Weight of permanent structural and non-structural components
Super Dead Load	Concrete = 24 kN/m^3 Steel = 77 kN/m^3 Brickwork = 19 kN/m^3 Compacted Earth = 19 kN/m^3
Superimposed DL	Floor Finishes = 1.436 kN/m^2 Partition Load = 0.957 kN/m^2 Ceiling Finish = 0.478 kN/m^2
	Masonry Load on exterior Beams = 14.60 kN/m
Live Load	LL = 2.872 kN/m^2
Seismic Load	Seismic zone = 3 Seismic zone factor, Z = 0.3 Soil profile = SD Seismic coefficient C_a = 0.36 Seismic coefficient C_v = 0.54
Wind Load	Wind speed = 112.7 km/h Exposure category = B Windward coefficient, C_q = 0.8 Leeward Coefficient, Cq = 0.5

Table 4. Material Properties

Concrete (28-days)	Columns = 28 MPa Shear wall = 28 MPa Beams and slabs = 21 MPa
Steel	ASTM A-615 Grade 60 (Min. yield strength 414 MPa)

V. RESULTS AND DISCUSSION

A storey-wise comparison is carried out in terms of performance point, storey drift ratio and hinge development states at the performance point for both the structural systems to assess their performance.

5.1. Drift Ratio

Ductility ratio is calculated as the ratio between the displacements at the performance point to the displacement at the elastic limit point. For 10, 15 and 20-storeys structure, the ductility ratio for the MRFS is found to be higher than that of BTS, which shows a more ductile behavior of MRFS as compared to the BTS. However, the difference between drift ratio values reduces as building height increases from 10 to 15-stories that indicates the increasing ductile behavior of BTS. Ductility ratio of BTS comes out to be more as compared to MRFS for 25-stotey and it further increases, when height is increased to 30-storey. It strengthens the argument for the suitability of BTS for high-rise building. Elastic limit or the stage of formation of first hinge for the BTS is higher as compared to the moment resisting frame system (MRFS). It means that the formation of hinges in MRFS takes place earlier as compared with the BTS.

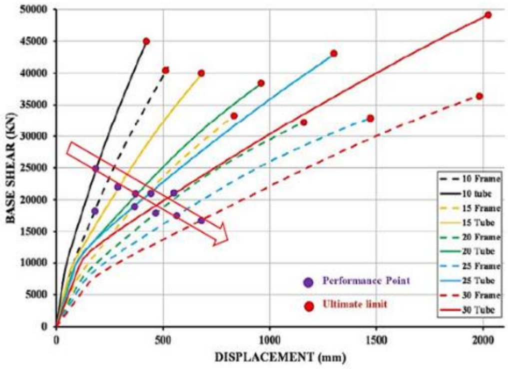


Figure 6. Combined capacity curves of both systems for all storeys

The combined results of both MRFS and BTS have been plotted in graphical form as shown in Fig. 6, which clearly depicts that, as the height of the building increases the inelastic limit for the structure is approached earlier. The probability of development of hinges at lower values of lateral loads increases. The arrow shows an inclined downward trend of the performance point with the increase of structure height, hence showing a more inelastic behavior of the structure as the number of stories are increased. Comparison of the performance point of the two structural systems by ADRS capacity spectrum method is shown in Fig. 7, which indicates a better performance of BTS over MRFS as the performance point against lateral load in BTS achieved at lesser displacement as compared to MRFS.

Values obtained for various parameters at the performance point for the two building systems is presented in Table 5. Base Shear value for both systems decreases with the increase in number of storeys, while displacement values for both systems increases with the increase in building height. Value of spectral acceleration is dependent on g-force and decreases with the increase in number of storeys, but spectral displacement, effective time and effective damping escalates with the increase of building height.

It is observed that storey drift ratios for BTS is well within the limit specified by the performance objective for all cases as shown in Fig. 8. In case of 10-storeys, maximum drift ratios for both the structure systems are observed at the seventh floor. Fig. 8 also reveals that maximum drift ratio value occurs at higher floor level with the increase of building height. When number of storeys are increased the maximum drift ratio occurs at 8th, 9th, 13th, and 14th floor for BTS and 11th, 12th, 14th and 17th floor for MRFS, corresponding to 15th, 20th, 25th and 30th storey height, respectively.

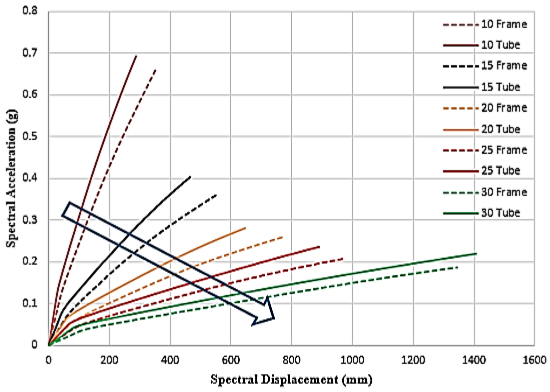


Figure 7. Performance points using ATC-40 capacity spectrum method of both systems for all storeys

Table 5: Various Parameters at Performance Point

Storey Level	Building	Base Shear	Displacement	Spectral Acceleration	Spectral Displacement	Effective Time Period	Effective Damping
		(kN)	(mm)	(g)	(mm)	(s)	
10	MRFS	21281.48	218.15	0.341	149.891	1.329	0.095
	BTS	24356.07	182.00	0.369	125.925	1.172	0.111
15	MRFS	18507.51	355.99	0.198	242.78	2.22	0.105
	BTS	21851.26	290.61	0.215	200.72	1.93	0.125
20	MRFS	17649.69	456.14	0.138	312.09	3.01	0.125
	BTS	21214.23	374.77	0.149	258.47	2.64	0.149
25	MRFS	17608.13	567.22	0.108	383.54	3.78	0.134
	BTS	20783.25	443.44	0.115	312.51	3.31	0.165
30	MRFS	16942.7	687.8	0.085	474.47	4.57	0.140
	BTS	20626.2	536.6	0.090	383.40	4.14	0.174

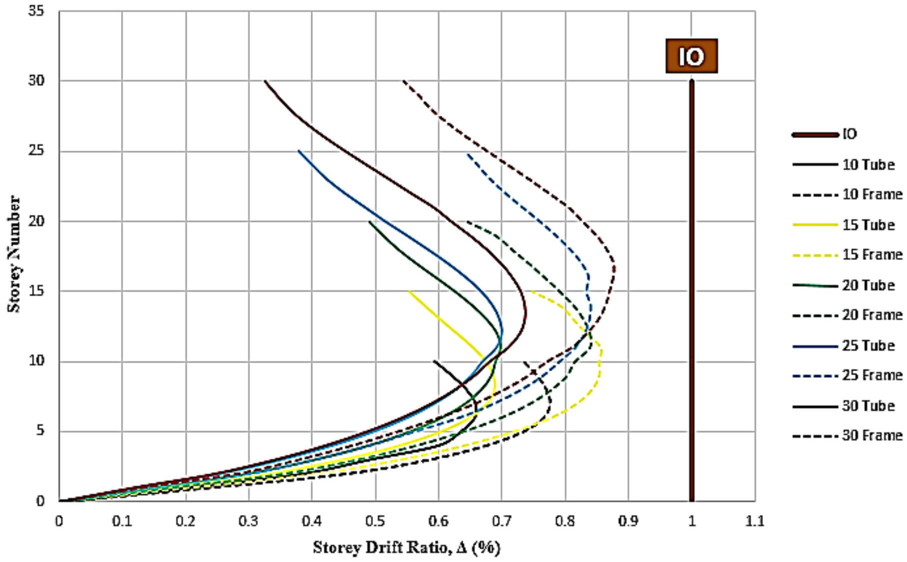


Figure 8. Storey drifts ratio of both systems for all storeys

Table 6: Structural element's performance levels at performance point

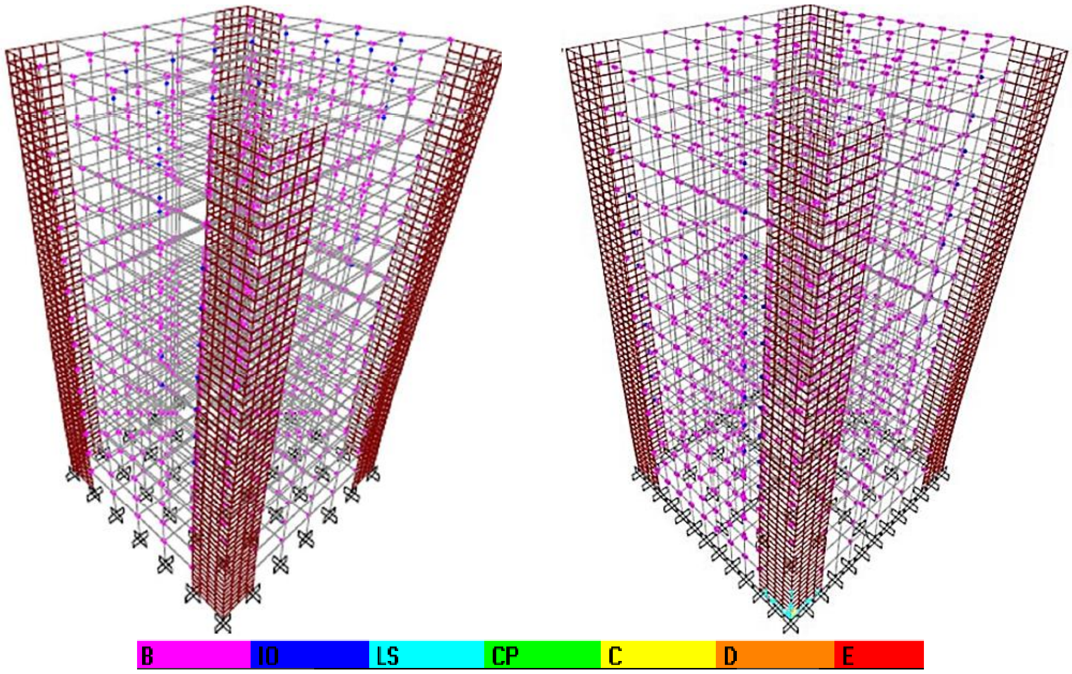
Storey Level	Type	Step	Displacement (mm)	Base Shear (kN)	A to B	B to IO	IO to LS	LS to CP	CP to C	C to D	D to E	Beyond E	Total
10	MRFS	19	217.14	21204.60	1322	390	8	0	0	0	0	0	2260
	BTS	12	183.85	24544.15	2147	1217	16	0	0	0	0	0	3380
15	MRFS	32	358.27	18594.61	1950	1399	41	0	0	0	0	0	3390
	BTS	26	284.37	21516.55	3329	1693	48	0	0	0	0	0	5070
20	MRFS	40	459.66	17745.39	2763	1725	32	0	0	0	0	0	4520
	BTS	33	376.03	20827.85	4499	2207	54	0	0	0	0	0	6760
25	MRFS	48	573.09	17731.75	3495	2107	48	0	0	0	0	0	5650
	BTS	39	443.85	21225.22	5742	2646	62	0	0	0	0	0	8450
30	MRFS	58	685.48	16902.50	4313	2411	56	0	0	0	0	0	6780
	BTS	48	542.07	20742.78	6938	3120	82	0	0	0	0	0	10140

5.2. Plastic Hinge State

Results illustrates that majority of hinges are formed in the range from Basic Occupancy (BO) to Immediate Occupancy (IO) range, while some hinges at the top storey have reached to from immediate Occupancy to life safety (IO to LS) range as well. Hinge development status shown Fig. 9 and Fig. 10 also revealed that most hinges, ranging IO to LS limits occur mostly at top floor for both types (i.e., BTS, MRFS) of building structure having less than 15-storeys but they develop within intermediate floor if number of storeys exceeds fifteen. It is also observed that majority of hinges were formed in the beam element in the direction of lateral force. This indicates the strong column and weak beam phenomenon, which is a desirable situation. Results of all storey cases at the performance point are summarized in Table 6 and total number of plastic hinges at each limit state are also provided. That clearly depicts that the as the height of the building increases, the inelastic limit for the structure is approached earlier. The probability of development of hinges at lower values of lateral loads increases. Further, in BTS number of hinges corresponding to each limit state were observed more than that of MRFS, which indicates a more ductile behavior of BTS over MRFS.

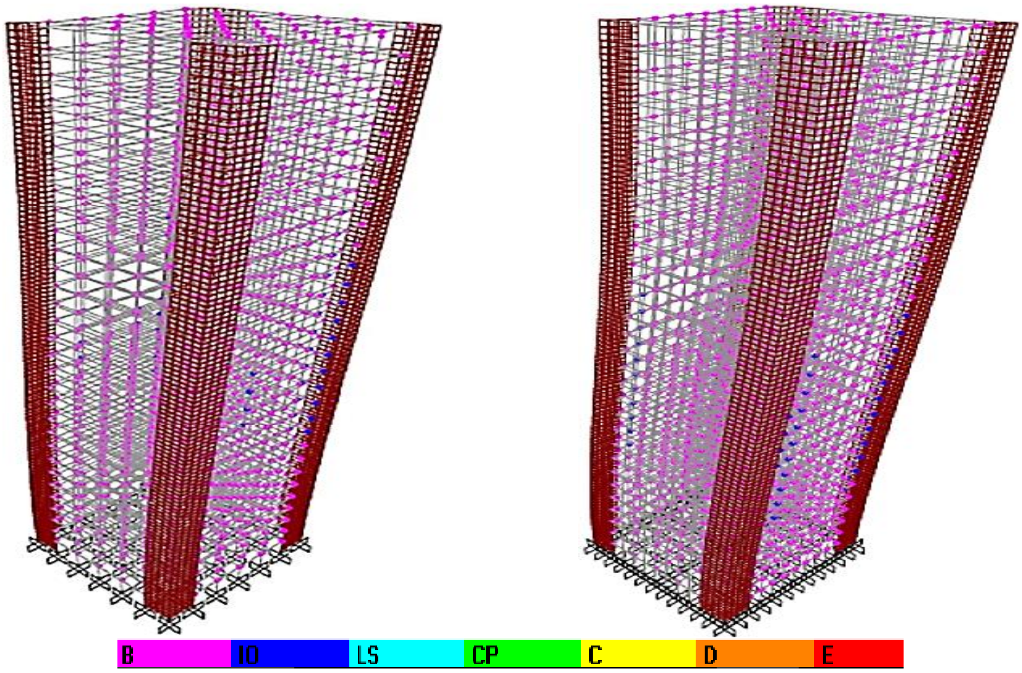
5.3. Performance and Cost Comparison

Displacement versus base shear value of each storey case for both BTS and MRFS are also plotted as shown in Fig. 12, which shows that BTS performs better than MRFS by adopting performance-based design. The MRFS are subjected to more displacement corresponding to lesser base shear value. Hence showing a more inelastic behavior of structure as the number of stories are increased. While comparing the performance of tall buildings, cost of structure also becomes an important parameter. In this regards the cost estimate of already evaluated structural system (i.e., BTS and MRFS) is also established.



(a) for MRFS (b) for BTS

Figure 10. Hinge status at performance point for 15-Storeys



(a) for MRFS (b) for BTS

Figure 11. Hinge status at performance point for 30-Storeys

The cost estimate is prepared by using the latest market rates. This cost includes the cost of structural items. The cost comparison of both the structural systems is shown in Fig.13. The comparison is carried out in terms of cost per square meter and the unit for cost is taken as Rupees (Rs.). It is evident that although the BTS is more design efficient as compared to the MRFS but in terms of cost, MRFS has an edge over the BTS.
However, the difference of cost decreases with the increased in height of structure. It was observed that initially the MRFS was more economical then the BTS, but this difference goes on decreasing as the number of stories are increased and is reduced from 15.22% for 10 storeys to 10.25% for the 30 storeys as shown in Fig. 14.

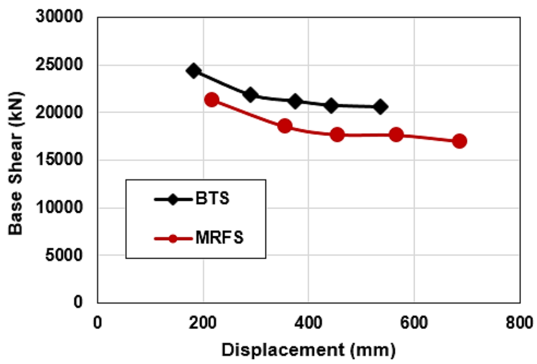


Figure 12. Performance comparison of BTS and MRFS

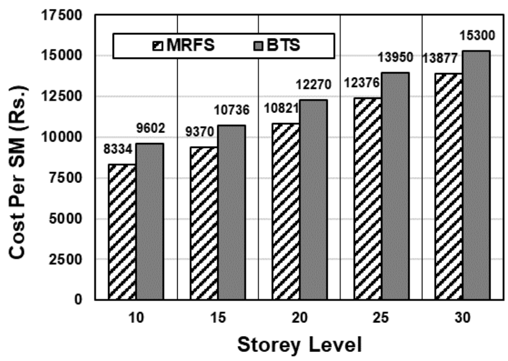


Figure 13. Cost Comparison with rest to number of storeys

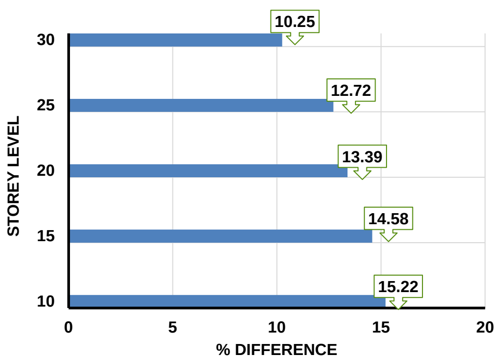


Figure 14. Percentage cost difference with respect to number of storeys

VI. CONCLUSIONS

Based on the analytical study the following conclusions are drawn.

- The bundle tube system (BTS) shows a better performance as compared to the moment resisting frame structures (MRFS) in terms of design parameters. The ductility ratio of BTS is 5.43 as compared to ductility ratio of MRFS of 5.37 up to 20th Storey. As the number of stories increases, the ductility ratio for BTS reaches 6.02 as compared to the ductility ratio of MRFS of 4.89. this depicts better performance of BTS as BTS is more ductile as compared to MRFS.
- The Performance-Based design gives an insight into the actual behavior of the building structure in terms of its performance, nature, location, and pattern of hinge formations and identifying the potential weak members. For 25-storey frame system, the hinges were developed at 9-13 floor beams of the outer frame. The collapse hinges were formed at the beams adjacent to the shear wall.
- The cost efficiency of BTS increases for high-rise buildings. The difference was reduced from 15.22% to 10.25%. In terms of meeting the design perimeters and cost effectiveness, BTS may be preferred for high-rise buildings. The MFS should be preferred for low-rise building structures, both in terms of design and cost efficiency.

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