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# **Analysis on the Structural Systems for Drift Control of Tall Buildings due to Wind Load: Critical Investigation on Building Heights**

Shafiqul Islam<sup>1</sup> and Md. Mashfiqul Islam<sup>2</sup>

## **ABSTRACT**

*The great metropolises of the world share common dilemmas. Increased population densities due to the migration of people from the countryside to the cities, combined with the rising price of developable land and the environmental politics of the day provide the urban planners with no better solution than to build higher. In Bangladesh this scenario is getting familiar from past few decades. As a result, constructions of tall buildings of more than 20 stories become necessary and already practiced especially for Dhaka city to support the current demands. As building increases in height, the lateral displacement of the building due to wind loads becomes one of the primary concerns. An excessive lateral displacement or inter-story drift causes the failure of both structural and non-structural elements. In design specifications, the calculated displacement at the top of a high-rise building and inter-story drifts at the final stage of the structural design process must be checked not to exceed specified limits with respect to building height as well as individual story height. To this end, this paper investigates the performance and efficiency of special structural systems in drift control of 20, 30, 40 and 50 stories high tall buildings due to wind load. Large Scale Bracing system, Shear wall with Bracing system, shear wall frame system and Tube in Tube with Shear wall systems are critically analyzed to investigate the drift control for those heights. The Shear wall with Bracing system showed the most acceptable results in drift control for all heights.*

**Keywords:** *Structural systems, tall buildings, drift control, inter-story drift, wind load.*

## **1. INTRODUCTION**

Drift control of tall building refers to maintain the lateral deflection of tall building at sufficiently low level to allow the proper functioning of nonstructural components

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(elevators, escalators etc.) and to avoid distress in the structure, to prevent excessive cracking due to deflection and consequent loss of stiffness. The adopted structural system should be sufficiently stiff to prevent dynamic motions (due to wind and seismic loading) becoming large enough to cause discomfort to occupants, prevent delicate work being undertaken, affect sensitive equipment and to avoid any redistribution of load to non-load bearing portions or infills. For buildings having small number of story, lateral loads rarely affect the design. But when the height of the building increases, the increase in size of structural members and the possible rearrangements of the structure to account for loads incurs a cost premium (Sazzad and Kamruzzaman, 2002).

From a structural engineers point of view, a tall building may be defined as one that, because of its height, is affected by lateral forces due to wind or earthquake actions to an extent that they play an important role in the structural design as well as deciding appropriate structural system to withstand those forces. One simple parameter to estimate the lateral stiffness of a building is the drift index, defined as the ratio of maximum deflection at the top of the building to the height due to lateral forces (Smith & Coull, 1991). Drifts (lateral deflections) of concern in serviceability checking arise primarily from the effects of wind. As per ASCE/SEI 7-05 (2006), the limit for drift index is below 1/600 (0.001667) to 1/400 (0.0025). These limits generally are sufficient to minimize the damage to cladding and nonstructural walls and partitions. Smaller drift limits may be appropriate if the cladding is brittle. Another important parameter to evaluate the stiffness of tall building is inter-story drift values. An absolute limit on inter-story drift may also need to be imposed in light of evidence that damage to non-structural partitions, cladding and glazing may occur if the inter-story drift exceeds about 10 mm (3/8in i.e. 0.375in) unless special detailing practices are made to tolerate movement (ASCE/SEI 7-05, 2006). Many components can accept deformations that are significantly larger. For conventional structures the preferred acceptable range is 0.0015 to 0.003 and sufficient stiffness must be provided to ensure that the top deflection does not exceed the value under extreme loading condition (Smith & Coull 1991, Islam et. al. 2011, Islam et. al. 2012).

Wind load presents the most critical lateral loading for modern tall buildings, which have lightweight skeletons that cause uncomfortable horizontal movements for occupants. Also, wind is not constant either with height or with time and is not uniform over the sides of a building. So, windy weather creates a variety of problems in tall buildings, causing concern for buildings owner and engineers alike. Where, excessive vibration due

to this load is a major obstacle in design and construction of a modern tall building. It should be limited to prevent both structural and nonstructural damage (El-Leithy et. al., 2011).

Concrete shear walls are widely used in tall buildings to provide lateral rigidity and to perform satisfactory in resisting loads due to wind without incurring structural or architectural damage (Park and Park, 1997). Shear walls are often parts of the elevator and service cores, while the frames are arranged in plan, and they are linked by floor slabs such that the building will deflect as a structure with rigid section. When a wall-frame structure is loaded laterally, the wall deflects in a flexural mode with concavity downward and a maximum slope at the top, and the frame deflects in a shear mode with concavity upward and a maximum slope at the base. Accordingly, the deflected shape of the whole structure has a flexural profile in the lower part and a shear profile in the upper part. The interacting forces cause the wall to restrain the frame near the base and the frames to support the wall at the top, and thus reduce the lateral drift of the structure. The major advantages of a wall-frame structure depend on the amount of horizontal interaction, which is governed by the relative stiffness of the walls and frames, and the height of the structure. Since the elastic capacity of the structure is limited by the material strength, survival generally relies on the ductility of structural system to dissipate energy (Pall and Marsh, 1981). The key idea in limiting the wind drift in a tall building is by changing the structural form of the building into something more rigid and stable to confine the deformation and increase stability. The stiffness (rigidity) and stability requirements become more important as the height of the structure increases, and they are often the dominant factors in the design (El-Leithy et. al. 2011). An important problem associated with wind induced motion of buildings is concerned with human response to vibration and perception of motion. At this point it will suffice to note that humans are surprisingly sensitive to vibration to the extent that motions may feel uncomfortable even if they correspond to relatively low levels of stress and strain. Therefore, for most tall buildings serviceability considerations govern the design and not strength issues (Mendis et. al. 2007). The major factors that has to be taken into account in selecting the appropriate structural system includes the internal planning, the material and method of construction, the external architectural treatment, the planned location and routing of the service systems, the nature and magnitude of horizontal loading and the height and proportions of the building. Common structural systems are framed system, braced-frame system, rigid-frame system, infilled-frame system, flat-plate and flat-slab system, shear

wall and coupled-shear wall system, shear wall-frame system, framed-tube (tubular) system, tube-in-tube and bundled-tube system, braced-tube system, outrigger-braced system, suspended structure system, core structure system, space structure system, hybrid structure system etc. In this paper, some special structural systems are critically analyzed to identify the sustainable option to control the drift of tall buildings. This research puts light on the performance, efficiency and compatibility of those structural systems for tall buildings to be built in the skyline of Bangladesh.

## **2. PROBLEM STATEMENT**

Four structural systems are selected to investigate the drift pattern due to lateral loading; they are large scale braced-frame system, shear wall with bracing system, shear wall-frame system and tube in tube system which showed lower drift index values in the analyses done in Islam et. al. 2012. The prototype models considering reinforced cement concrete (RCC) structures are created for 20, 30, 40 and 50 storied tall building for these four systems.

RCC tall buildings of different structural system are modeled considering 20, 30, 40 and 50 storeys with story height 10ft using ETABS 9.2, which is a renowned structural analysis software. The sizes of the beams are 12in x 15in, 12in x 18in, 12in x 21in and 12in x 24in and the sizes of the columns are 24in x 24in, 27in x 27in, 30in x 30in and 33in x 33in for 20, 30, 40 and 50 storied buildings respectively. The thickness of the shear walls are considered 12in, 14in, 16in and 18in and the cross sections of the bracings are considered 12in x 12in, 15in x 15in, 18in x 18in and 21in x 21in for 20, 30, 40 and 50 storied buildings respectively. The thickness of the slab for all structural system are maintained 6in. The wind load is applied as per UBC 1994 (Uniform Building Code) which is equivalent to BNBC 1993 considering exposure condition A and wind velocity 210 km/hr. Load combinations are applied as per BNBC 1993 specifications. The dead load is considered 40 psf and live load 60 psf. Figure 1 shows elevations of different structural systems investigated in this study and Figure 2 shows typical floor plans.

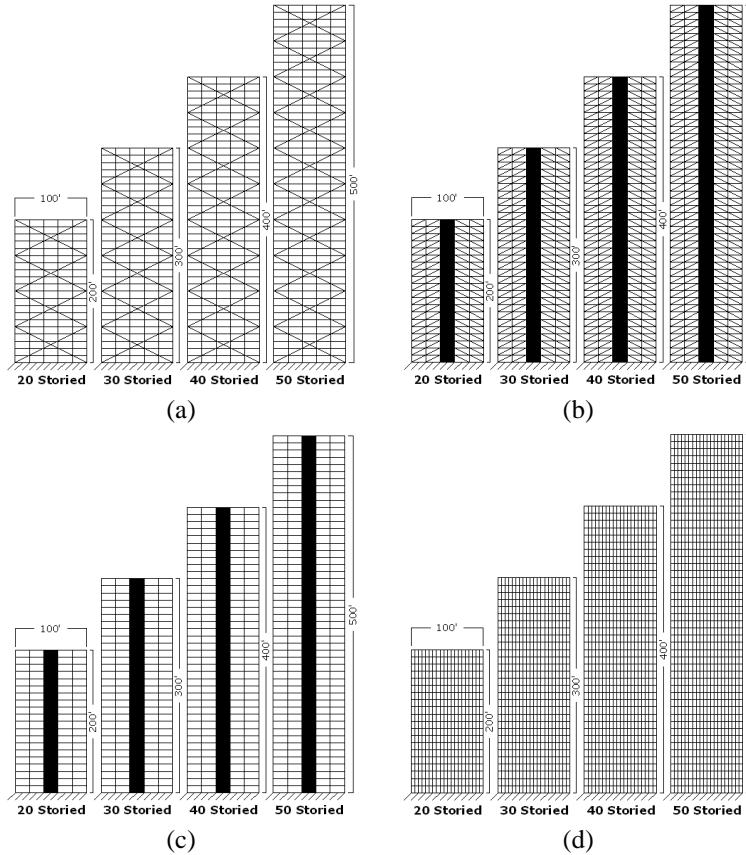


Figure 1: Elevation of 20, 30, 40 and 50 storied buildings (a) Large scale bracing system (LSB), (b) Shear wall with Bracing system (SWB), (c) Shear wall Frame system (SWF) and (d) Tube in Tube system (TT).

### 3. ANALYSIS RESULTS AND DISCUSSION

Here the pertinent parameters of a tall buildings, such as, deflection and its pattern, bending moments and shear forces of columns are extensively studied to determine the best of among four systems stated earlier. The structural system with higher capacity to reduce the deflection, bending moment and shear force may be selected for tall building construction.

### 3.1 Building Height Effect

The effect of height of tall buildings are clearly visible in Figures 3, 4, 5 and 6. The drift of Large Scale Bracing system (Figure 3) increases significantly with heights and also this is found for its inter-story drift. The inter-story drift of Large Scale Bracing system shows a zigzag pattern which is definitely due to the bracing-beam-column connections. It is also found from the inter story drift results that the first story drift is significantly higher which may become desastorous as it happens for a soft story. This is due to the absence of shear wall. Again after 40 stories the wind speed is high enough that makes a abrupt variation of the inter-story drift patten. The top lateral deflection for 20, 30, 40 and 50 stories are 1.61in, 3.65in, 6.91in and 11.5in respectively and maximum inter story drifts are 0.12in, 0.18in, 0.25in and 0.32in respectively .

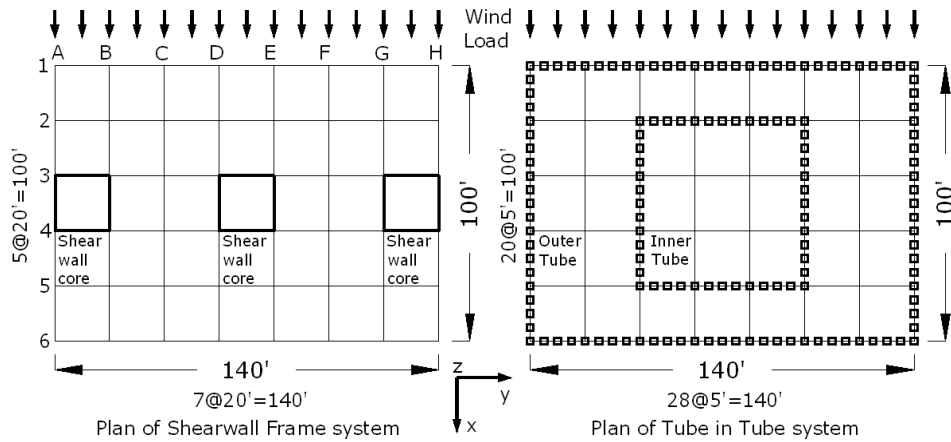


Figure 2: Typical floor plan of Shear wall-frame and Tube in Tube system.

For the Shear wall with Bracing system (Figure 4) the lateral deflection is found less increment with heights and the inter-story drift is found to become almost constant after midheight which is a indication of stable control of the drift due to lateral loading. The top lateral deflection for 20, 30, 40 and 50 stories are 0.65in, 2.16in, 5.35in and 10.23in respectively and maximum inter-story drifts are 0.03in, 0.07in, 0.14in and 0.24in respectively.

The Shear wall Frame system (Figure 5) less control on lateral deflection compared to above systems and the inter story drifts show a extensively large drift at the mid height with a decreasing pattern to the upper stories. This system provides information on the



less control on the inter-drifts. The top lateral deflection for 20, 30, 40 and 50 stories are 1.64in, 4.57in, 9.41in and 15.96in respectively and maximum inter-story drifts are 0.1in, 0.2in, 0.29in and 0.38in respectively.

Tube in Tube system shows similar pattern of lateral deflection like Large Scale Bracing system (Figure 6). The inter-story drift of this system shows a increasing tendency in lower stories and a gradual decreasing tendency towards the upper stories. Tube in Tube system shows a significant drift control for 50 storied building compared to lower storied. The top lateral deflection for 20, 30, 40 and 50 stories are 3.19in, 6.39in, 10.08in and 10.49in respectively and maximum inter-story drifts are 0.26in, 0.286in, 0.37in and 0.286in respectively.

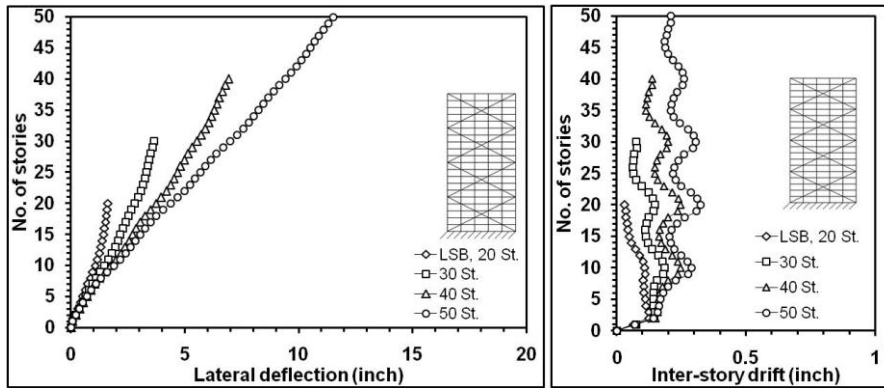


Figure 3: Lateral deflection and Inter-story drift of Large Scale Bracing system

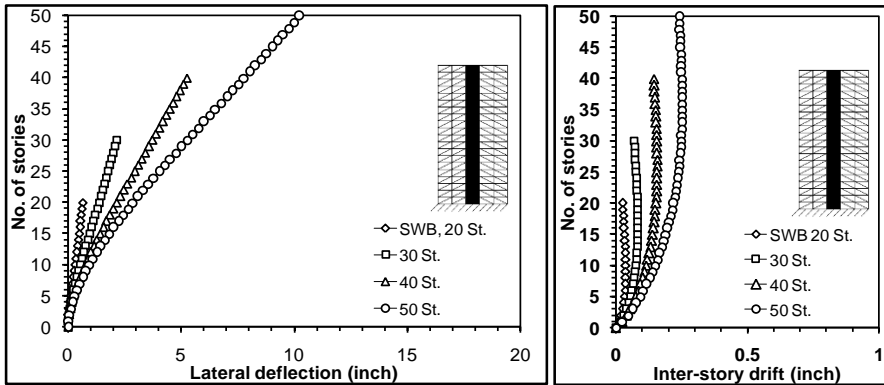


Figure 4: Lateral deflection and Inter-story drift of Shear wall with Bracing system

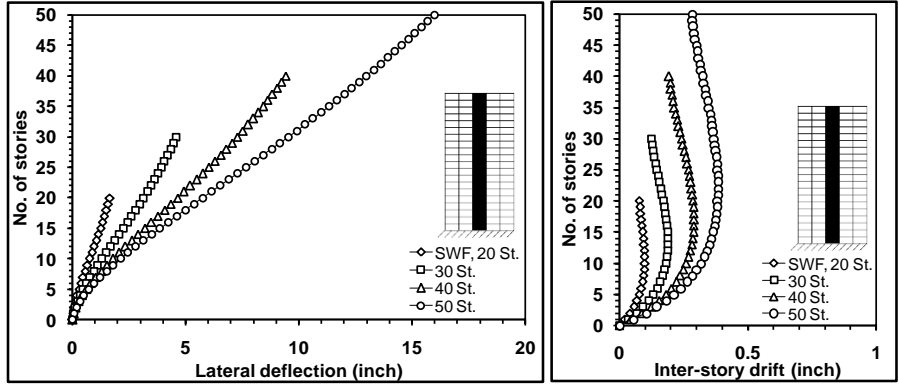


Figure 5: Lateral deflection and Inter-story drift of Shear wall-frame system

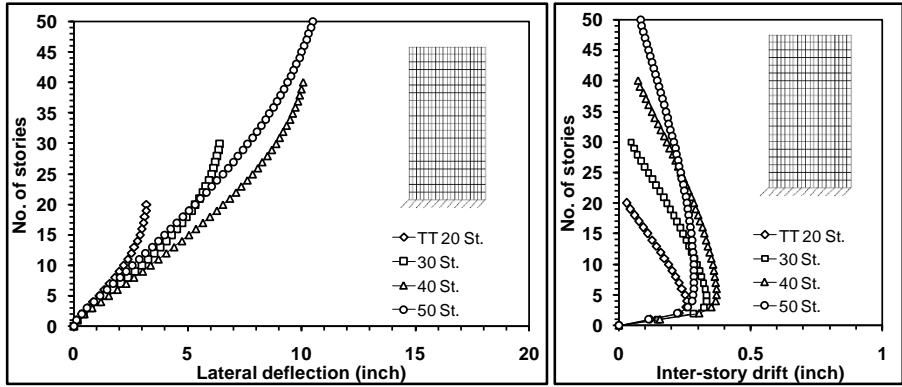


Figure 6: Lateral deflection and Inter-story drift of Tube in Tube system.

### 3.2 Bending Moment Effect

The bending moment diagrams of the column A6 (Figure 2) of the tall buildings are shown in Figures 7, 8, 9 and 10. The bending moment diagram of Large Scale Bracing system (Figure 7) shows a different pattern with heights. The bending moments of columns have found lower in the story where the bracings are connected and larger in other stories. The maximum positive moments are 241, 406, 572 and 510 kip-ft and maximum negative moments 22, 25, 25 and 25 kip-ft for 20, 30, 40 and 50 storied buildings respectively.

The Shear wall with Bracing system shows a uniform decreasing pattern of bending moment with height and also highest moment resisting capacity compared to other

system. The maximum positive moments are 31, 62, 107 and 161 kip-ft and maximum negative moments 16, 16, 15 and 14 kip-ft for 20, 30, 40 and 50 storied buildings respectively.

The Tube in Tube system and Large Scale Bracing (Figure 7 and 10) showed similar pattern of bending moment as none of these two systems having shear walls. The maximum positive moments of Tube in Tube system are 210, 395, 621 and 652 kip-ft for 20, 30, 40 and 50 storied buildings respectively and no negative moments developed. Again the maximum positive moments of Shear wall Frame system are 62, 132, 235 and 353 kip-ft for 20, 30, 40 and 50 storied buildings respectively and maximum negative moments 6, 6 and 0.1 for 20, 30 and 40 storied buildings respectively.

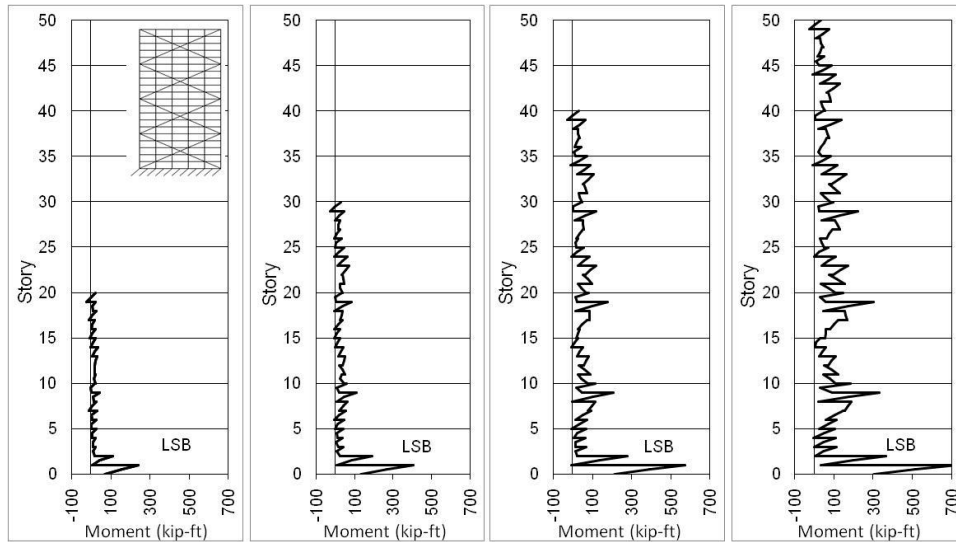


Figure 7: Bending moment diagram of Large Scale Bracing system.

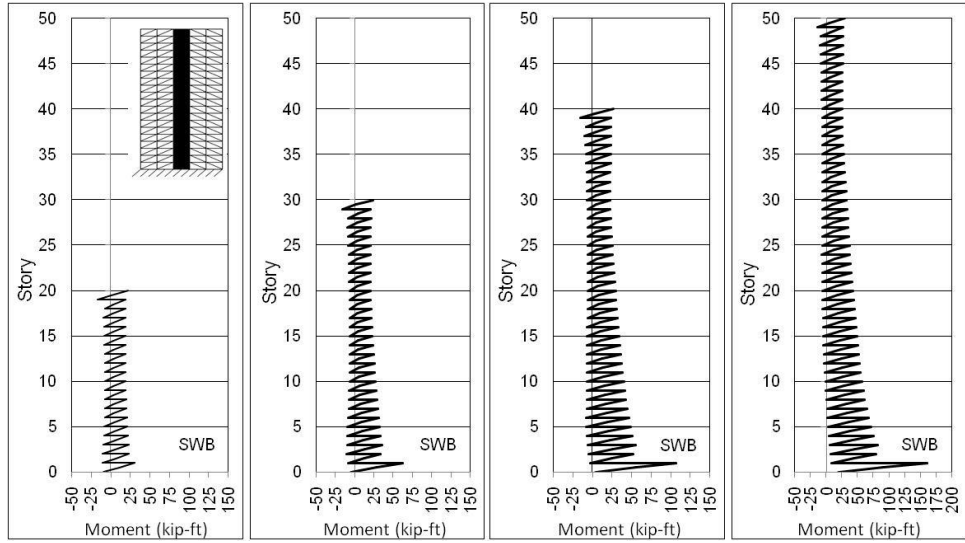


Figure 8: Bending moment diagram of column of Shear wall with Bracing systems.

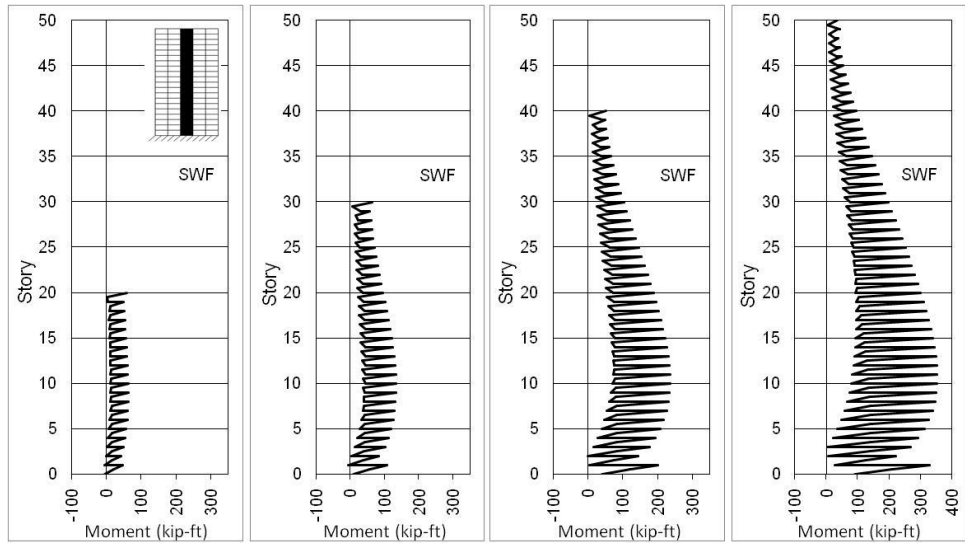


Figure 9: Bending moment diagram of column of Shear wall-Frame systems.

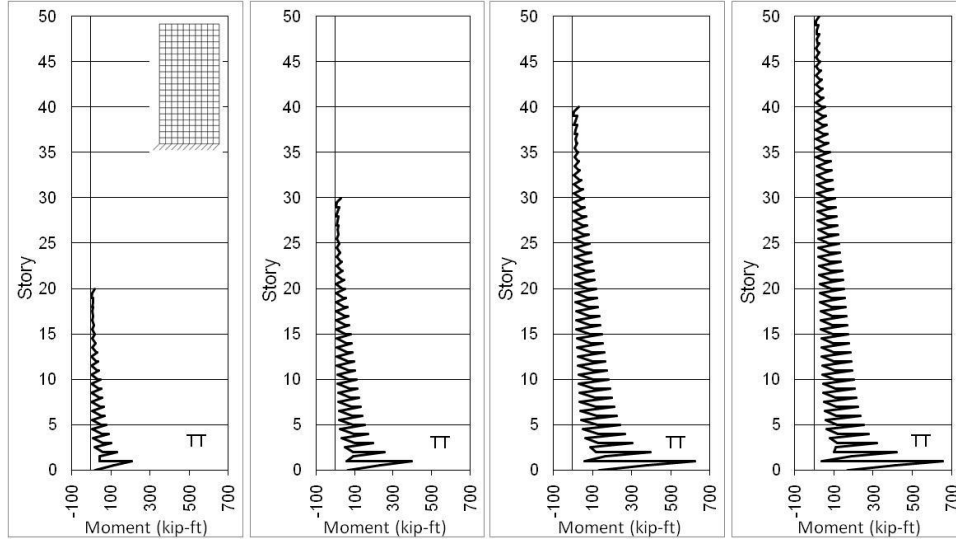


Figure 10: Bending moment diagram of column of Tube in Tube systems

### 3.3 Shear Force Effect

The shear forces in the columns of different structural systems are showed in Figures 11, 12, 13 and 14. The Large Scale Bracing system (Figure 11) shows a gradual decreasing pattern of shear force in columns with heights. Shear wall with Bracing system (Figure 12) shows a more or less stable value of shear force for all heights even also for top story. Shear wall Frame system (Figure 13) shows a significant increase of shear force with increasing height in parabolic pattern also for top stories. On the other hand the Tube in Tube system (Figure 14) shows a completely different patterns. Comparing all the structural systems, the Shear wall with Bracing system is found the most efficient in controlling shear force in the building columns. The values of maximum shear forces are for Large Scale Bracing system 29kips 52kips 80kips & 107kips for 20. 30. 40 and 50 storied buildings respectively. These values for Shear wall Bracing systems are 0.5, 3, 7 & 13 kips, for Shear wall Frame structures are 1, 5, 14 & 24 kips and for Tube in Tube systems are 13, 23, 35 & 36 kips respectively.

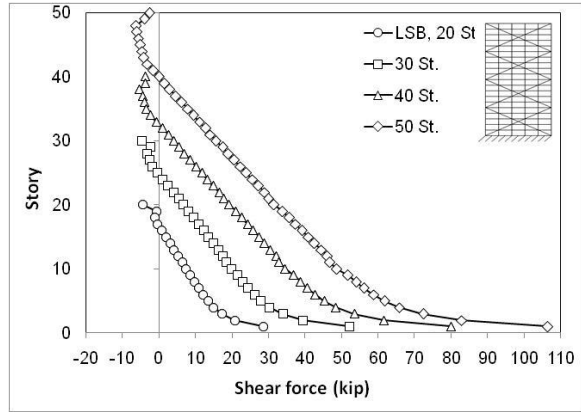


Figure 11: Shear force of Large Scale Bracing system

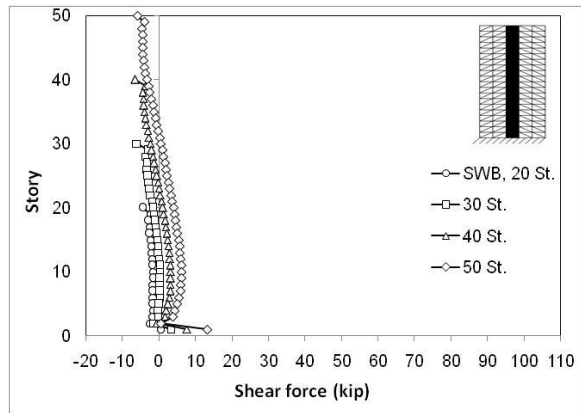


Figure 12: Shear force of Shear wall with Bracing system

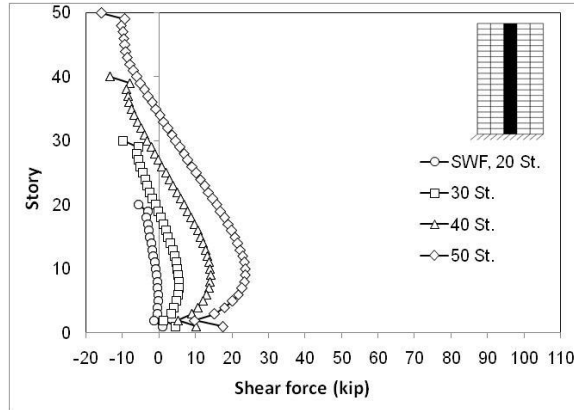


Figure 13: Shear force of Shear wall-Frame system

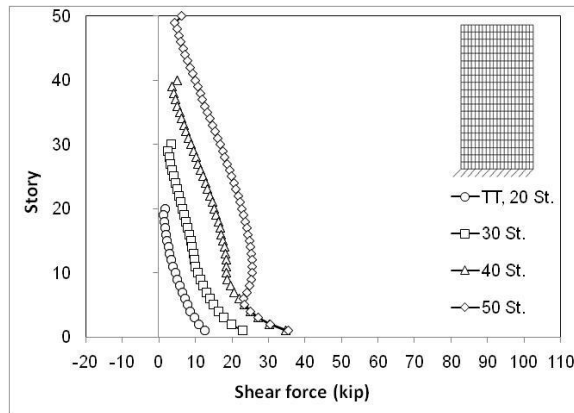


Figure 14: Shear force of Tube in Tube system.

#### 4. COMPARISON OF STRUCTURAL SYSTEMS

The comparative representations of lateral deflection and inter-story drift results for 20, 30, 40 and 50 storied buildings are shown in Figures 15, 16, 17 and 18 respectively. It is found from Figure 15 that the Shear wall with Bracing system efficiently minimizes the drift and also the inter story drift is minimum up to 20 stories. Moreover the two systems (SWB and SWF) with shear walls deflect in a flexure fashion but Large Scale Bracing and Tube in Tube system deflects in a shear fashion and the inter-story drift of Large Scale Bracing shows a zigzag pattern.

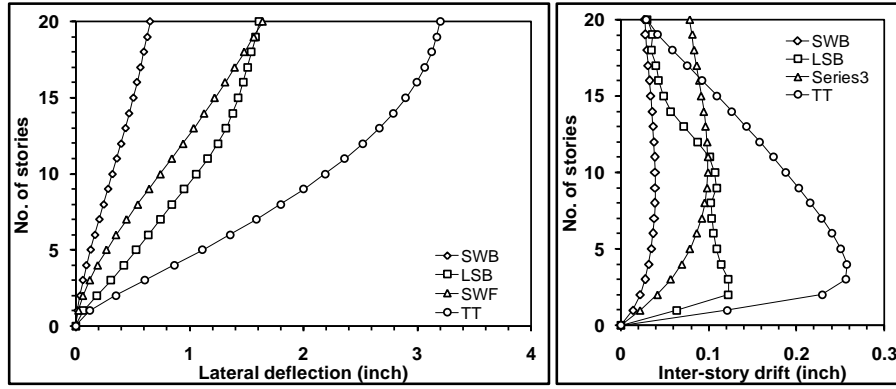


Figure 15: Lateral deflection and inter-story drift of different structural systems of 20 stories.

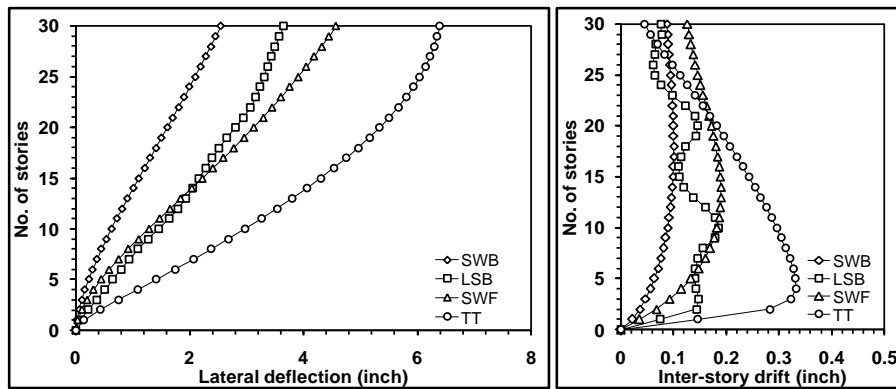


Figure 16: Lateral deflection and inter-story drift of different structural systems of 30 stories.



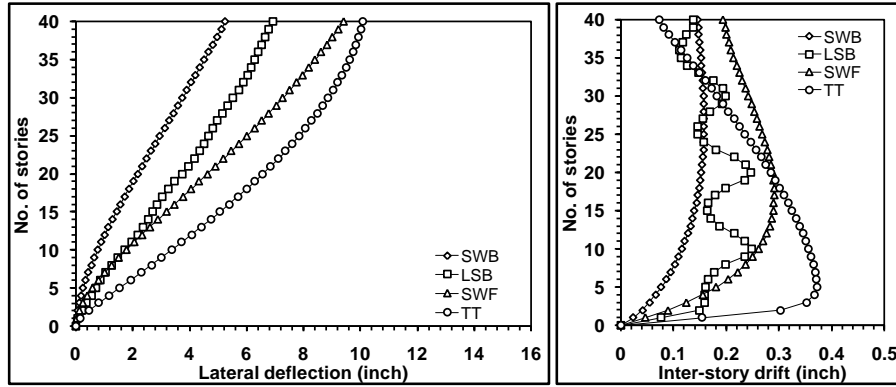


Figure 17: Lateral deflection and inter-story drift of different structural systems of 40 stories.

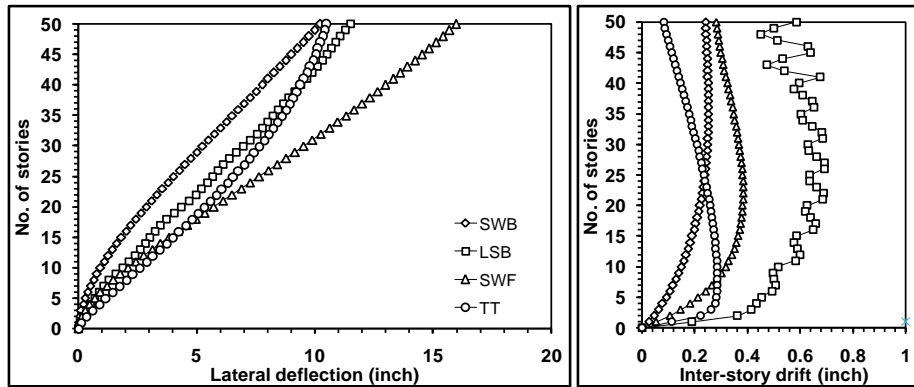


Figure 18: Lateral deflection and inter-story drift of different structural systems of 50 stories.

#### 4.1 Drift Index Effect

Drift index is defined as the ratio of maximum deflection at the top of the building to the height due to lateral forces which represents the lateral stability of a structural system. Sound engineering judgment is required when deciding on the drift index limit to be imposed. The Drift Index values along with descriptions of the tall buildings made of different structural system analyzed in this research are showed in Table 1 and Figure 19. According to ASCE/SEI 7-05 (2006) requirement (drift index limit 0.0025), the drift index of all the systems remain within this limit except 50 storied building of SWF. The Shear wall with Bracing system is found the most efficient structural system for drift control.

Table 1: Description of structural systems

Building I.D.	No. of Stories	Height (ft)	Drift Index	Structural system
SWB 20	20	200	0.00027	Shear wall with Bracing system (SWB)
SWB 30	30	300	0.00060	
SWB 40	40	400	0.00110	
SWB 50	50	500	0.00171	
LSB 20	20	200	0.00067	Large Scale Bracing system (LSB)
LSB 30	30	300	0.00101	
LSB 40	40	400	0.00144	
LSB 50	50	500	0.00192	
SWF 20	20	200	0.00068	Shear wall-Frame system (SWF)
SWF 30	30	300	0.00127	
SWF 40	40	400	0.00196	
SWF 50	50	500	0.00266	
TT 20	20	200	0.00133	Tube in Tube system (TT)
TT 30	30	300	0.00178	
TT 40	40	400	0.00210	
TT 50	50	500	0.00175	

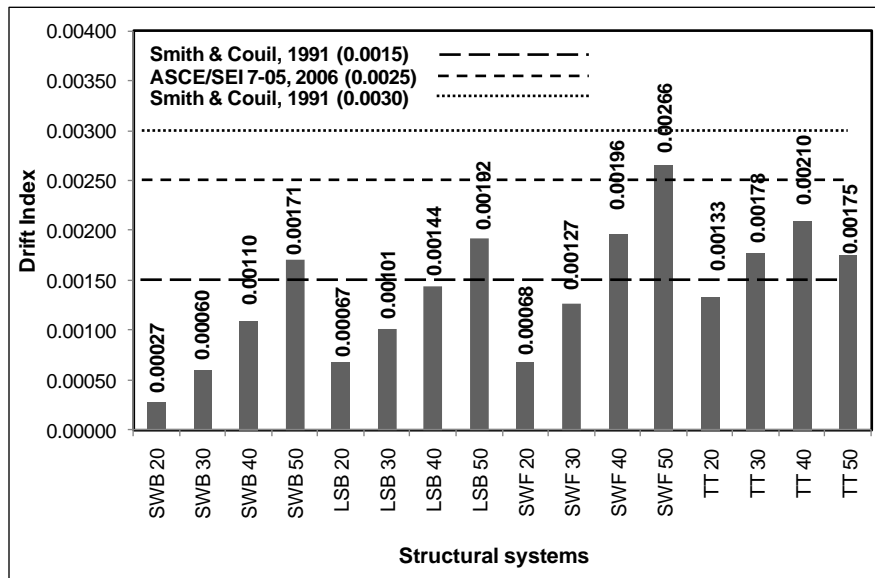


Figure 19: Drift index of structural systems (Building I.D. as in Table 1)

#### 4.2 Material Cost Effect

An approximate cost analysis is done based on the materials quantity, material lifting cost, formwork & shuttering charges for structural construction and also considering the foundation cost is constant for all the systems in context of Bangladesh (Figure 20). The

construction cost for LSB, SWB, SWF and TT systems are considered 1080, 1170, 1000 and 1190 Tk./sft respectively excluding the finishing work. Again the increment of the cost for every 5 stories are considered cumulatively 12.5%, 7.5%, 5% and 15% respectively for mentioned structural systems evaluating the amount of material consumption, material lifting cost and variation in formwork with heights. This investigation shows that (Figure 20), although TT system for 50 and above stories satisfactorily controls the drift, it is found most costly system as the material consumption for inner and outer tube is higher and also huge quantity of material lifting increase the construction cost. SWF system shows the least cost but the drift control capability is lower compares to LSB and SWB systems. For LSB system, there is a variation of formwork for bracing in each floor which makes it costlier compared to SWB which requires repetitive formworks for bracing in each floor. This evaluation clearly shows that in case of costing, SWB system efficiently controls the drift.

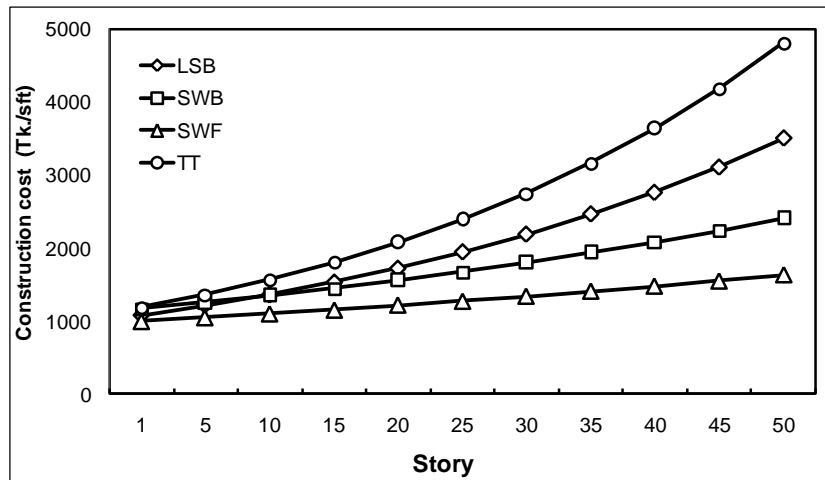


Figure 20: Construction cost analysis of the structural systems.

## 5. CONCLUSION

The findings of this research are summarized as follows:

1. The drift control of Shear wall with Bracing (SWB) system is found to be most effective for tall buildings compared to other systems analyzed in this research.

2. The Shear wall with Bracing system shows a uniform decreasing pattern of bending moment with height and also highest moment resisting capacity compared to other systems.
3. The inter-story drift of Large Scale Bracing (LSB) system is found to be abruptly higher at the lower stories compared to other systems which is due to the absence of shear wall. In that case there may occur as catastrophic damage due to excessive lateral deflection. It is recommended to provide adequate shear wall in the structural system to countermeasure this phenomenon.
4. Shear wall with Bracing (SWB) system shows almost stable value of shear force for all heights which is an indication of better control on the lateral forces on building by the structural system.
5. Construction cost analysis of the systems clearly shows that the for tall building Shear wall with Bracing (SWB) systems is also the economic choice to control the drift due to lateral loading. All of above, the SWB system is found to be a sustainable solution to control the drift of tall building in context of economy as well as structural perspective.

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