

Comparison of shear lag in structural steel building with framed tube and braced tube

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Abstract. Under lateral loads Framed Tube (FT) system exhibits reduction of cantilever efficiency due to the effect of shear lag. Braced Tube (BT) represents a valuable solution to overcome shear lag problems by stiffening the exterior frame with diagonal braced members. This study investigates the effect of shear lag on BT and FT under wind load. Shear lag and top-level displacement results are compared with previous findings by researchers on FT and BT systems. The investigation of the effect of various configurations in BT on the reduction the shear lag is another objective of this study. The efficiency of each structure is evaluated using the linear response spectrum analysis to obtain shear lag. STADD Pro software is used to run the dynamic analysis of the models. Results show there is relatively less shear lag in all the BT configurations compared to the FT structural system. Moreover, the comparison of the obtained result with those derived by previous studies shows that shear lag is not proportional to lateral displacement. With respect to results, optimum BT configuration in term of lower shear lag caused by lateral loads is presented.

Keywords: braced tube; framed tube; high-rise building; lateral load; shear lag; steel building

1. Introduction

Many high-rise buildings employ the framed tube (FT) system. FT is one of the basic structural forms of tubular systems (Coull and Subedi 1971, Foutch and Chang 1982). FT can be defined as a fully, three-dimensional system that utilizes the entire building perimeter to resist lateral loads (Carpinteri *et al.* 2010). Ali and Moon (2007) attributes the earliest application of the FT to Khan (Khan 1972), who thought of this concept in 1961. The 43-storey De Witt-Chestnut Apartment Building in Chicago is the first known building designed as an FT by Khan (1972). Ali and Moon (2007) identified that the purpose of the optimal design of a framed tube is to limit the shear lag effect and aim for a more cantilever-type behaviour of the structure within reasonable and practical limits, i.e., by achieving a cantilever deflection of 50 to 80 per cent of the total lateral sway of the building.

Moon (2010), introduced a stiffness-based model technique in consideration of primary

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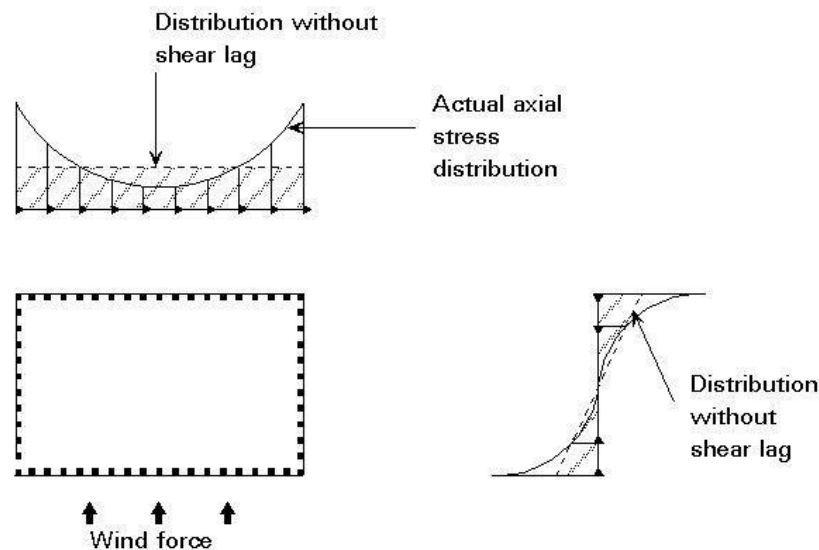


Fig. 1 Axial load distribution and shear lag effects (Chok 2004)

dimension of the BT member in high-rise buildings. The author stated that this method is extremely cost-effective and efficient for the preliminary design of steel BT structural system. This leads to producing built environments using efficient quantities of resources. Mazinani (2011) investigated the behaviour of FT and BT subjected to lateral loads. He compared the lateral displacement of FT and BT due to wind loads.

Rahgozar *et al.* (2011) presents detailed analysis of displacement and stress distribution functions in a combined system of the FT, tube-in-tube, with the outrigger-belt truss in a tall building. They also investigated the effects of shear lag in these types of structures.

As shown in Fig. 1, the axial forces in the corner columns of FT system are higher than those of the middle columns.

In addition, the load distribution is non-linear for both the web frame (i.e., frame parallel to wind), and the flange frame (i.e., frame perpendicular to wind) along the side. This is because the perimeter of the FT is different from a solid wall tube.

This effect is referred to as the shear lag, which limits the FT application to 50- or 60-storey buildings unless the column spacing is very small as was the case with the 109-storey World Trade Tower Centre building in the United States (Fig. 2), having columns 1.0 m apart. For taller buildings with column spacing of 3.0 to 5.0 m, the frames parallel to the lateral loads act as multi-bay rigid frames. In these cases, as the column and beam, designs are controlled by their bending action rather than axial. They result in unacceptably large sizes (Mazinani 2011). Only 25 per cent of the total sway comes from the cantilever component, with the remainder coming from the frame shear-racking component (Taranath, 1998). Due to this shear racking, the corner columns take more than their usual share of axial load, while those in between take less compared to an ideal tube (Taranath 1998). Although Leonard (2007) showed that dia-grid and BT systems could reduce shear lag problems by stiffening the exterior frame, shear lag still plays an important role in the design of tubular high-rise structures. Consequently, optimization on BT should result in the least shear lag effect when compared to the shear lag effect on FT structures. He pointed out that



Fig. 2 World Trade Center



Fig. 3 John Hancock Center of Chicago

due to two massive effects: the shear lag effect reduces the efficiency of the perimeter structure, at first by increasing the stress concentration on the corner columns on the web and flange frames then by reducing the axial stresses in the middle columns. Under wind load, the accumulation of these two factors results in an increase in the lateral displacement and reduces the efficiency of the structure.

Khan (1983) first applied the BT in the 100-storey John Hancock Centre, in Chicago, in 1970 (Fig. 3), which was awarded the 25-Year Architectural Excellence Award by the American Institute of Architects in February 1999 (Iyengar 2000). It is by far the most commonly used method for increasing the efficiency of the FT (Mazinani 2011).

The diagonal members of a BT with connections to the columns at each intersection eliminate the effect of shear lag in both the flange and web frames. As a result, when subjected to lateral loading, the structure behaves more like a braced frame, with a greatly diminished bending of frames. Consequently, the spacing of the columns can be larger, and the size of the columns and spandrels can be reduced, thereby allowing larger window sizes than those in the conventional tube structure. For instance, in the 100-storey John Hancock Centre, which has a BT system, the column spacing on the broad face is 12.2m and 7.62m on the short face (Iyengar 2000). In the BT structure, the bracing also contributes to the improved performance of the tube, in carrying gravity loading. The differences between the gravity load stresses in the columns are evened out by the brace which transfers axial loading from the greater to the less stressed columns. In other words, the bracing guarantees that the perimeter columns act together in carrying both gravity and horizontal wind loads. Therefore, a very rigid cantilever tube is generated, the behaviour of which under lateral load is very close to that of a pure rigid tube (Mazinani 2011).

Along the flange frame, the nonlinearity of stress distribution can result in positive or negative shear lag (Mahjoub *et al.* 2011). In the perimeter of the structure, whenever the stress in the corner columns is greater than that of the centre columns, there is positive shear lag. However, a negative

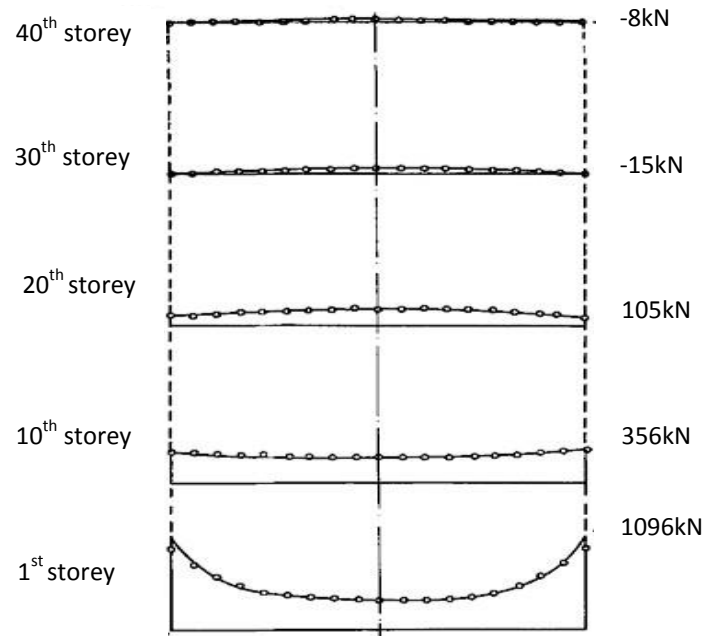


Fig. 4 Axial forces in flange frame of 40-storey building (Singh and Nagpal 1994)

shear lag occurs when the stress in the corner column is lower than the middle columns. Singh and Nagpal (1994) investigated the variation in shear lag along the height of the FT structure. As shown in Fig. 4, at the base of the structure, the variation in axial forces in the perimeter column has the highest value, and, consequently, the shear lag is higher at the base of the structure. This shear lags decreases along the height of the structure until a certain point when it reaches zero. After this point negative shear lag appears. This is due to the axial forces in the middle columns being higher than, those in the corner columns. Mahjoub *et al.* (2011) also studied on a method to evaluate the negative shear lag in the FT systems. Chok (2004) studied shear lag in FT and BT, and compared the FT and BT defined by one type of diagonal brace –X-diagonal bracing – and reported that BT significantly decreased the shear lag to almost half compared to that of the FT in the flange and web. He did not compare other types of diagonal braces in BT or the height and length of the diagonal braces in BT. Kim *et al.* (2009) investigated the seismic performance of FT and BT. The latter showed a stiffness greater than the former. However, they only studied the X-diagonal braced on seismic load.

Zahiri-Hashemi, Kheyroddin, and Farhadi (2013), investigated the shear lag behaviour of BT in two geometric configurations of multi-story building. The results indicate that in term of shear lag there are significant differences between the anatomy of BT with X and Chevron bracing. Previous researchers mostly stressed an effect of the shear lag higher in FT than in BT, but none directly compared them each other. Furthermore, many configurations of BT systems exist in literature. Therefore, there is a need for more studies on the effect of the configuration on the shear lag ratio for BT and FT.

2. Objective

This study analyses a structural system subjected to wind load. The main objective of the research is to study the effect of shear lag on BT and FT under wind load. The objective of this research are focused on:

1. To explore the effect of shear lag on the FT system and BT system;
2. To compare the shear lag and top level displacement in FT and BT system;
3. To study the effect of different BT configurations on shear lag effect.

3. Methodology

As highlighted previously, FT structural systems suffer from shear lag. The use of BT is able to reduce this weakness and improve the stiffness of structure against lateral load. Factor f , is the ratio between the axial force at the corner columns to the axial force in the middle of the panel. It can be used to compare the shear lag effect in some structural systems. The worst shear lag effect usually happens at the bottom of the building. A shear lag ratio less than 1, known as negative shear lag, occurs at the top level of a building, while a shear lag ratio greater than 1, known as positive shear lag, is found at the bottom of a structure (Chang and Zheng 1987, Mazinani 2011). The focus of this study is the analysis of the positive shear lag.

Numerous types of BT systems have been used in high-rise buildings. In this research, to investigate the optimum shape of BT, three BT configurations were analysed, namely, the single 'X' diagonal member, single parallel diagonal member and alternate diagonal member. These were compared with the conventional FT model. This research involves three phases. All three phases are applicable for 80-storey buildings.

3.1 Phase 1

Phase 1 involves using the STAAD Pro software to model a default steel structure. For the simplest idealization, a structure is modelled using the following assumptions:

Each level of the building is 3.8 m high, whereas the width of the building is 40 m with a column-to-column distance of 8 m. Fig. 5 shows the 3D and 2D plan views of a typical model. The geometric parameters for the buildings are listed in the following sections.

3.1.1 Section properties and loads assumption

The efficiency of the system is compared by using the same size for all columns and beams for the models. Sections UC 356×406×634 and 533×210×82 are used for the column and beam members respectively. Note that all joints at the same plane are constrained by stiff floor slabs. This causes all the joints to move together along the same level. In this case, constrictive effect of stiff slabs on the out-of-plane deformation of thin-walled open section bracings as presented by Carpinteri, Corrado, Lacidogna, and Cammarano (2012) is not taken into consideration. Section UC 305×305×283 is used for all brace members. In the bottom part of the building, the structure is rigidly fixed. Fig. 5(a) shows the default structural model.

The concrete cores are designed along the X- and Y-axes. The thickness of the core is 0.5 metres. Fig. 5(b) illustrates the 2D plan view of a typical core model for a building.

For the simplest idealization, the live load, dead load and wind load are applied in this research.

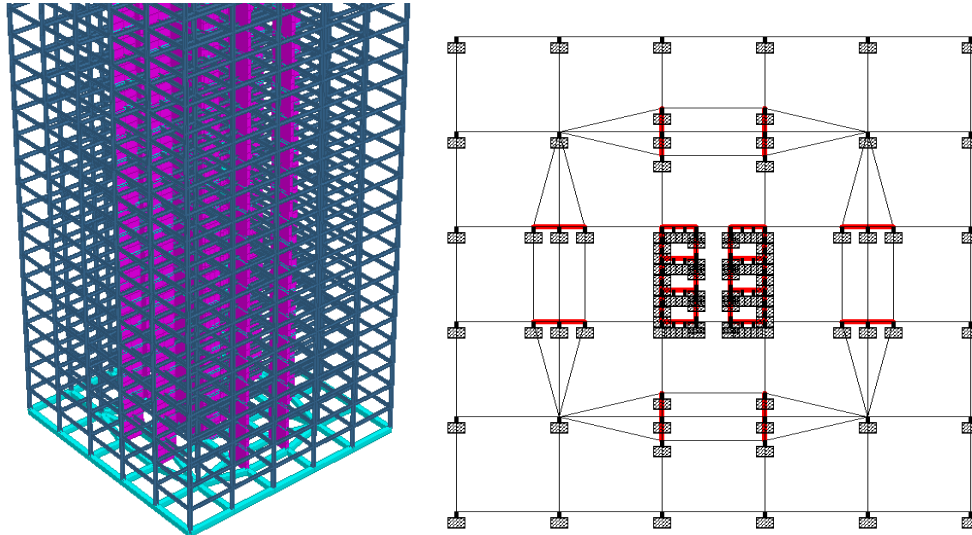


Fig. 5 Default model

To determine the deflection and shear lag, the maximum values are considered for all these models. The structure is assumed to have a 4 kN/m^2 dead load and 3 kN/m^2 live load uniformly distributed in the floor slabs. ASCE 2005 design code was used in determining the wind load. It is assumed that this building is located in a city centre with an altitude of 50 m; with a wind base speed of 45 m/s. A building classification of category II is used in this research with a B Exposure Category (ASCE 2005). For the purpose of verification, the model was also loaded at all joints on the windward and leeward sides of the building. The placement of the point loads is such that the rigid floor slab constraint will distribute the load evenly throughout all the joints on the same level of the building. For wind pressure, at each level of the structure at windward and leeward refer to Mazinani (2011).

3.2 Phase 2

Phase 2 involves the addition of a diagonal member to the default structural model to create a BT model and additional columns to create an FT model to the default structural model in phase 1. Three configurations in three different schemes were modelled with different diagonal member configurations chosen to obtain a wider understanding of the behaviour of this system when subjected to lateral load and its contribution to the performance of BT system. Fig. 6 shows these nine different configurations.

Scheme One includes three types of BT in which the diagonal members are repeated at every 10 levels. In Scheme Two the perimeter features of the structure are divided into two framed diagonal members. Scheme Three has a single framed diagonal member on every face of the perimeter. In all configurations, the diagonal members are equal in every façade.

Scheme One includes three diagonal member configurations 1A, 2A and 3A. Model 1A has a single X- diagonal member at every tenth level where the inclined diagonal members are positioned corner-to-corner. The diagonal configuration in model 2A and model 3A are single

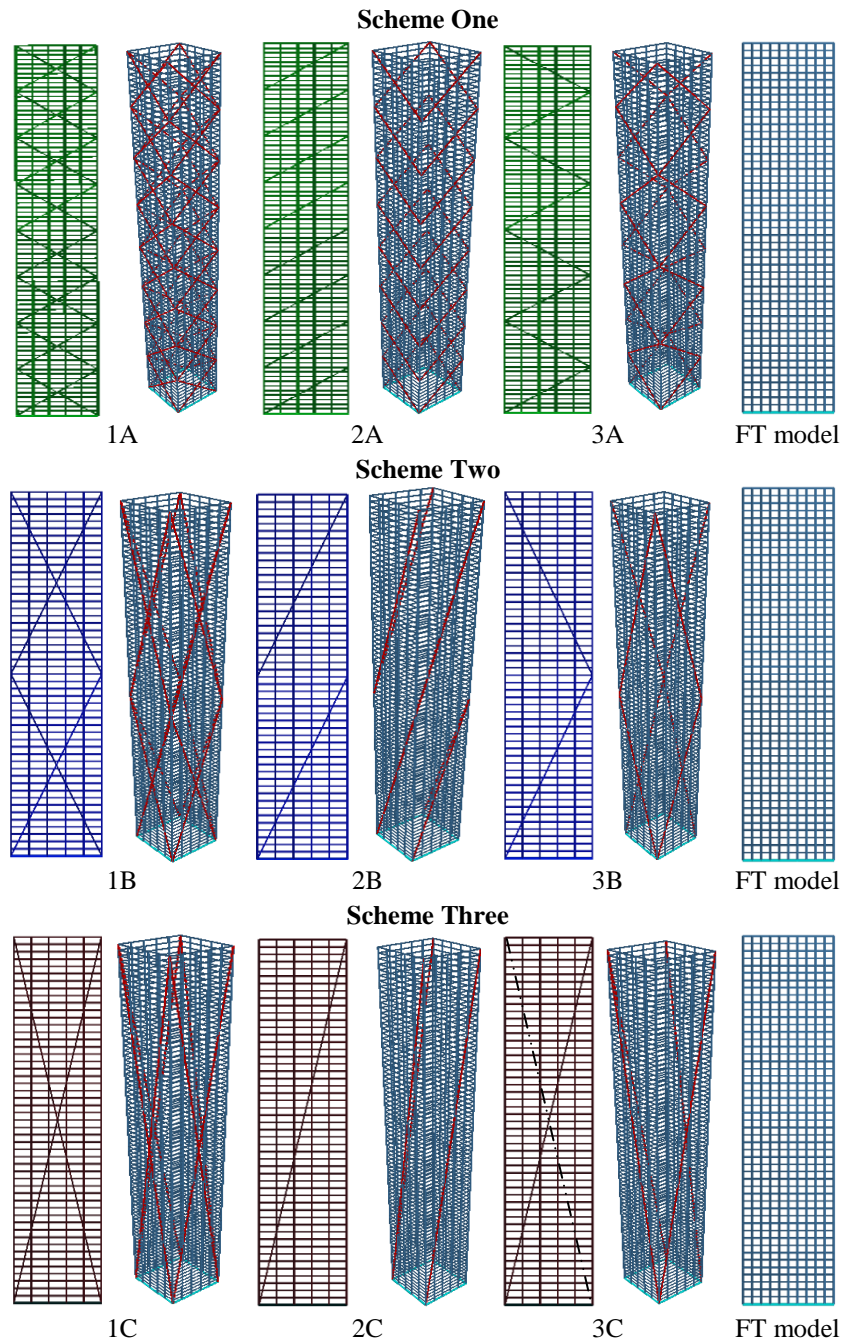


Fig. 6 Configuration of BT models

units and repeated every 10 levels. In mode 2A, all the diagonal members are parallel to each other between the two opposite sides and same façade of the structure. In model 3A the diagonal members alternate (zigzag) in the façades and repeated at every tenth level of the building as

illustrated in Fig. 6. The configuration in this model is in similar direction for the opposite façade. In Scheme Two, the configuration of 1B includes two X-diagonal members. In configuration 2B, there are two parallel diagonal members, and configuration 3B includes two alternating diagonal members on each façade of the building. In Scheme Three, configuration 1C is just a single X-diagonal member. Configuration 2C is a parallel single diagonal member on opposite sides of the building. Configuration 3C is a single diagonal member on opposite sides of the building and in opposite directions to each other. Note that the configurations of diagonal members for all sides of the models are equal and configurations between two opposite sides are in the same direction except for model 3C. Fig. 6 illustrates the side view and 3D view of the perimeter of the structural models.

To evaluate the effectiveness of the BT system with a standard FT system, all nine configurations of the BT (see Fig. 6) are compared with the FT system, as illustrated in Fig. 7. Note that the section properties and plan dimensions of the FT are equal to those used in BT models. However, to benefit from the FT structure, instead of a diagonal member in the BT, additional columns are added between the columns along the perimeter of the default model. Consequently, the FT model is composed of four corner columns with 36 exterior columns of 4 metre spacing, as shown in Fig. 7. Additional column along the perimeter of the default model was highlighted in Fig. 7.

3.3 Phase 3

Phase 3 includes the comparison and evaluation of all these BT models with the FT model. To determine the shear lag ratio in the BT system and compare it with the FT, a parametric study of the BT system with various arrangements is carried out. The parameters of consideration include the inclination angle of the brace elements, the number of floors included under a single and double diagonal element and configuration type of brace elements. The models are dynamically

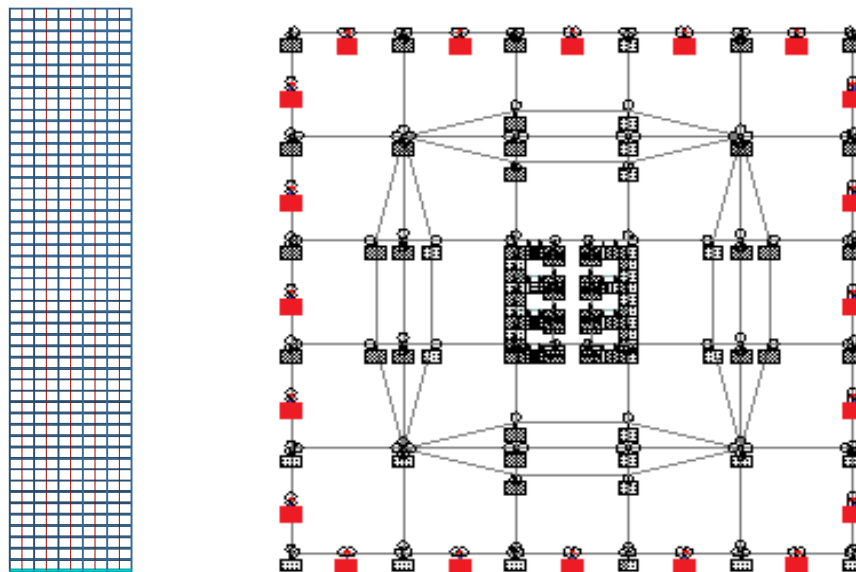


Fig. 7 FT model

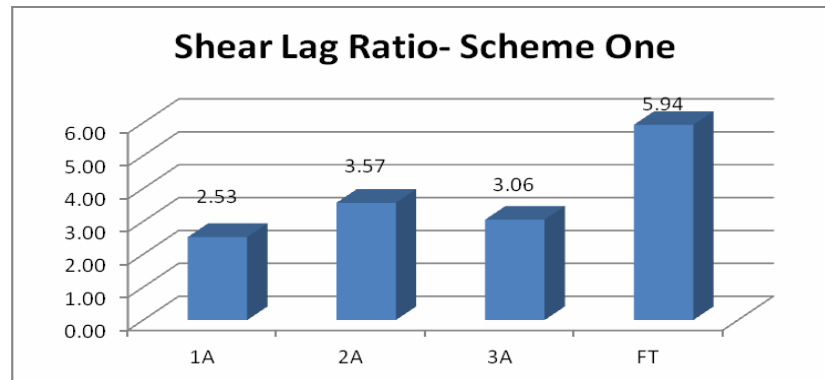


Fig. 8 Shear lag ratio in BT and FT systems, Scheme One

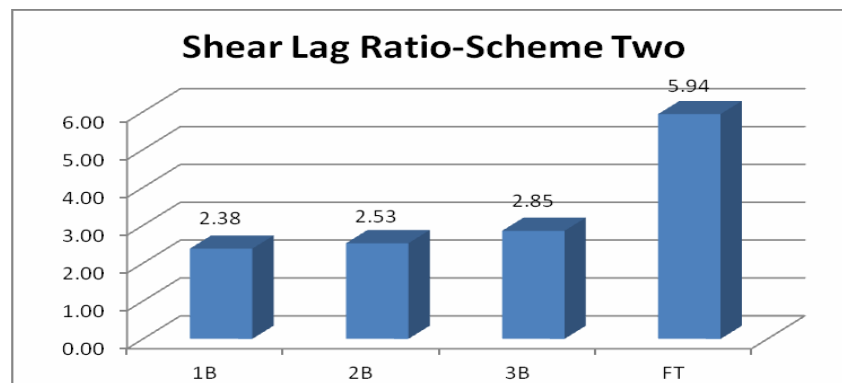


Fig. 9 Shear lag ratio in BT and FT systems, Scheme Two

analysed to obtain axial loading for the corner columns and middle columns under wind load and obtain the factor f , and the shear lag ratio in the BT and FT systems. A comparison of the top displacement and shear lag ratio is made in this phase. STAAD Pro software program evaluates and analyses all the models under wind loads. The output data were converted into an Excel sheet for comparison, analyses and evaluation.

4. Results and discussion

Fig. 8 illustrates the shear lag ratio in BT models and compares these values with the shear lag ratio in the FT model for Scheme One. It shows that in this scheme, the shear lag ratio of the FT model is much higher than the BT models. The results show that model 1A has the lowest shear lag ratio. The value of shear lag in the FT model is more than twice that of model 1A. In model 1A the axial forces and stress in the corner columns decrease. This causes a reduction in the shear lag. However, models 2A and 3A, with a single diagonal brace, result in an imbalance in the stress distribution and an increase in the shear lag ratio of the models.

Fig. 9 shows similar characteristics to Scheme One where the FT model in Scheme Two still has the highest shear lag ratio compared to the BT models. Amongst the BT models, the largest

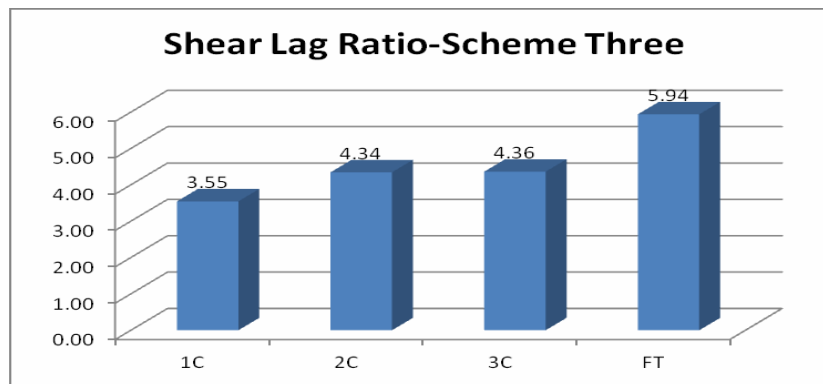


Fig. 10 Shear lag ratio in BT and FT systems, Scheme Three

shear lag ratio in BT models occurs in model 3B with two alternating diagonal members on each façade of the building.

Fig. 10 illustrates the effect of the shear lag ratio on the variation of configurations on lateral loads for Scheme Three. As with Scheme One and Scheme Two, the maximum shear lag ratio occurs for the case of the FT model. Model 1C with just a single X-diagonal member has lower shear lag in comparison to other models.

A comparison between Schemes One, Two and Three in Figs. 8, 9 and 10, shows that the BT models in Scheme Two have lower shear lag. This is due to the fact that the stress and axial load distribution between corner column and middle columns is more balanced. This is in contrast with the findings of Mazinani (2011) regarding lateral displacement of BT Models. Table 1 classifies the top displacement and shear lag ratio (Mazinani 2011). Mazinani (2011) pointed out that BT models with a diagonal brace member in the lower angle (Scheme One) had lower lateral displacement. However, in terms of shear lag, the diagonal member with the lower angle in Scheme One causes a much greater decrease in the axial forces in the corner columns than in the middle columns. This increases the imbalance of the axial force between the corner columns and the centre columns. Consequently, the shear lag ratio value in Scheme One is higher compared to Scheme Two.

Table 1 compares the shear lag value in this study with the top-level displacement presented by Mazinani 2011. Scheme Three with higher value of shear lag in all configurations shows higher value of top-level displacement compared to the others.

All the values of shear lag ratio observed for the three Schemes are positive at the bottom of the models. These are in agreement with the findings of Chok (2004). The results of the three schemes for the 80- storey building show that the BT had lower shear stiffness compared to the FT structure model. Moreover, in BT system the diagonal members efficiently resist the loading since the stresses are more uniformly distributed between corner and middle columns belonging to the flange frame (in the direction of the lateral load) than in the FT system. It can be concluded that the X-diagonal brace of the perimeter of the structure performs better than a single diagonal braced in terms of shear lag.

Furthermore, all the BT models show a lower shear lag effect than the FT model. The comparison between results presented by Mazinani (2011) and those derived from this study, in terms of lateral displacement and shear lag ratio, as shown in Table 1, indicates that Scheme Two exhibits lower shear lag while Scheme One exhibits lower lateral displacement.

Table 1 Comparison of shear lag ratio and top level displacements

Scheme One			Scheme Two			Scheme Three		
Models	Shear Lag ratio	Top displacement (Cm)	Models	Shear Lag ratio	Top displacement (Cm)	Models	Shear Lag ratio	Top displacement (Cm)
1A	2.53	68.76	1B	2.38	97.18	1C	3.55	139.62
2A	3.57	83.24	2B	2.53	126.32	2C	4.34	171.57
3A	3.06	86.03	3B	2.85	128.28	3C	4.36	166.28
FT	5.94	266.00	FT	5.94	266.00	FT	5.94	266.00

This indicates that the minimum shear lag effect does not guarantee optimum structural performance in lateral displacement. This concurs with the findings of the previous research on shear lag by Leonard (2007). This phenomenon occurs where lateral displacement is in combination with the displacement due to bending and shear.

The results in Schemes One, Two and Three show that single diagonal members in any configuration cannot be efficient. The result indicated that the X-diagonal brace equally reduces the axial force in the two corner columns belonging to the same facade of structure. However, the single diagonal brace due to singular brace configuration reduced the axial force unequally in the two corner columns belonging to the same facade of the structure. This causes an imbalance in the axial load of the perimeter columns. Although this results in an increase in the shear lag in these types of BT models, the shear lag in any type of single diagonal brace in BT is lower than the FT model. In terms of lateral displacement, a single diagonal brace cannot be the optimum configuration in the BT system as shown by Mazinani (2011). He showed that X-diagonal brace had a lower lateral displacement and drift in comparison with a single diagonal member. Consequently, the X-diagonal member resulted in lower shear lag and lateral displacement than a single diagonal brace.

The comparison of the shear lag ratio variances between alternate and parallel models in the same scheme from Schemes One to Three in Figs. 8, 9 and 10 was carried out. This comparison shows that an increase in the angle of the diagonal brace from Scheme One with 44° to Scheme Three with 83° would mean that the difference values of the shear lags in the alternate (Models 3A, 3B, 3C) and parallel (Models 2A, 2B, 2C) diagonal braces in each Schemes would be decrease.

5. Conclusions

The X-diagonal member not only significantly increases the stiffening of the structure with a decrease in the storey drift and top-level displacement but also decreases the axial force on the corner columns. Subsequently, the shear lag ratio decreases resulting in a reduction of the shear lag effect on structures. As a result, an X-diagonal member that starts from the corner-to-corner is better at reducing the lateral displacement than a single diagonal brace in alternate and parallel configurations.

The phenomenon of the shear lag effect was studied at the base of structures. The positive shear lag ratio at the base of the structure confirmed the findings of previous researches. Shear lag ratio decreases notably with an increase in the angle of the diagonal members in Scheme One and

Scheme Two. Similarly, it increases again from Scheme Two to Scheme Three. This illustrates that the diagonal member in Scheme Two, with a reduction in the axial load on the corner column, creates a balanced distribution of axial loads between the corner column and the centre column thereby resulting in a decrease in the shear lag ratio in this scheme. The shear lag ratio of a single diagonal member on the same side of the building increases due to the unbalanced stress distribution and axial load distribution on the structure.

A comparison between the shear lag effect and lateral displacement shows that the shear lag effect does not correspond directly to lateral displacement. For instance, the shear lag ratio in the single parallel diagonal brace member in Scheme Two (Model 2B) is similar to the X-diagonal member in Scheme One (Model 1A). Whereas in terms of lateral displacement 1A notably performed better than 2B. This phenomenon is a combination of the deformation due to bending and shear. However, the deformation caused by bending is much higher than the shear in taller structures. Consequently, the shear lag effect does not directly affect the lateral displacement.

The changes in shear lag effect, storey drift and lateral displacement on the top level of the BT are strictly dependent on the respective configuration.

In conclusion, the shear lag ratio is lower in the BT system compared to the FT system. Of all the BT systems, the single X-diagonal member has the preferred lower shear lag ratio than the single parallel and alternate BT. In terms of stress distribution and cost effectiveness, Scheme Two is relatively better than Schemes One and Three.

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