Investigation of Shear Lag Effect in Tall Tube-type Buildings

Niloufar Mashhadiali[a*], Fatemeh Molaei [b], Hossein Siavoshi [b]
[a] Department of Mineral Engineering, New Mexico Tech, Socorro, USA
[b] Department of Mining and Geological Engineering, University of Arizona, AZ, USA

Abstract

The dominant structural systems used for high-rise buildings are tube-type systems. Tall tube-type structures act as a cantilever box girder and become prone to the shear lag phenomenon. This phenomenon causes nonlinear stress along the side of the tubular structures, while the beam theory assumes the stress to be linear. This mechanism reduces the efficiency of tube-type structural systems to resist lateral loads. This study explains a detailed discussion of the shear lag effect and the cause of its existence in two cases, positive and negative, through simple numerical analyses. To this end, the impact of lateral deformation on the shear lag effect was investigated in three tube-type structural systems: framed tube, diagrid, and hexagrid with different heights of 50-, 80-, and 110- story buildings subjected to wind load. The lateral deformation of the model structures was compared with the planer deformation (shear and bending deformation) of the cantilever box girder as the benched mark. Analysis results illustrated that the tube type structural system configuration affected the shear and bending deformation portions and the shear lag effect. Based on the results, the direction of the shear flow was changed according to the slope direction of the tangent line of the deflection curve (first deviation) and caused two cases, positive and negative ones. From the numerical results of candidate models, when the tangent line's angle became zero, the shear lag became minimum. When the curvature of the deflection curve (second deviation) was changed (upward into inward), the shear lag became maximum.

Keywords: Tall Building, Tube Type Structural System, Shear Lag Effect, Diagrid, Hexagrid, Framed Tube

---

[*] corresponding author: Graduate student, Department of Mineral Engineering, New Mexico Tech, Socorro, USA
E-mail: niloufar.mashhadiali@student.nmt.edu

1. Introduction

The tube-type system is the most effective structural framework for tall buildings. In tall tube-type buildings, locating the main structural system on the perimeter causes the building to behave like a cantilevered box girder. The shear lag effect is an unavoidable phenomenon revealed to any box structures that are loaded laterally [1-4]. Thus, tubular structures are prone to forming the shear lag phenomenon. It changes the expected plane section assumptions in box structures and causes non-uniform stress along the sides, which is inconsistent with the elementary beam theory.

The shear lag phenomenon was exhibited in tall buildings with framed tube systems. Researchers recognized the importance of the shear lag effect in tubular structures a long time ago. This phenomenon reduces the efficiency of the tube-type structural system [5-7]

Most existing research reported the shear lag effect in tube-type tall buildings, and few papers studied its reason [8]. Although many studies on the shear effect have long been conducted, they couldn't achieve a unit conclusion, being applicable to all tube-type structural systems with different configurations. From the previous results, the shear lag effect appears in two cases of positive and negative. In the first studies, the shear lag effect was positive and led to a higher stress level at the corner columns of the perimeter frames compared with the inner columns. Foutch and Chang [9] recognized an anomaly shear lag effect, opposite to the positive shear lag (PSL), called negative shear lag (NSL). Chang and Zheng [10] confirmed the occurrence of negative shear lag in the box girder. Since then, research was developed to study the origin of the shear lag effect and the relation between two positive and negative ones. Krístek and Studnicka [11] indicated that in the box girder, the cause of negative shear lag was the varying shear flow as if the shear flow becomes constant, the shear lag does not happen. Singh and Nagpal [12] also reported negative shear lag in framed tube buildings and indicated that the negative shear lag originated from the positive shear lag. Rovnák and Rovnáková [13] discussed Singh and Nagpal's conclusion and stated a different opinion. They concluded that the positive and negative shear lags were not dependent on one another.

In the second part of the studies, extensive research was developed to evaluate stress distribution in tubular structures, considering the shear lag phenomenon. Haji-Kazemi [7] studied this phenomenon in a cantilever box girder representing the framed tube buildings to provide an exact analysis method for evaluating stress and displacement in the perimeter columns. Lee et al. [14] considered the additional bending stresses in the framed-tube structures subjected to lateral loads to estimate the shear lag effect. Mahjoub et al. [15] studied the performance of the framed tube to assess the axial stress distribution on the exterior panels, considering the shear lag effect.

Despite the need for a solution, there was not a general explanation for the shear lag problem. Therefore, in the third part of the studies, a simple method continued to evaluate the shear lag effect in tall buildings. Leonard [16] considered the shear lag effect in the diagrid system with a given factor. This factor is the ratio between axial stress at the corner column and axial stress at the middle of the panel. Since then, several studies have been conducted to evaluate the shear lag effect with this factor [17-20]

Recently, Shi and Zhang [21] have presented a simplified calculation of the shear lag effect for diagrid structures. However, little study has been conducted to evaluate the shear lag effect's cause and characteristics in tall tube-type buildings. Typical research illustrated that the shear lag effect in tube-type structures is affected by lateral deflection [22-24]. Thus, assessing the relationship between the tall buildings' shear lag effect and lateral deflection is required. The lateral deflection of a structure consists of two modes of shear and bending deformation. The overall deflection of a tube structure is due to the shear and bending deflection components of a rigid frame, usually specified as the shear racking and cantilever components [25]. For various structural systems, the portion of shear and bending deformations are different.

However, the introduction section was studied the shear lag effect in three parts. First: the concept of the shear lag effect and cause and origin. Second: finding solution and distribution of shear and axial stress, and the third: evaluating it with a recommended shear lag factor.

Based on the previous research, all of them confirmed the shear lag effect as a problem in tubular structures. This problem has two sides. One side is related to origin, source, and reason, and another side is associated with the solution. Most of the previous research has proposed a reason for it and then tried to solve it. However, they could not achieve a unique reason and solution covering different tubular structures and find a unique answer to what causes the shear lag to be in two types of negative and positive.

This paper discussed the cause of the shear lag effect by evaluating it with the shear lag factor recommended by previous studies.

This research evaluates the reason for the shear lag effect and the cause of its existence in two cases, positive and negative. The elementary beam theory assumption for the analysis of tall tube-type buildings is also discussed. To this end, the impact of lateral deformation components on the shear lag effect is examined through different numerical analysis models, including 50-, 80-, and 110-story building models with different framed tubes, diagrid, and hexagrid tube-type structural systems.

2. Descriptions

2.1 Tube-type structural systems

Framed tube system

Khan [26] first proposed the framed tube system as the ideal structural system of a hollow tube located around the building. It was a rigid frame with closely spaced columns joined by deep girders on all facades that would behave like a tube frame.

Diagrid system

Nowadays, the diagrid system has been widely used as the most efficient tube-type structural system for tall buildings. It contains multiple diagonal elements triangulated at the exterior faces of the building. The diagonal angle plays a significant role in the ultimate strength of diagrids [27-37]

Hexagrid system

Based on academic research, a tubular space-truss structure, called hexagrid, was firstly studied by Mashhadiali and Kheyroddin [37]. Hexagrid structure is constructed by multiple grids with a hexagonal pattern around the building, limited by mega columns. It resists lateral loads by truss action controlled by four mega corner columns. Some studies were conducted to develop the newly hexagrid [39-43].

2.2 Shear lag phenomenon

Two assumptions considered by the beam theory are that a plane remains a plane after bending and that the slope of beam deformation θ is small and is defined as (Eq. 1):

$$\theta = \frac{d\Delta}{dx} \tag{1}$$

where Δ is the beam deformation at location x.

This assumption resulted in the linear distribution of stress in the beam cross-section. The curvature of building deflection ϕ, is defined as (Eq. 2):

$$\Phi = \frac{1}{R} = \frac{d^2\Delta / d^2x}{[1 + (d\Delta / dx)^2]^{3/2}} \tag{2}$$

where R is the radius of curvature.

Based on the above assumptions, the second derivative of the deflection $d^2\Delta/d^2x$ results in (Eq. 3):

$$\frac{1}{R} \approx \frac{d^2\Delta}{d^2x} = \frac{d\theta}{dx} \tag{3}$$

The axial strain, ε, is defined as (Eq. 4):

$$\varepsilon = z\frac{d\theta}{dx} \tag{4}$$

The axial stress, N, is determined based on the bending moment at the distance of z, from the central line, and it is distributed uniformly along the side of the beam. From Hooke's stress-strain laws (Eq. 5):

$$N = \frac{Mz}{I} = Ez\frac{d\theta}{dx} \tag{5}$$

M is the bending moment at the x location, and E and I are Young's modulus of the material and the moment of inertia of the beam section, respectively.

As a cantilever beam, the stress distribution is nonlinear in tall tube-type buildings due to the shear lag effect (S.L.). The shear lag phenomenon occurs in two cases. In the cases of negative shear lag (concave) (S.L.$^-$), the stress in the center of the flange panel exceeds the corner of the panel, and for the positive shear lag (convex) (S.L.$^+$), the stress distribution is in inverse (Fig. 1a)

Under the lateral loading, the exterior frames perpendicular to the load direction is referred to as flanges (f). Those aligned in the direction of loading are referred to as tube cantilever webs (w).

Nonlinear shear stress distribution causes changes in longitudinal axial stress. Fig. 1b shows the shear and bending stress produced by beam theory and the shear lag effect.

From the equilibrium equations, for example, for the flange panel (Eq. 6):

$$\sum F_x = 0 \quad , \quad N_x = N + N_s \tag{6}$$

The shear stress, N_s, is defined as a conditional relation which is shown in the figure based on the shear flow ni. It is defined as (Eq. 7):

$$N_s = \begin{cases} n_0 \leq 0 \\ n_{i-2} - n_{i-1 \leq 0} \\ n_{i \geq 0} \end{cases} \tag{7}$$

n_0 and n_i are the shear flow at the central line and external edge, respectively. The resultant stress of $2n_0$ is a negative direction at the centerline. Thus, the axial stress, N_x at the external edge, is more than N, and at the internal edge, it is less than N. This results in a positive form of shear lag effect.

However, the direction of axial stress, n, is related to the slope of the tangent line of deformation θ. When the slope becomes opposite, the result becomes reverse, and negative shear lag forms.

From Eq. 5, the zero slope of the deformation curve leads to a zero shear lag effect. When the slope becomes greater, the shear lag becomes more significant. At the point where the curvature is changed (upward into inward), the slope and, consequently, the shear lag becomes maximum (Fig. 2).

In tube-type buildings, combining two modes of shear and bending deformations results in changing slope (first derivation of deflection) and the curvature of building deflection and affects the shear lag effect. In fact, combining lateral stiffness of two web and flange panels results in the lateral displacement profile.

In this study, the dimensionless factor 'Shear lag ratio' is defined to estimate the shear lag effect. This parameter is the ratio of the resultant axial stress at corner elements (σ_c) to the consequent axial stress at the middle elements (σ_m) of the same story level (Eq. (8)). This ratio is calculated for both web (w), and flange (f) faces.

$$\text{Shear lag ratio} = \frac{\sigma_c}{\sigma_m} \tag{8}$$

Therefore, the shear lag ratio is less than one in negative shear lag while it is more than one in positive shear lag [16].

In this study, the shear lag effect was investigated and compared at different story levels of the model structures.

2.3 Cantilever beam deformation

In simple words, tall buildings may account for cantilevered vertical beams (Fig. 3). Where **u** and β are the lateral deformation and rotation measure, respectively; the terms; Δ_h and Δ_v are the horizontal and vertical displacement of the building, respectively.

From a motion perspective, the optimal design is related to a state of uniform bending deformation (χ^*) and shear deformation (γ^*) under the lateral loading [44].

The displacement at the top of the beam is given by Eq. (9).

$$\Delta(H) = \gamma * H + \frac{\chi * H^2}{2} \tag{9}$$

H: Building Height.

Where γ*H corresponds to the shear deformation and χ*H^2 /2 corresponds to the bending deformation.

A dimensionless factor S, which is the ratio of the bending displacement to the shear displacement [44], is expressed as Eq. (10):

$$S = \frac{\chi * H^2}{2} / \gamma * H \tag{10}$$

The maximum displacement is considered at the top of the beam as (Eq. (11)):

$$\Delta(H) = \frac{H}{\alpha} \tag{11}$$

Typical α value is used to determine maximum lateral displacement.

Integration of Eqs. (9) and (10) with Eq. (11) expands to (Eqs. (12)- (13))

$$\chi* = \frac{2S}{H(1+S)\alpha} \tag{12}$$

$$\gamma* = \frac{1}{(1+S)\alpha} \tag{13}$$

From the measure of the shear mode of deformation and overall lateral displacement, the S factor, which is the ratio between bending and shear deformations, can be computed based on the proposed method by Smith and Coull [45] through the SAP2000 program [46]. In this method, the joints of models are restrained in the z direction (u3) to obtain the shear mode of the deflection (Fig. 4 a, b). Then, the bending mode is calculated by minus of shear mode and overall lateral displacement.

3. Analysis and design

3.1 Analytical models

A series of model structures with different aspect ratios (Ratio between the building height to the plan width) of 50-, 80- and 110- story buildings were considered for the framed tube, diagrid, and hexagrid systems to evaluate their structural behavior as shown in Fig. 4 c, d. The width of the plan, 56 m, is constant in all model structures, and the story height of the building was considered

4m. Thus, the different aspect ratios for different building heights were obtained 3.6, 5.7, 7.9, respectively.

Based on the optimal angle (65 to 70 degrees) achieved by Moon's [26], Kim's [17], and Mashhadiali's [38] conclusions, the angle of 66° was considered for diagrid structures. In the building with a similar aspect ratio, the internal members were designed with the same cross-section because they were considered to carry only gravity loads. Rigid diaphragms were assigned to the composite floor slab, and the diaphragms were not tied rigidly to the perimeter grids. The floor system is composite

The structural software used to design 3D models was SAP2000 [46]. The model structures were analyzed subjected to wind load established by the document SEI/ASCE 7 [47]. The Dead and live loads were considered 5 and 2.5 kPa, respectively. The design parameters were assumed to be category III, exposure B, and the basic wind speed 110 mph. The models were designed based on AISC [48] requirements. The stress ratios in typical steel members were checked based on the design philosophy of LRFD and considered to be less than 1.0. The design methodology was applied to satisfy H/400 (α:400) allowable lateral displacement.

Steel material with yield stress 345 MPa was applied to structural elements. The Design sections of box, tube, and W sections were assigned to the columns, diagonal elements, and beams, respectivly.

3.2 Analytical results

A building framed-tube system consists of closely spaced columns on the building perimeter joined to each other with deep spandrel beams.

In resisting overturning moments of the framed tube system, the overall bending results in axial deformation of the columns (elongation or shortening) as a cantilever bending on the flange panel, and the overall shear racking of the frame is related to bending of the beams and columns with double curvature on the web panel [25].

The S factor was computed from the measure of the shear mode of deflection and overall lateral displacement (Table 1).

Results illustrated that in framed tube building models, the shear deflection component governed the lateral deflection, and the portion is significantly more than the bending component. However, it decreased by increasing the height of the building. Fig. 5 illustrates the axial stresses of framed tube structures in the web (w) and flange panel (f). To evaluate the shear lag effect, the numerical shear lag ratio (Eq. 8) was calculated at different story levels (P1:0.125H, P2:0.25H, P3:0.5H, P4:0.75H, P5: 0.875).

In framed tube models, lateral displacement first is upward, and then it is changed to inward at point 1, where the shear lag ratio is maximum due to changes in curvature. Comparing numerical results with the beam theory achievements confirmed that the shear lag effect was changed based on the slope and curvature of the building deformation.

From the results, the least shear lag effect occurred at zero slope of the building deformation, which is at points 4, 3, and 3 in 50-, 80, and 110 story buildings, respectively, and positive and negative shear lag occurred in opposite directions due to change in slope at bottom and top of point related to zero slope (Fig. 6). In the 50-story building model at points 1,2, and 3, the shear lag factor is more than one, and it is considered positive where the curvature is downward, and the slope of lateral displacement profile is clockwise (CW). In this model, at point 4, the shear lag factor is about one, and it is considered zero where the curvature is downward, and the slope of the lateral displacement is zero. At point 5, the shear lag factor is less than one, and it is considered negative where the curvature is downward, and the slope of lateral displacement profile is counterclockwise (CCW).

In the 80 and 110-story building models at points 1 and 2, the shear lag factor is more than one, and it is considered positive where the curvature is downward, and the slope of lateral displacement profile is CW. In this model, at point 3, the shear lag factor is about one, and it is considered zero where the curvature is downward, and the slope of the lateral displacement profile is zero. At point 4, the shear lag factor is less than one, and it is considered negative where the curvature is downward, and the slope of lateral displacement profile is CCW. At point 5, the shear lag factor is more than one, and it is considered positive where the curvature is upward and CCW.

In all framed tube models, the curvature of the lateral deflection is downward due to significant shear deformation. However, at the top of the building models, it is upward due to negative stiffness. It happens because the stiffness is more than that it is needed for the shear force induced by the lateral load and the shear lag effect is not accurate.

As mentioned earlier, diagrid structures are constructed with triangulated exterior structural elements.

In resisting overturning moments of the diagrid system, the overall bending results in axial deformation in diagonal elements as a cantilever bending on the flange panel, and the overall shear racking of the diagrids is related to the axial deformation in diagonal elements on the web panel.

Results stated that the major portion of diagrid model deformation was significantly related to bending deflection produced by the axial deformation, and the fewer portions are connected to shear deformation (Table 2). In diagrid models, lateral displacement is upward and then inward.

Following is the typical axial stress diagram in SAP diagrid structures (Fig. 7). Because the diagrid system has diagonal members, the shear lag effect should be computed from the resultant vertical axial forces at the special node. Comparing numerical results with the beam theory achievements confirmed that the shear lag effect was changed based on the slope and curvature of the building deformation.

From the results, the least shear lag effect occurred at the zero slopes of the building deformation at points 1 and 3. At some points of the buildings, negative shear lag occurred due to the direction of the slope, and at the other points, a positive one occurred (Fig. 8). In the 50-story building model at point 2, the shear lag factor is less than one, and it is considered negative where the curvature is upward, and the slope of lateral displacement profile is counterclockwise (CCW). In this model, at point 3, the shear lag factor is about one, and it is considered zero where the curvature is upward, and the slope of the lateral displacement is zero. At point 4, the shear lag factor is more than one, and it is considered positive where the curvature is upward, and the slope of lateral displacement profile is clockwise (CW). At point 5, the shear lag factor is more than one, and it is considered positive where the curvature is downward, and the slope of lateral displacement profile is clockwise (CW).

In the 80-story building model at point 1, the shear lag factor is about one, and it is considered zero. At point 2, the shear lag factor is less than one, and it is considered negative where the curvature is upward, and the slope of the lateral displacement profile is clockwise (CW). In this model, at point 3, the shear lag factor is about one, and it is considered zero where the curvature is upward, and the slope of the lateral displacement is zero. At point 4, the shear lag factor is more than one, and it is considered positive where the curvature is downward, and the slope of lateral displacement profile is clockwise (CW). At point 5, the shear lag factor is more than one, and it is considered negative where the curvature is downward, and the slope of lateral displacement profile is counterclockwise (CCW).

In the 110-story building model at point 1, the shear lag factor is about one and is considered zero. At points 2,3,4 and 5 the shear lag factor is less than one, and it is considered negative where the curvature is upward, and the slope of lateral displacement profile is clockwise (CW).

In all diagrid models, the curvature of the lateral deflection is upward due to significant bending deformation.

Hexagrid structural system contains multiple grids with hexagonal patterns, locating at the building exterior, which is limited by the mega columns, is subjected to the shear lag effect.

In resisting overturning moments of hexagrid system, the overall bending results in axial deformation in diagonal and vertical elements of the grids and shortening and elongation of the mega columns as a cantilever bending on the flange panel. The overall shear racking of the hexagrids is related to the bending of the mega columns and axial deformation in diagonal elements on the web panel.

Results illustrate that in the hexagrid structures, both shear and bending deflections are contributed to the lateral deflection (Table 4). However, it was significant by increasing the building height.

The calculation of the axial stress in the hexagrid system is simple due to vertical elements at the joints (Fig. 9).

Comparing numerical results with the beam theory achievements confirmed that the shear lag effect was changed according to changes in the slope and curvature of the building deformation. The lateral deformation of hexagrid models tended to deform more straightly due to the balance between bending and shear mode deflection. This is due to the configuration of hexagrid structural system. The shear lag ratio confirmed the results (Fig. 10).

In 50, 80, and 110-story building models, at all points, the shear lag factor is about one, and it is considered zero where the slope of the lateral displacement is zero.

Thus, the shear lag effect in hexagrid models was less than framed tube and diagrid structures. This result was more significant by increasing the building height.

4. Discussion

The tall tubular structure with the most similar behavior to a cantilevered beam with the same height (H) and width (B) is desirable for optimum design. Fig. 11 shows the comparing results of shear and bending deformation of the cantilevered beam from Eqs. (12), (13), and the candidate structures from SAP2000, calculated for various S factors. The results compared the specific height of the model structures (H: 440, 320, 200) and α:400.

Results illustrated that the proposed method is able to estimate the S factor, which is the ratio between bending and shear deformation for tall tube-type building models through the SAP2000 program. This method is more accurate for model structures with an aspect ratio of about 6 and even more. Thus, it can be concluded that high-rise tubular buildings behave similarly to the box girder more than one with a low aspect ratio. However, in 50 story model buildings, the shear deformation is closer to the box girder deformation than the bending deformation.

The results of shear mode deflection state that in framed tube structures, the major portion of building deformation is shear deflection. In diagrid structures, bending deflection governs the lateral deflection. In contrast, in hexagrid structures, both deformation modes contribute to the lateral displacement. It made the lateral deformation curve be upward and inward.

Combining two modes of deflections causes changes in the direction of the slope of the deformation curve and, consequently, changes in axial stress distribution. Eventually, the shear lag effect occurs. At story levels with zero slopes, a minimum shear lag occurred on the building models' lateral displacement profile. Changing the slope direction in the opposite direction along with the height of the building models and changing the axial stress direction caused the shear lag effect to exist in two cases, positive and negative.

The numerical results of the shear lag ratio in structural models under lateral loads confirmed the beam theory achievements about the conception of the shear lag effect. At the story level, where the ratio is more than one (Positive), the slope direction is opposite to the level where the ratio is less than one (Negative).

Comparing numerical results indicated that framed tube structures had the most shear lag effect.

The bending deflection of the framed tube structures is due to axial column deformation, whereas the shear deflection is due to the bending of individual spandrels and columns [25].

From the analysis results, in the frame tube system, the flexible spandrels and the government of shear mode in lateral displacement are the causes of the shear lag effect. In fact, shear racking action comes from web frames. On the web frames, the primary resistance of the columns, which are in tension and compression, is modified by the flexibility of the spandrel beams. This causes the axial stresses to be nonlinear. Thus, based on the concept of the space truss system, elimination of bending action and replacing it with axial deformation causes the shear lag effect to reduce.

Thus, results indicated that the shear lag effect decreased in diagrid and hexagrid systems more than the framed tube system. In hexagrid structures, more balance between shear and bending deflection resulted in less shear lag effect.

5. Conclusion

This study investigated the conception of the shear lag phenomenon through the numerical analysis conducted on different tube-type buildings such as a framed tube, diagrid, and hexagrid structural systems with various aspect ratios.

Although the beam theory assumes that the axial stress distribution is linear in tube-type structures, the shear lag causes the axial stress to be nonlinear. This phenomenon appears in two cases, positive and negative forms, in two opposite directions.

To evaluate the base of the shear lag phenomenon, the axial stress distribution in tubular structures under lateral loads was evaluated based on the beam theory. Results indicated that it was directly related to the slope of the tangent lines on the deformation curve (first derivation of deflection). Zero slopes of the deformation curve led to minimum shear lag effect, and by changing the slope direction, the positive or negative shear lag occurred.

In tall tube-type buildings, combining two modes of shear and bending deformations results in changing the direction of the slope and the curvature of building deflection and affects the shear lag effect. In this study, the two components of lateral deformation of building models were compared with the planer deformation of a cantilevered vertical beam.

To evaluate the shear lag effect in building models, the shear lag ratio was defined as the ratio of the resultant axial stress at corner element (σ_c) to the resultant axial stress at the middle element (σ_m) of the same story level. Therefore, the shear lag ratio is less than one in negative shear lag, while that is more than one in positive shear lag. It was calculated at different story levels along with the height of the building.

Comparing the numerical results of the shear lag ratio with the beam theory achievements indicated that changing slope direction of lateral deformation of models caused two cases of positive and negative ones so as, at the point with zero slopes of deformation curve, the shear lag ratio was about 1. Before and after this point, by changing the direction of slope, the positive or negative occurred.

Analysis results illustrated that the configuration of the tube-type structural system affected the shear and bending deformation portions and, consequently, the shear lag effect. The results of shear mode deflection state that in framed tube structures, the major portion of building deformation is shear deflection, and in diagrid structures bending deflection governs the lateral deflection, while in hexagrid structures, both deformation modes contribute to the lateral displacement.

Results indicated when two portions of shear and bending deformation for lateral displacement were balanced; the shear lag effect for tube-type buildings was minimum. Results showed that using a truss system such as hexagrid and diagrid structures significantly reduced the shear lag effect comparison to the corresponding framed tube system with flexible spandrels.

From the least to greatest, the shear lag effect occurred in hexagrid, diagrid, and frame tubes, respectively.

In this paper, the buildings were designed under the wind load because, in tall buildings, the wind load is more critical than the earthquake. However, the results are extendable for different tubular structural systems with different lateral deformations, resulting from various lateral loadings, building heights, and configurations, etc.

This study is a numerical study to discuss the shear lag effect in tubular structures. Further investigation and parametric study are needed to achieve more accurate results accounting for this effect in tube-type structures.

Acknowledgment

The author wishes to thank the committee for their cooperation. The author also is thankful to anonymous referees for the helpful recommendations.

References

[1] Kuzmanovic B. O., Graham H. J.Shear lag in box girders. J. Struct. Div., 1981;107(9): 1701–1712.

[2] Lee S. C., Yoo C. H., Yoon D. Y. Analysis of Shear Lag Anomaly in Box Girders. J. Struct. Eng. 2002; 128(11): 1379–1386.

[3] Rovnak M., Duricova A. Discussion on analysis of shear lag anomaly in box girders. J. Struct. Eng. 2004; 128 (11): 1860–1861.

[4] Zhou S. J. Shear lag analysis of box girders. Eng. Mech, 2008; 25(2), 204–208.

[5] Khan F. R. Amin N. R. Analysis and design of framed tube structures for tall concrete buildings. Special Publication, 1972; 36, 39–60.

[6] Coull A., Bose B. Simplified analysis of framed-tube structures. J. Struct. Div., 1975; 101(11): 2223–2240.

[7] Haji-Kazemi H., Company M. Exact method of analysis of shear lag in framed tube structures. Structural Design of Tall Buildings, 2002; 11(5), 375–388.

[8] Reissner E. Least work solutions of shear lag problems. J. Aeronaut. Sci., 1941; 8(7): 284–291.

[9] Foutch D. A., Chang P. C. A shear lag anomaly. J. Struct. Eng. 1982; 108 (7): 1653–1658.

[10] Chang S. T., Zheng F. Z. Negative shear lag in cantilever box girder with constant depth. J. Struct. Eng. 1987; 113 (1): 20–35.

[11] Kristek V., Studnicka J. Negative shear lag in flanges of plated structure. J. Struct. Eng. 1991; 117 (12): 3553–3569.

[12] SinghY., Nagpal A. K. Negative shear lag in framed-tube buildings. J. Struct. Eng. 1994; 120 (1): 3105–3121.

[13] Rovnák M., Rovnáková L. Discussion: Negative Shear Lag in Framed-Tube Buildings. J. Struct. Eng. 1996;122 (6).

[14] Lee K.K., Lee L.H. Lee E.J. Prediction of shear-lag effects in framed-tube structures with internal tube(s). Struct. Design Tall Build. 2002; 11: 73–92.

[15] Mahjoub R., Rahgozar R., H. Saffari. Simple method for analysis of tube frame by consideration of negative shear lag. Aust. J. Basic Appl. Sci. 2011; 5 (3): 309–316.

[16] Leonard J. Investigation of Shear Lag Effect in High-rise Buildings with Diagrid System. M. E. Thesis. 2007.

[17] Kim J. Lee Y.H. Seismic performance evaluation of diagrid system buildings. Struct. Design Tall Build. 2010. 22 (17): 736–749.

[18] Zahiri-Hashemi R., Kheyroddin A. Farhadi B. Effective number of mega-bracing, in order to minimize shear lag. Struct. Eng. Mech, 2013. 48(2): 173-193.

[19] Mazinani I., Jumaat M.Z., Ismail Z., Chao O.Z. Comparison of shear lag in structural steel building with framed tube and braced tube. Struct. Eng. Mech, 2013; 49(3): 297-309.

[20] Gaur H., Goliya R.K. "Mitigating shear lag in tall buildings. Int J Adv Struct Eng. 2015; 7: 269–279.

[21] Shi Q., Zhang F. Simplified calculation of shear lag effect for high-rise diagrid tube structure. J. Build Eng., 2019; 22, 486–495.

[22] Samat R. A., Chua F. T., Mohd Mustakim N. A. H., Saad S., and Abu Bakar S. Lateral Displacement and Shear Lag Effect of Combination of Diagrid-Frame. E3S Web Conf., 2018; 34, 1–8. https://doi.org/10.1051/e3sconf/20183401009

[23] Dat B. T., Traykov A., Traykova M. Shear-lag effect and its effect on the design of high-rise buildings. E3S Web Conf., 2018; 33: 1–13.

[24] Moghadasi M., Taeepoor S., Rahimian Koloor S. S., Petrů M. The Effect of Lateral Load Type on Shear Lag of Concrete Tubular Structures with Different Plan Geometries. Crystals, 2020; 10(10), 897.

[25] Taranath B. Wind and earthquake resistant buildings: Structural analysis and design. New York: Marcel Dekker. 2005.

[26] Khan F.R. Recent structural systems in steel for high-rise buildings. In Proceedings of the British Constructional Steelwork Association Conference on Steel in Architecture. London: British Constructional Steelwork Association. 1969.

[27] Moon K., Connor J. J., Fernandez J. E. The Struct. Design Tall Build. Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 2007. 205–230.

[28] Lee D-K, Starossek U., Shin S-M. Optimized topology extraction of steel framed diagrid structures for tall buildings, Int J Steel Struct. 2010; 10(2):157–164.

[29] Zhang C., Zhao F., Liu Y. Diagrid tube structures composed of straight diagonals with gradually varying angles. The Struct. Design Tall Build., 2012; 21(4), 283–295.

[30] Montuori G. M., Mele E., Brandonisio G., De Luca A. Geometrical patterns for diagrid buildings: Exploring alternative design strategies from the structural point of view. Eng. Struct., 2014; 71, 112–127.

[31] Zhao F., Zhang C. Diagonal arrangements of diagrid tube structures for preliminary design. Struct. Design Tall Spec. Build. 2015; 24: 159-175.

[32] Liu C. Q., Ma K. Calculation model of the lateral stiffness of high-rise diagrid tube structures based on the modular method. Struct. Design Tall Build., 2017; 26(4): 1–12.

[33] Angelucci G., Mollaioli F. Diagrid structural systems for tall buildings: Changing pattern configuration through topological assessments. Struct. Design Tall Build., 2017; 26(18), 1–17.

[34] Asadi E., Adeli H. Seismic performance factors for low- to mid-rise steel diagrid structural systems. Struct. Design Tall Build., 2018; 27(15): 1–18.

[35] Liu C. Q., Li Q., Lu Z., Wu, H. A review of the diagrid structural system for tall buildings. Struct. Design Tall Build., 2018; 27(4): 1–10.

[36] Heshmati M., Khatami A., Shakib H. Seismic performance assessment of tubular diagrid structures with varying angles in tall steel buildings. Struct., 2020; 25: 113–126.

[37] Thai H.T., Ngo T., Uy B. A review on modular construction for high-rise buildings, Struct., 2020; 28: 1265-1290.

[38] Mashhadiali N., Kheyroddin A. Proposing the hexagrid system as a new structural system for tall buildings. Struct. Design Tall Build., 2013; 22(17): 1310–1329.

[39] Mashhadiali N., Kheyroddin A. Progressive collapse assessment of new hexagrid structural system for tall buildings. Struct. Design Tall Build., 2014; 23(12): 947–961.

[40] Mashhadiali N., Kheyroddin A., Zahiri-Hashemi R. Dynamic increase factor for investigation of progressive collapse potential in tall tube-type buildings. J. Perf. Constr. Fac., 2016; 30(6).

[41] Lee H. U., and Kim Y. C. Preliminary Design of Tall Building Structures with a Hexagrid System. Procedia Engineering, 2017; 171:1085–1091.

[42] Mashhadiali N., Kheyroddin A. Quantification of the seismic performance factors of steel hexagrid structures. J. Constr. Steel Res., 2019. 157: 82–92.

[43] Mele E., Fraldi M., Montuori G. M., Perrella G., and Della Vista, V. Hexagrid-Voronoi transition in structural patterns for tall buildings. Frattura Integr. Strutt., 2019; 13(47): 186–208. https://doi.org/10.3221/IGF-ESIS.47.15

[44] Connor, J. J. Introduction to structural motion control. Prentice Hall Pearson Education. 2007.

[45] Stafford Smith B, and Coull A. Tall Building Structures, Analysis and Design, Wiley: New York. 1991.

[46] SAP2000. Structural analysis program, Version 16.0.0: Integrated finite element analysis and designof structures. Berkeley, CA: Computers and Structures. 2016.

[47] ASCE. Minimum design loads for buildings and other structures. ASCE/SEI 7. Reston, VA: ASCE. 2016.

[48] AISC. Seismic provisions for structural steel buildings. ANSI/ AISC 341-16, Chicago. 2016.