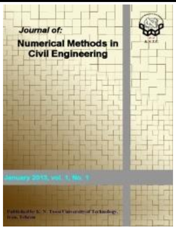

Numerical Methods in Civil Engineering

Analyzing the Behavior of Hybrid Steel System of Tube in Tube with Bracing and Belt Truss

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Abstract:

Nowadays, due to the escalation in construction of high-rise structures, the need for selecting a proper resistant structural system against earthquake and wind has increased significantly. These systems should show an optimized use of materials and should be presented as a hard and efficient structure. A good example of a high efficient system in high-rise buildings can be indicated is, the tubular system that was introduced by Fazlur Khan for the first time. It has been applied in most tall buildings all over the world. The major weakness of these systems is shear lag which restricts the column capacity from functioning properly. An appropriate solution to resolve this problem is using a braced tube system. Also, because of increasing height of the structure, the use of braced tube structures alone is not effective to control the lateral structures. Therefore, a combination of the braced tube with the inner tube and belt truss is more efficient. This paper focuses on the behavior of the hybrid steel system of tube in tube with bracing and belt trusses. To this aim, some buildings were modeled with different structural systems and different number of stories and were analyzed in terms of shear lag in web and flange, lateral displacement and drift, and absorption percent of shear force under earthquake forces. From the results obtained, it can be concluded that the belt truss does not have a favorable impact on the shear lag in the flange, but it reduces drift significantly. In addition, by adding external bracing to tube in the tube structure with belt trusses, the performance of structure improved remarkably in the aspect of shear lag, lateral displacement and absorption percent of the shear force .

1. Introduction

In terms of structural definition, tall buildings are introduced as a structure whose height necessitates special requirements in designing or if its period is more than 0.7S. Other criteria used the height-to-width aspect ratio to define a tall building. IF H/B is between л and1.5л, it could be known as a tall building. Tubular frames were the progress of the conventional flexural frames. In general, tubular systems are a combination of close columns and deep beams which are located in perimeters of the building. System behavior under lateral loads is the same as a hollow cantilever.

The distance between the external columns is normally 2 to 3 meters (up to 4.5 m) and the depth of peripheral beams varies between 0.6 to 1.3 meters [1]. The first application of tubular system was in Dewitt – Chestnut building in Chicago (1961)[2]. The major weakness of this system is shear lag which results in the non-uniform distribution of axial forces in the structural columns. Therefore, it reduces the resistant moment and also leads to non-optimal use of consumed materials. One way to improve the performance of the tubular frames is the braced tube system that increases the length of spans and decreases the shear lag of columns. The best sample of this system can be in John Hancock building (a steel structure) and Ontario center building (a concrete structure) [1]. Bracing makes the peripheral columns act together against the lateral and gravity loads, so the whole tube becomes stiffer to reduce the shear lag. Efficiency and

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performance of high-rise buildings could be improved by using the belt truss (or outrigger) that ties the outer tube to the core. The belt truss is attached to the core by rigid connections, and it is attached to the external columns by hinge connections. When the shear force is trying to bend the building, the belt truss acts like a lever arm and creates axial tensions in peripheral columns, directly. These columns could resist against deformation of the core. In other words, horizontal shear forces only appear in the concrete core (or inner tube). Belt truss transfers vertical shear from the core (or inner tube) to outer frame. Therefore, by using the outrigger, the building behaves seamlessly and functions like a cantilevered tube. Tall buildings could have one or several outriggers. Increasing the number of belt trusses provides much better integrative behavior of outer and inner columns. The belt trusses could be placed inside the building in locations where diagonal braces do not create a barrier in the function of the building (like mechanical stories). Some examples of buildings with the belt truss system could be, The First Wisconsin Center and One Houston Center Buildings [1].

2. Previous Research

For the first time, Professor Fazlur Khan propounded tubular systems among designers and engineers by using this system in a 43-story (Dewitt-Chestnut) building in 1963. Subsequently, he, as well as other researchers all over the world, conducted many studies on tubular systems [1].

Khan (1983) first applied the braced tube system in 1970, in the 100-story John Hancock Centre, in Chicago, which was awarded the 25-Year Architectural Excellence Award by the American Institute of Architects in February 1999 [3]. It was by far the most commonly used methods for increasing the efficiency of the tubular systems [4]. Ali and Moon (2007) identified that the purpose of the optimal design of a framed tube was to limit the effect of shear lag on the cantilever-type behavior of the structure. A cantilever deflection of 50 to 80 percent of the total lateral sway was achieved [2]. Singh and Nagpal (1994) investigated the variation in shear lag along the height of the framed tube structure. At the base of the structure, the variation in axial forces in the perimeter column had the highest value, and, consequently, the shear lag was higher at the base of the structure. The shear lags decreased along the height of the structure until a certain story where it reached zero [5]. Moon, (2010), introduced a stiffness-based model technique in consideration of the primary dimension of the braced tube member in high-rise buildings. The author stated that this method was extremely cost-effective and efficient for the preliminary design of the steel braced tube structural system. This led to creating an environment using efficient quantities of resources [6]. Mazinani (2011) investigated the behavior of framed tube and braced tube systems subjected to lateral loads. He also compared the lateral displacement of the framed tube and braced tube systems due to wind loads [4].

In 2010, the lateral displacement of a 60-story building with one, two, and three belt trusses on different heights of the structure was investigated and it resulted in 34, 42 and 51% reduction (respectively) in lateral deformation in comparison with structures without the belt truss [7].

In 2013, the optimal position of the belt truss in a tall building was investigated based on the maximum strain energy of belt truss. The effect of adding the belt truss and the concrete core to the tubular system was investigated under lateral loading by modeling rotary spring in the position of belt truss based on energy method. The optimal position of the belt truss for the centralized load at the top of the structure resulted in the uniform distribution and the triangular distribution of lateral load at 0.667, 0.441 and 0.490 of height from the base level, respectively [8]. In addition, the optimal position of the outrigger in the reinforced concrete structure was investigated under wind load and earthquake. The optimal position of the outrigger was observed in the middle of the height of the structure [9]. Based on the conducted studies in 2013, to increase the structural performance of high-rise steel structures, the optimal position of belt truss was investigated. The results showed that the optimal position for belt truss was at the one-third upper of the height in order to control the lateral displacement. In addition, in order to find the optimal position for belt truss to withstand progressive destruction, the most possible position for the sudden failure of the column was in one-third lower of the height [10]. Additionally, the results of studies on the optimal position of belt truss in high-rise buildings showed that the use of belt truss at regular intervals from above the building was effective in reducing overall lateral displacement. The optimal position was approximately at half height from the bottom of the building, where the axial forces and moments were minimal compared to the rest of the situations [10]. Similarly, there were other investigations that were performed on tubular systems and outriggers [11, 12]. Hemmati and Kheyroddin investigated the behavior of large-scale bracing system in tall buildings subjected to earthquake loads [13]. In this paper, the performance of hybrid tubular systems with belt truss and mega braces has been conveyed.

3. Geometry, analysis and design of structural properties

This study has tried to compare components of hybrid tube systems on the basis of the shear lag, lateral displacement, and shear absorption. The name of different structures was defined as follows:

- The outer tube with the inner tube with 24, 48, and 72 stories (TnT).
- The outer tube with the inner tube and external braces with 24, 48, and 72 stories (TnTB).
- The outer tube with the inner tube and belt truss with 24, 48 and 72 stories (TnTO).
- The outer tube with the inner tube and belt truss and external braces with 24, 48, and 72 stories (TnTBO)

It is worth mentioning that n was number of stories (24, 48, and 72). It was considered that there was one belt truss in the building with 24 stories at the highest level (H),and there were two belt trusses in the building with 48 stories in levels of H and $\frac{H}{2}$, 3 belt trusses in the building with 72 stories in levels of $\frac{H}{3}$, $\frac{2H}{3}$, H (H is the height of the building from the base). To investigate the effect of type of bracings in the belt truss, two conventional bracings such as cross bracing (X) and chevron bracing were studied.

3.1 Geometry properties

To study the effects of altitude in high-rise tubular buildings, structures with 24, 48 and 72 stories, were considered respectively. The height of each story was 3.9 meters. Figure 1 shows the plan of building with tube in tube systems. Dimensions of the plan of tube in tube system were assumed to be 54×54 m^2 and columns distance was 4.5 meters.

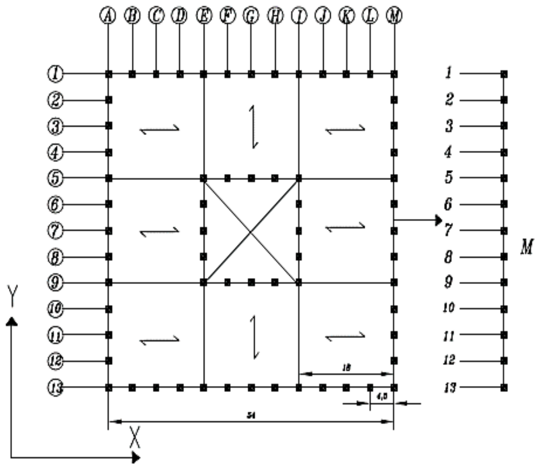

Fig. 1: The plan of mentioned systems

For studying the effect of mega braces on shear lag of tube in tube system, two types of chevron and X bracing were added to the outer tube separately. According to equation offered by Kheyroddin and Zahiri Hashemi [2] for X and chevron braces in the steel building, the number of stories in a mega brace can be calculated by following equations (1 and 2):

The number of braced stories of X- mega bracing:

$$\frac{Nb}{N} = 0.6\left(\frac{H}{B}\right)^{-1} \quad (1)$$

N: The total number of stories

Nb: number of stories which braced as X-braces

H: The total height of the structure

B: Dimensions of plan

Nb: was rounded to the nearest multiple of 1 to 4 of numbers of spans. In this paper, according to the specifications of buildings, Nb selected was 12 for X-braces.

The number of braced stories of Chevron- mega bracing:

$$\frac{Nb}{N} = 0.6\left(\frac{H}{B}\right)^{-1.4} \quad (2)$$

Nb was rounded to the nearest multiple of 1 to 4 of numbers of spans divided by two. In this paper, due to the geometry of the structure, Nb selected was 6 stories for Chevron bracing.

According to the extensive functionality of software ETABS in linear and nonlinear structural analysis, this software was chosen for analyzing and designing the buildings. Codes used for gravity and seismic loading; were standard No.2800-05 (Third Edition) [14] and UBC Code [15].

In the case of ductility, the buildings were assumed to have the average ductility. Ceilings were the hybrid deck in all buildings. Since the functions of the building were meant for commercial and office applications, they were located in the group of the highly important buildings (Group 2). The general location of buildings was in Tehran. Despite the fact that structures were regular in plan and the height of all structures was more than 50 meters, spectral analysis was used. The spectrum of standard 2800 was used as the earthquake spectrum. Due to the important effect of further modes in high-rise buildings, the number of sway modes in all structures had been selected in such a way in which the

total mass was nearly 100% of the effective structural mass. The compositions of the modes were on the basis of the squares method (CQC). In all modes, dynamic base shear values were equal to 100% of base static shear. In addition, in the part of load combination, the combination of DL + LL was defined as the effect of load combination of P-Δ.

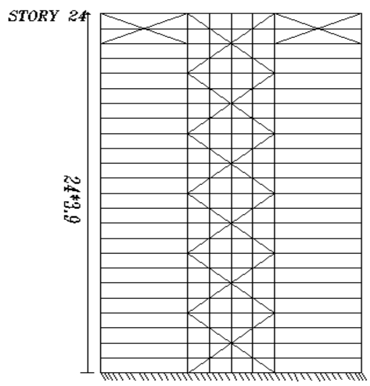

Fig. 2: A sample of X-belt truss the in the 24-story building.

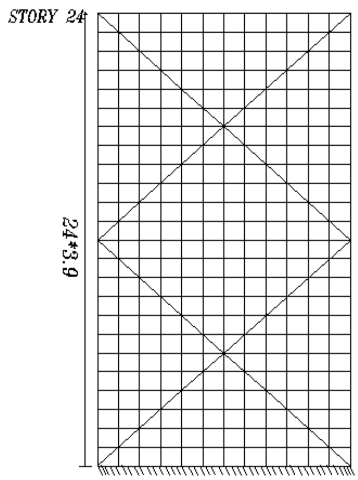

Fig. 3: A sample of X-mega braces in the 24-story building.

4. The behavior of the hybrid tube in tube systems under earthquake loading

4.1 Shear lags in the flange

In order to evaluate the results of structural analysis, the dimensionless parameter of the shear lag index on the flange was defined. It is worth mentioning that the shear lag index was introduced as the ratio of the axial force of the corner column into the axial force of the central column. If the amount of the shear lag index were close to 1, the shear lag would decrease in the flange. If the value of the shear lag index were more than 1, the shear lag would become positive. In addition, if the index value was less than 1, negative shear lag would occur. One method of reducing the shear lag in the flange in tubular buildings was adding bracing to the outer tube. In the following, the shear lag of hybrid tube systems would be discussed. For this purpose, the axis M was selected as a flange in the direction X, as it was shown in Figure 4.

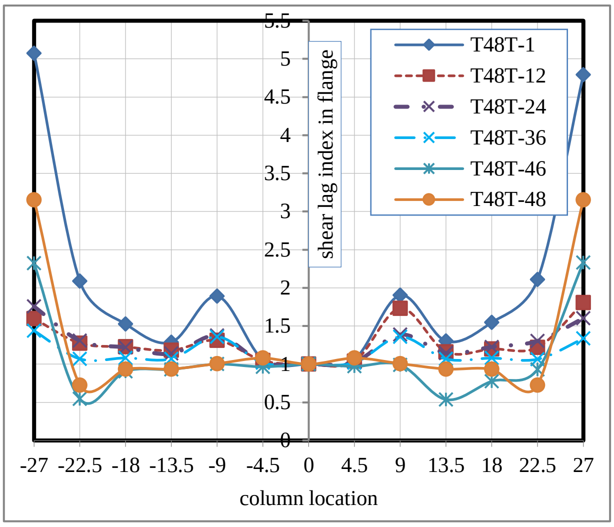

Fig. 4: The diagrams of shear lag index of flange in T48T (48-story building with tube in tube system) at different stories.

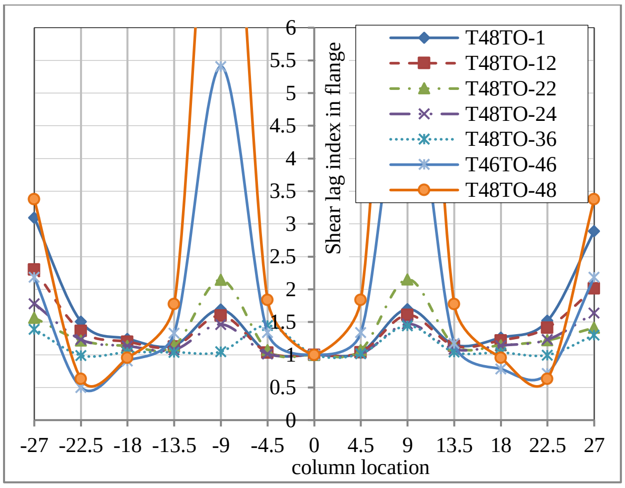

Fig. 5: The diagrams of shear lag index of flange in T48TO (48-story building with tube in tube system and X- belt trusses) at different stories.

As it can be seen in Figure 5, in T48T, shear lag in the flange was reduced at lower stories with increasing height, but at stories adjacent to belt truss, shear lag increased unexpectedly (shear lag raised sharply at story 22 and 48). According to Figure 5, an increase was seen in columns 5 and 9, which were at junctions of the outer tube and belt truss. This increase was due to the higher axial force in columns axis 5 and 9 which were adjacent to outriggers (or belt trusses). The amount of shear lag at story 46 in the same axis reached its maximum value of 5.46. Therefore, it showed a 81.7% increase compared to T48T. In other words, not only did the addition of a belt truss improve shear lag in the flange axes, but it also increased the shear lag significantly at junctions of belt truss to the outer tube.

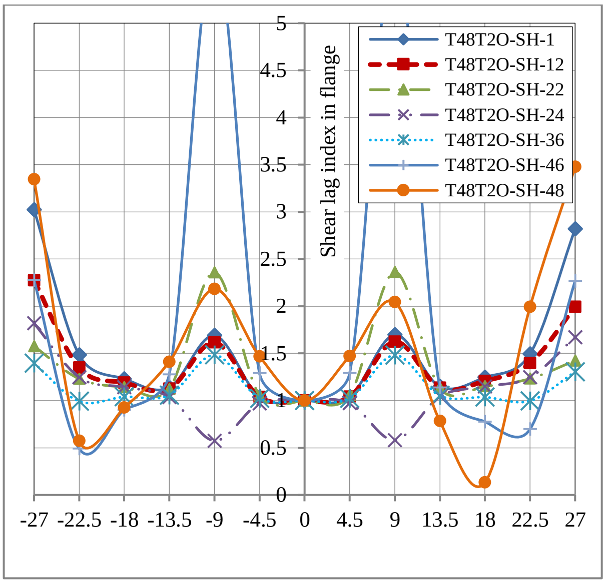

Fig. 6: The diagrams of shear lag index of flange in T48TO-SH (48-story building with tube in tube system and chevron-belt trusses) at different stories.

As it was observed in Figure 6, the shear lag index in flange axes decreased by increasing height, but shear lag indicated a large increase in the axes 5 and 9 at stories adjacent to belt trusses. This increase was less at upper stories, where the belt trusses were chevron-type, compared to the same building with X- type belt trusses. As it can be perceived in the 48-story building, shear lag index in axis 9 was equal to 2.05. Therefore, the chevron-belt truss slightly increased shear lag in the last stories. However, in other stories, X-bracing had more influence than chevron bracing in reducing shear lag.

The effect of the braced outer tube on the flange shear lag in the tube in tube system will be discussed in further paragraphs of this study. As mentioned earlier, one method of reducing the shear lag of the flange was the addition of mega braces to the outer tube.

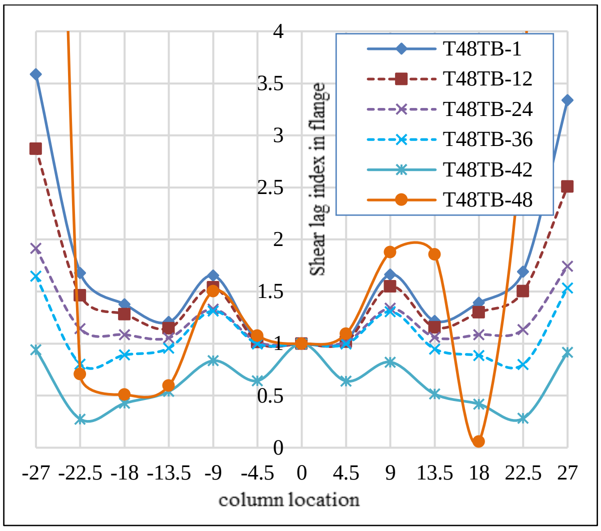

Fig. 7: The diagrams of shear lag index of flange in T48TB (48-story building with tube in tube system and X –bracing on outer tube) at different stories.

As seen in Figure 7, adding braces to the outer tube of the tube in tube system reduced the shear lag of flange. As a result, negative shear lag occurred at lower stories and positive shear lag occurred at upper stories. According to Figure 7, the shear lag increased sharply at upper stories in the 48-story building with X-braces. However, due the fact that the concept of shear lag was the optimal use of cross-section and this issue was not important for upper stories, one could say that X-bracing reduced shear lag in the flange axes of the tube in tube system. By adding bracing on the outer tube, the shear lag in corner columns and the columns of axes 5 and 9 got closer to 1. For example, by adding bracing on external frames of the hybrid system with 48 stories, the shear lag index in column 9 of story 12 decreased to 1.5 and compared to the tube in tube system, it showed a 16% decline.

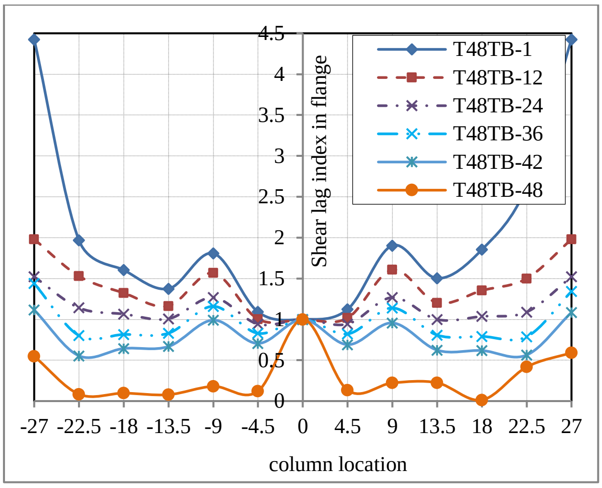

Fig. 8: The diagrams of shear lag index of flange in T48TB-SH (48-story building with tube in tube system and chevron-bracing on outer tube) at different stories

As seen in Figure 8, the shear lag in the flange decreased by adding chevron bracing to the outer tube. Therefore, at lower stories, the shear lag in the flange was positive and at the upper stories, the shear in the flange was negative. Moreover, the shear lag in the flange decreased by increasing height, and in contrast to the X-braces, the shear lag in the flange continued to decrease even in the last stories. Thus, the use of chevron braces for outer tubes resulted in reducing the shear lag in the flange, even in last stories. However, in comparison with the type of braces, the X-braces caused further reduction in the shear lag in the flanges. For example, the index of the shear lag of column 9 of story 12 in T48TB-SH was equal to 1.65 and in T48TB-X was equal to 1.5, which showed nearly 10% reduction.

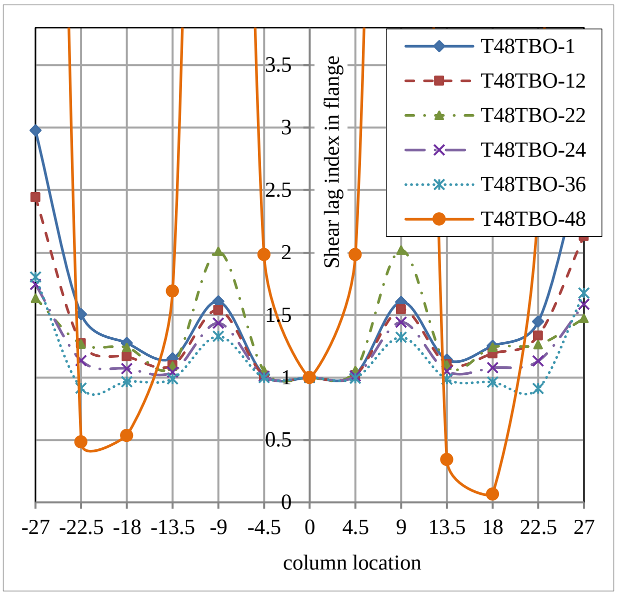

Fig. 9: The diagrams of shear lag index of flange in T48TBO-X (48-story building with tube in tube system and X bracing on outer tube and X- belt trusses) at different stories.

As it was mentioned formerly, by adding the belt truss, shear lag in the flange at different stories was reduced. However, the amount of shear lag in the flange increased at stories adjacent to trusses, and this increase was further in corner columns and columns of axis 9 and 5 where outrigger was attached to the outer tube. By adding braces to T48TO, the shear lag in the flange became less, but it still showed an increase in corner columns and columns of axes 5 and 9 rather than other columns. For instance, in the 24-story building, column 9 of story 24 had a 13% drop. Therefore, adding braces to the external tube had indicated a favorable effect on reducing the shear lag of the flange at stories adjacent to belt trusses. In the last six stories, due to the presence of X- braces and belt truss, the shear lag index rose abruptly, and in 48 story-building, the maximum value in the last story reached 17.31.

In Figure 10, the effect of the type of braces on the shear lag of the braced tube with belt truss was shown. According to the figure, the flange shear lag in T48TBO-SH decreased by increasing height, and this decrease was observed even at last six stories. In T48TBO-X, in comparison with T48TBO-SH, the shear lag index of the flange showed a great increase in the last six stories, but in other stories, it had a greater effect than T48TBO-SH on reducing the shear lag.

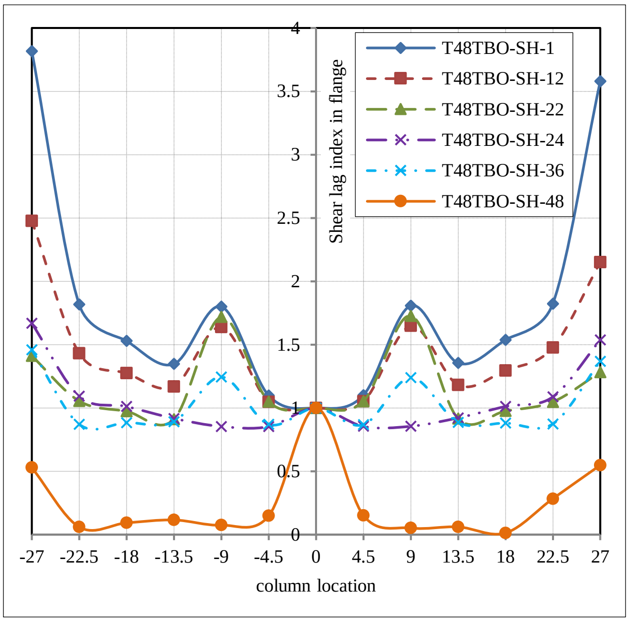

Fig. 10: The diagrams of shear lag index of flange in T48TBO-SH (48-story building with tube in tube system and chevron bracing on outer tube and chevron-belt trusses) at different stories.

At upper stories, the optimal utilization of cross-sectional capacity was not considered due to the overdesigning of the building. Therefore, it could be concluded that T48TBO-X had a greater effect on the reduction of the shear lag. For example, in the 48-story building of this hybrid system, shear lag in the column of axis 9 on the12th story represented a 9% reduction by adding X-bracing compared to adding chevron-bracing.

4.2 Effect of deep peripheral beams on flange shear lag

To investigate the effect of deep peripheral beams, 72-story buildings with tubular systems were studied, including: tube in tube, bundled tube and braced tube combined with belt truss. It should be noted that, in order to investigate the effect of peripheral beams on the shear lag, the deep beam with dimensions of 200x150 cm and thickness of 45mm for the web and the flange were chosen. Initially, the impact of peripheral deep beams on T72T was analyzed. As can be seen from the comparison of Figures 11 and 12, deep peripheral beams had a greater effect on the reduction of the shear lag in the flange, and when the shear lag index ranged from 0.9 to 1.7.

In addition, by increasing height, the shear lag of the flange decreased. The shear lag of the flange increased significantly only in the last three stories, and due to the fact that this increase was in the last stories, it could be neglected. Therefore, adding deep peripheral beams had a better effect on reducing the shear lag of the flanges. For example, in T72T-deep beam, the value of the shear lag index in the corner column of the first story was 1.4, which was 40% less than T72T.

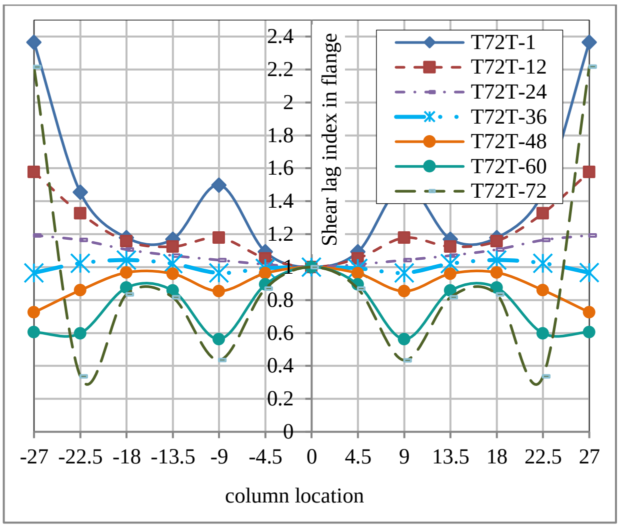

Fig. 11: The shear lag index of flange in T72T (the 72-story building with tube in tube system).

In the following study, the effect of adding deep peripheral beams on the shear lag in T72TBO was investigated. It can be seen from comparing Figure13 and Figure 14, increasing depth of beam had a better impact on reducing the shear lag of the flange. The shear lag index in T72TBO- deep beam ranged from 0.8 to 1.4 in most stories. In T72TBO- deep beam, as the height increased, the shear lag decreased, but there was a sudden increase in the shear lag in the last three stories due to the presence of belt trusses. In addition, by comparing Figure12 and Figure14, it was observed that the tube in tube system with a deep beam had a closer behavior to the ideal tube.

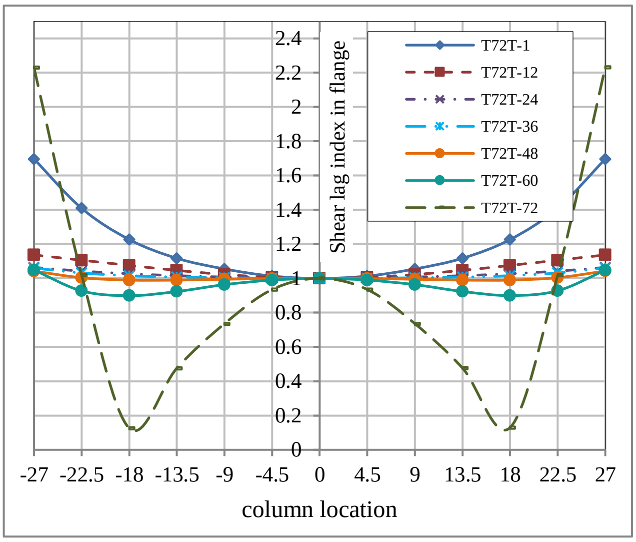

Fig. 12: The shear lag index of flange in T72T- deep beam (the 72-story building with tube in tube system and deep peripheral beams).

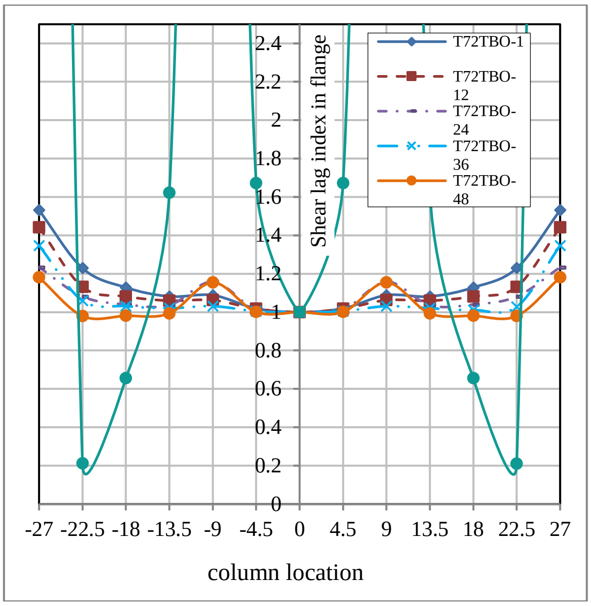

Fig. 13: The shear lag index of flange in T72TBO-X (72-story building with tube in tube system and X- belt trusses).

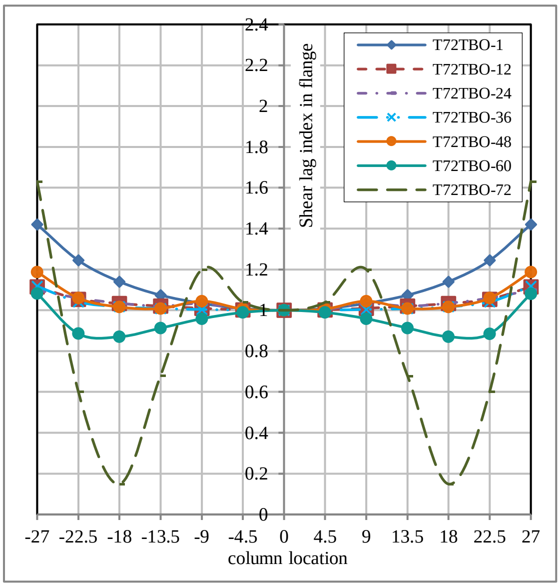

Fig. 14: The shear lag index of flange in T72TBO-deep beam (72-story building with tube in tube system and X- belt trusses and deep peripheral beams).

4.3 Shear lag in web

The deformation of the tubular system with an ideal tube exhibited some differences. As shown in Figure 16, the axial stress in the web of the ideal tube was linear so that axial stress would be under pressure at the top of the neutral axis of the plan and it would be under tension at the bottom of the neutral axis of the plan. However, this axial stress was different from the actual tubular system. The axial stress in the corners of the columns was maximal and the axial stress decreased in columns that were closer to the neutral axis. Therefore, this phenomenon was referred to as shear lag in web. Therefore, this difference in stress distribution between the actual tube and the ideal tube concluded that cross-sectional capacity was not used optimally. As a result, an attempt was made to decrease the shear lag in the web. In this section, the effect of peripheral beams, as well as belt trusses and braces on external frames of tubular systems, were investigated on the shear lag of web.

In order to study shear lag in web, 72-story buildings with tube in tube systems (TnT), tube in tube system with belt trusses (TnTO), tube in tube system with belt trusses and external bracing (TnTBO) were considered. To check the shear lag in web in the direction of X, Axis 13 was selected to be assessed, as shown in Figure 15. Moreover, for simplicity of analysis, the shear lag index in web was defined as the ratio of the axial force in columns to the axial force in corner columns. The index of shear lag in web of the ideal tube was linear and related to the position of the column in web and the neutral axis in the plan as shown in Figure 16.

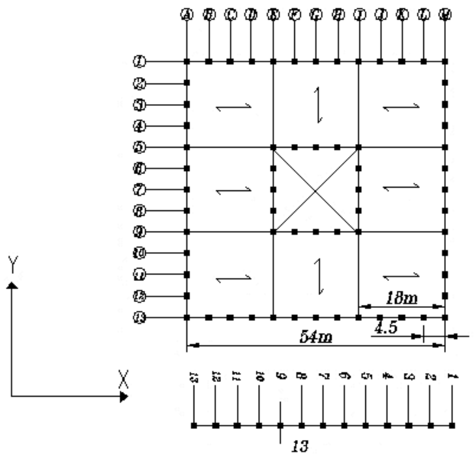

Fig. 15: Numbering column of axis 13 to control the shear lag in web.

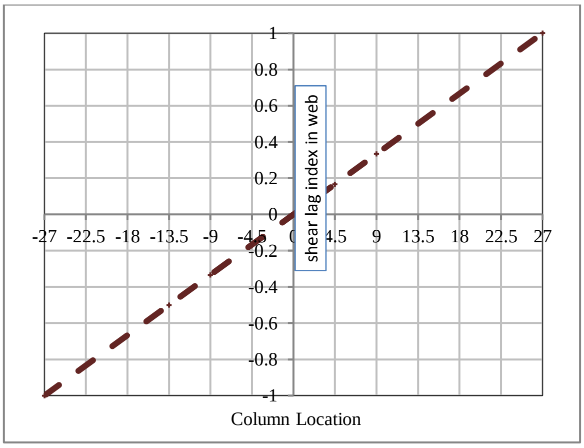

Fig. 16: The index of shear lag in web of the ideal tube under lateral load.

Figure 17 shows the index of shear lag in the web of 72-story building with tube in tube system (T72T), and Fig.18 displays the variation of shear lag index at different stories.

As shown in Figure 17, the diagonal lines represented the ideal shear lag index in axis 13. If the shear lag of column was closer to the considered diagonal line, the shear lag in web would be reduced. For example, if the shear lag index of column 2 was closer to the ideal shear lag of column 2, the shear lag in web would decrease. In addition, if the absolute value of the index of shear lag in web was more than ideal shear lag, the shear lag index in web would be positive, otherwise, shear lag index in web would be negative. Figure 18, showed that in the shear lag index at different stories, the vertical lines with dotted points represented the ideal shear lag in the web columns and as the height increased, the shear lag gradually decreased to the ideal value. For example, the column 8 of the 30th story reached the ideal value, and then, a positive shear lag occurred. In other words, by increasing height, the shear lag decreased. Subsequently, there was a sudden jump at the shear lag index and it reached 0.29 at story 60 and displayed a large difference with its ideal index value (0.167). Therefore, the shear lag in tube in tube system was significantly different from the ideal shear lag and the cross-sectional capacity had not been used optimally.

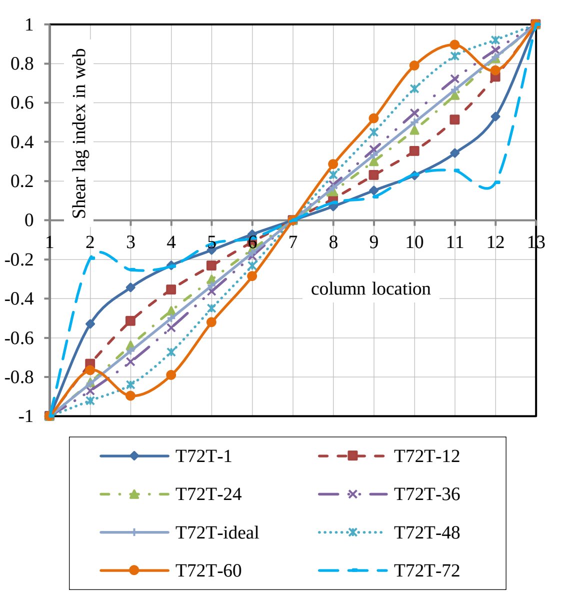

Fig. 17: The shear lag index of web of T72T.

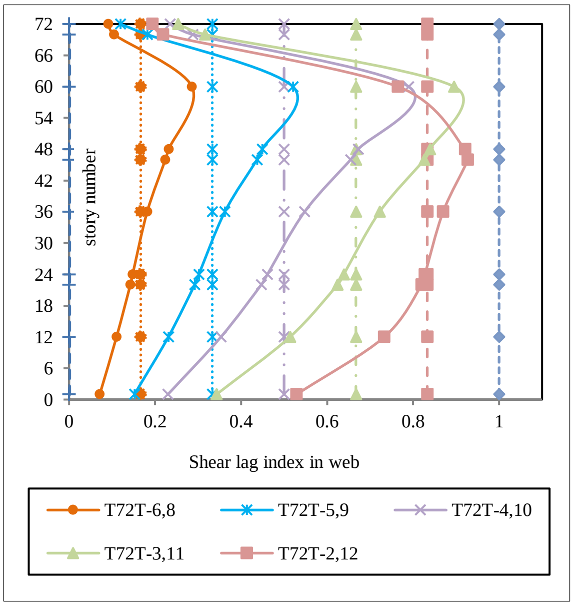

Fig. 18: Variation index of shear lag in the web of T72T.

One way of reducing the shear lag in web was peripheral deep beams. In the following, the effect of peripheral deep beams on the shear lag in T72T system was investigated. As noted above, the dimensions of the peripheral beams chosen were 250cm× 150cm with thickness of 45 mm for the web and flange of peripheral beams.

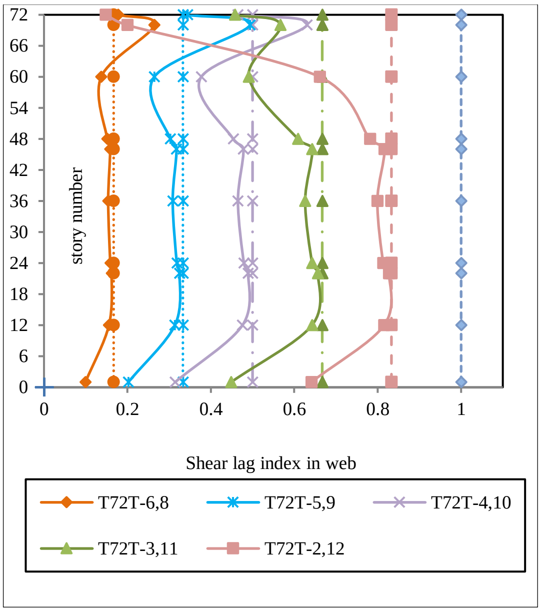

Fig. 19: The shear lag index in web of T72T-deep beam.

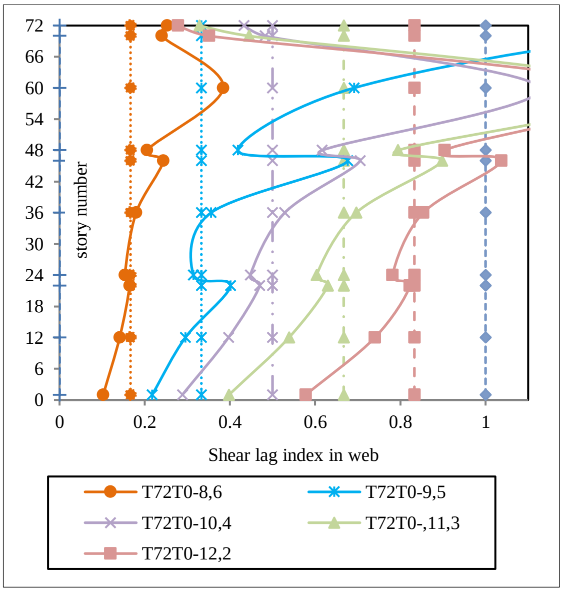

Fig. 20: Variation index of shear lag in web of T72TO.

As shown in Figure 19, deep peripheral beams had a desirable effect on reducing the shear lag index. Moreover, by increasing the height, the shear lag index decreased and became closer to ideal value. This value was very close to ideal tube from base up to story 48 (with very little difference). From then on, the shear lag had further increase, which was much higher than shear lag index of T72T (Figure 18). For instance, comparing Figures 18 and 19, by increasing the depth of peripheral beams in tube in tube system, the shear lag index of the axis 6 at story 60 reached

0.15, which was closer to 0.167 resulting in a 48% reduction in the shear lag index. As can be seen in the above figure, in the last three stories, a sudden jump appeared in the shear lag index. The column axis 2 and 12 experienced further increase than other columns.

As shown in Figure 20, by addition of the belt truss to tube in tube system, shear lag in web increased. This increase was observed to be more at the position of the belt truss. In other words, a sudden jump occurred. In the following figures, the effects of deep peripheral beams on shear lag in web of tube in tube system with X -belt trusses were analyzed.

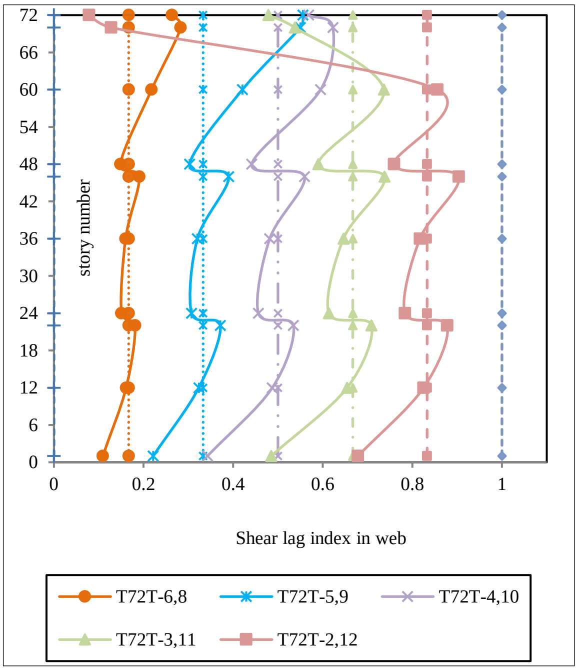

Fig. 21: The shear lag index in web of T72TO-deep beam.

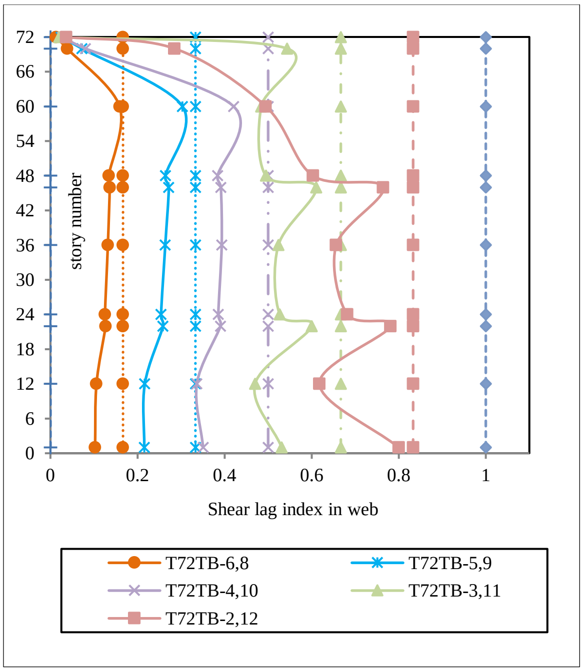

Fig. 22: Variation index of shear lag in web of T72TB.

It was seen from the comparison of Figures 20 and 21, a sudden jump in the index of shear lag was seen in tube in tube system with belt trusses with deep peripheral beams at the location of the belt trusses. At story 48, the maximum shear lag index of web in column 10 had a value of 0.59. The shear lag index of the same column at story 48 in the tubular system with belt truss (according to Figure 48) was 0.71, which represented a 21% decrease. By observing Figure 22, the addition of external bracing on the tube in tube system increased the shear lag in the web. By adding X-bracing, there was a negative shear lag in all stories. In the following figures, the effects of deep peripheral beams on the shear lag of the braced tube were investigated.

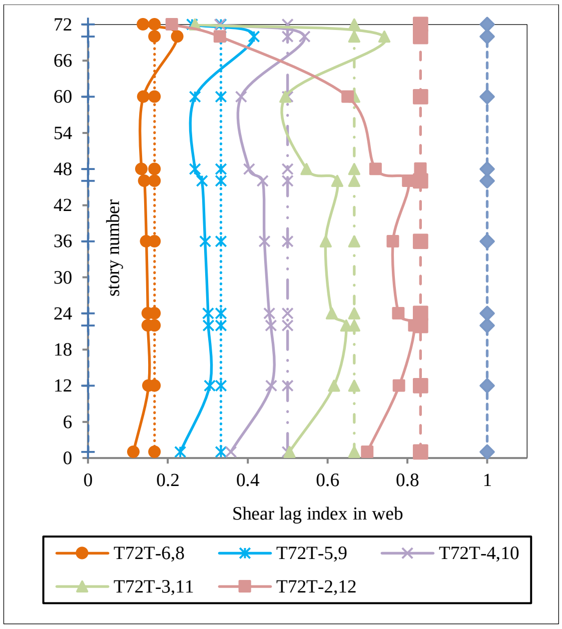

Fig. 23: Effect of peripheral deep beams on shear lag index in web of T72TB-deep beam

According to Figure 23, the addition of X-bracing on the outer columns increased the index of shear lag in the tubular system with deep beams, due to the increased axial force in the two connection points of axes 5 and 9. For example, at 36th story of T72TB-deep beam, column 2 had the shear index of 0.76, which showed a difference of less than 0.833 in comparison with the braced tubular system (Figure 22). Therefore, increasing the depth of the peripheral beams was an effective way of reducing the amount of the shear lag in the tubular systems combined with belt truss.

In the successive figures, the simultaneous effect of adding the belt truss and X-mega bracing to the tube in tube system was examined with regards to the aspect of the web shear lag. Initially, the effect of a 72-story braced tube with belt trusses on shear lag was investigated.

As shown in Figure 24, simultaneous insertion of braces and belt truss did not have a satisfactory effect on the reduction of shear lag in the web. Conversely, the shear lag had suddenly increased at some stories. According to the figure, at first, the shear lag in web decreased with increasing height. Then, at stories adjacent to the belt trusses, there was a jump in the amount of the web shear lag index. Because there were three belt trusses at height in a 72-story building, this phenomenon occurred three times at height. Therefore, the addition of braces and belt truss did not have a constant and uniform effect on the improvement of the shear lag.

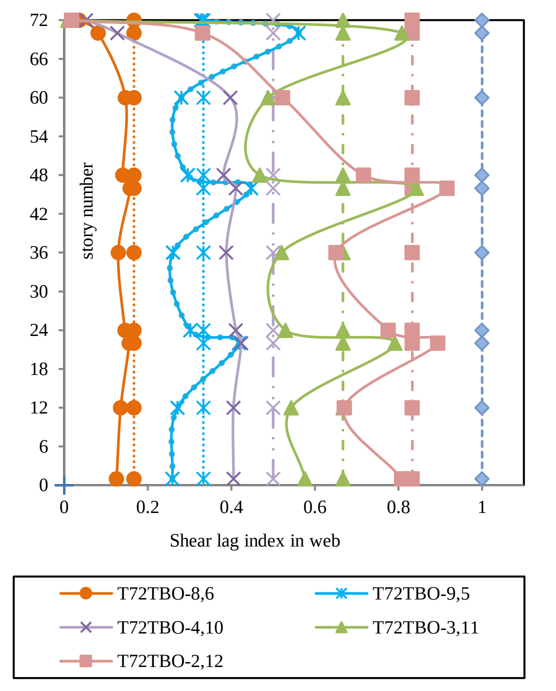

Fig. 24: Variation index of shear lag in web of T72TBO.

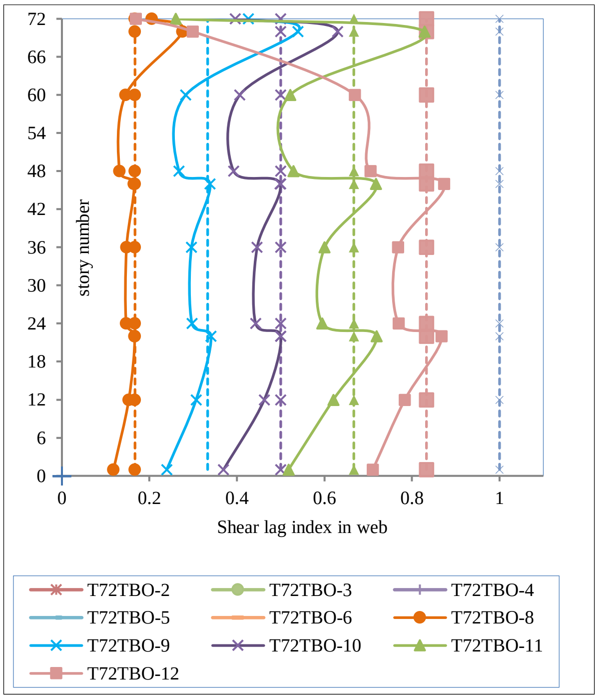

Fig. 25: Effect of Peripheral deep beams on shear lag index in web of T72TBO-deep beam

Based on Figure 25, the tube in tube system with external bracing and belt trusses surrounded by deep peripheral beams (T72TBO-deep beam) reduced the shear lag compared to the braced tube with belt truss, T72TBO (Figure 24). However, the system also did not show a steady trend in decreasing the shear lag. At stories adjacent to belt trusses, the shear lag increased suddenly with increasing height. Then, it decreased until it reached the position of the belt truss again. This behavior occurred three times through the height of the building.

Adding braces and belt trusses to the structure would cause more force in some columns and increase the shear lag at once. Therefore, this braced structure would not have a good effect on decreasing shear lag compared with a tubular system with deep peripheral beams.

5. Lateral drift

As shown in Figures 26 and 27, the drift decreased by adding the belt truss on the outer tube. Although the effect of adding bracing on the reduction of drift had been greater than adding belt trusses, there was a sudden reduction in drift at the location of the belt truss. Finally, by adding bracing on the outer tube and the belt truss simultaneously to the tube in tube system, the greatest decrease in lateral drift could be noticed. By comparing all analyzed hybrid tubular systems, it was observed that braced tube in tube system with belt truss had more impact on reducing drift. This discussion was defined as a ratio of lateral displacement in hybrid tubular systems to lateral displacement of tube in tube system (or $\Delta_{hybrid}/\Delta_{tube}$).

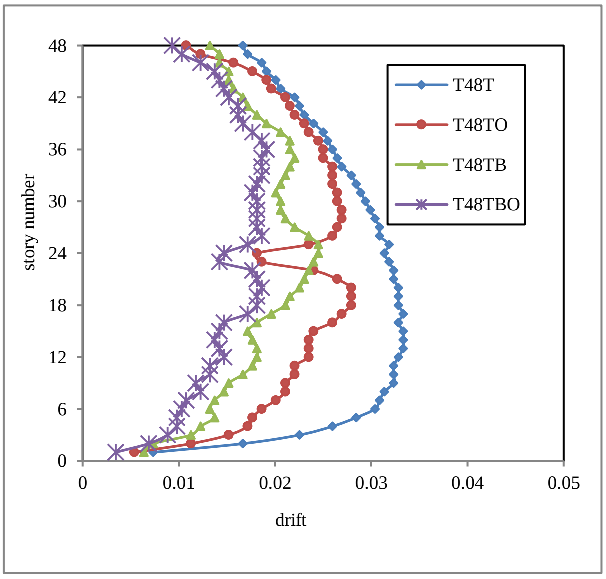

Fig. 26: Comparison of lateral drift in tube in tube systems of 48-story buildings.

As shown in Figures 26 and 27, the lateral drift of T48TO, compared to T48T, decreased by 25% at the maximum value, but the addition of mega braces had a greater effect on the reduction of the lateral displacement, and this reduction for T48TB was 52% compared to T48T. In addition, the addition of both bracing and belt trusses to T48T decreased drift by 63%.

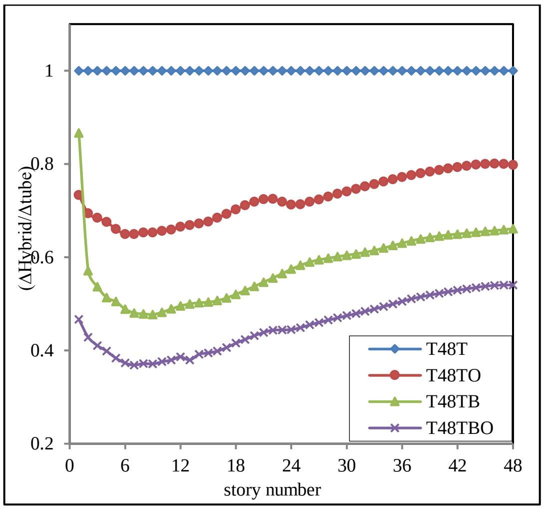

Fig. 27: Diagram of $\Delta_{hybrid}/\Delta_{tube}$.

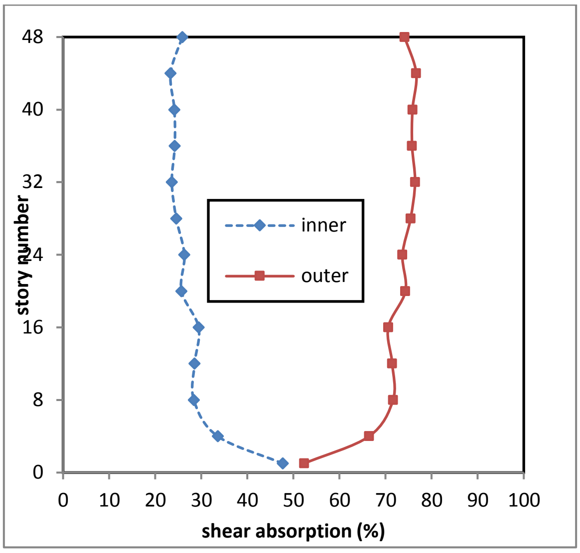

Figure. 29: Percentage of the shear absorption of inner and outer tubes of T48T.

6. Shear absorption of each tube

When the lateral force was applied to tubular systems, the columns were able to withstand against this force; in other words, the columns and braces of each story had to resist against the shear force. At this time, the purpose of this section was to obtain the shear absorption of each tube, meaning how much lateral load was borne by the columns and braces in each tube. This issue was important because its investigation improved the understanding of the lateral load absorption mechanism by the structural resistant system and also, which tube was more effective in absorbing the horizontal load. Considering the above, it was perceived that this parameter had a great influence in designing structures. It would be possible to identify sections which played an important role in supporting lateral force and subsequently, necessary equipment could be considered for them. In this way, an optimal structure could be economically achieved. It should be noted that in this paper, the inner and outer tubular system were also shown in Figure 28.

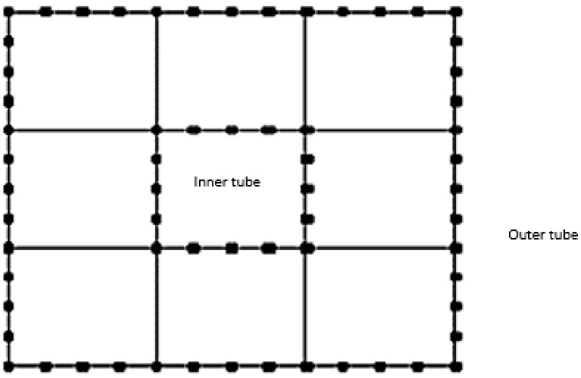

Fig. 28: Introduction of tubes of tube in tube system.

The shear absorption percentage of inner tube was equal to the total shear force of inner tube columns to shear force of all columns in each story. In addition, the absorption percentage of the outer tube was equal to the total shear force of outer tube columns to shear force of all columns in each story.

As shown in Figure 29, the percentage of shear absorption of inner tube decreased with increasing height (for instance, a 22% reduction in the shear absorption percentage in the first story).

At upper stories, more than 70% of the shear was tolerated by the outer tube. Table 2 showed the absorption of shear force in a 72-story building with the tube in tube system, and Figure 30 shows the shear absorption percentage of these tubes.

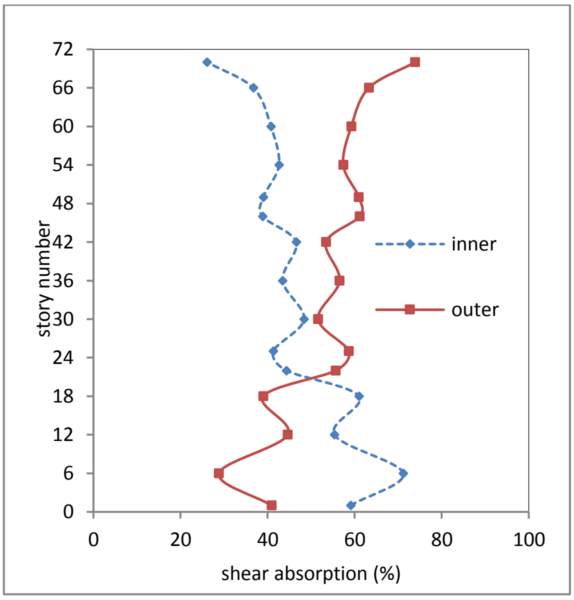

Fig. 30: Percentage of shear absorption of inner and outer tubes of T72TO-X.

Table 1. The absorption ratio of the inner and outer tubes of the 48-story building in tube in tube system (T48T)

story number	shear of inner (ton)	shear of outer tube (ton)	story shear (ton)	absorption ratio of the inner tube	absorption ratio of the outer tube
1	2390.24	2621.56	5011.8	0.48	0.52
4	1669.5	3304.8	4974.3	0.34	0.66
8	1367.9	3452.27	4820.17	0.28	0.72
12	1306.1	3268.9	4575	0.29	0.71
16	1251.87	3002.5	4254.37	0.29	0.71
20	1017.78	2944.2	3961.98	0.26	0.74
24	960.83	2688.3	3649.13	0.26	0.74
28	794.2	2438.8	3233	0.25	0.75
32	681.1	2205.25	2886.35	0.24	0.76
36	581.73	1817.72	2399.45	0.24	0.76
40	451.21	1416.5	1867.71	0.24	0.76

Table 2. The absorption ratio of the inner and outer tubes of T72TO-X.

story number	shear of inner (ton)	shear of outer tube (ton)	story shear (ton)	absorption ratio of the inner tube	absorption ratio of the outer tube
1	5900	4086.72	9987.52	0.59	0.41
6	7139.6	2892.56	10032.16	0.71	0.29
12	5248.93	4233.34	9482.3	0.55	0.45
18	5511.9	3525	9036.9	0.61	0.39
22	3784.25	4751.52	8535.77	0.44	0.56
25	3401.27	4831.13	8232.4	0.41	0.59
30	3799.99	4051.97	7851.96	0.48	0.52
36	3129.64	4073.72	7203.36	0.43	0.57
42	3044.5	3492.66	6537.16	0.47	0.53
46	2331.04	3669.9	6000.94	0.39	0.61
49	2176.97	3401.37	5578.34	0.39	0.61
54	2084.47	2806.7	4891.17	0.43	0.57
60	1541.1	2239.04	3780.14	0.41	0.59
66	915.37	1577.41	2492.78	0.37	0.63
70	385.17	1091.31	1476.48	0.26	0.74

In the following figures, the addition of braces to the outer tube in the tubular system was examined. These braces were Chevron- type or X-type. Figure 31 shows the absorption diagram of a 72-story building with braced tube in tube system (X-type). As shown in Figure 31, by the addition of braces on the outer tube of the tubular system, stiffness was greatly increased, and the outer tube played a more significant role in comparison with the inner tube to absorb the story shear. Furthermore, this system did not exhibit uniform behavior in the rate of shear absorption by increasing height. In stories, where the mega braces formed a complete X-braces, the shear absorption of the inner tube increased and the shear absorption of the outer tube decreased. As can be seen, in stories 12, 24, 48, 36, 60 and 72, the absorption percentage of the inner tube was increased and the absorption percentage of the outer tube was reduced, conversely. Since the tensile and compressive forces of the braces were transmitted to the corner columns in mega braces, the resultant shears and moments entering the vertical columns decreased. As a result, the percentage of shear absorption at these stories in the outer tube was reduced. According to Figure 31, the inner tube in T72TO-X had a small contribution in the shear absorption. Its shear absorption ranging from 10 to 20%, which was 26% lower than T72T system at the first story.

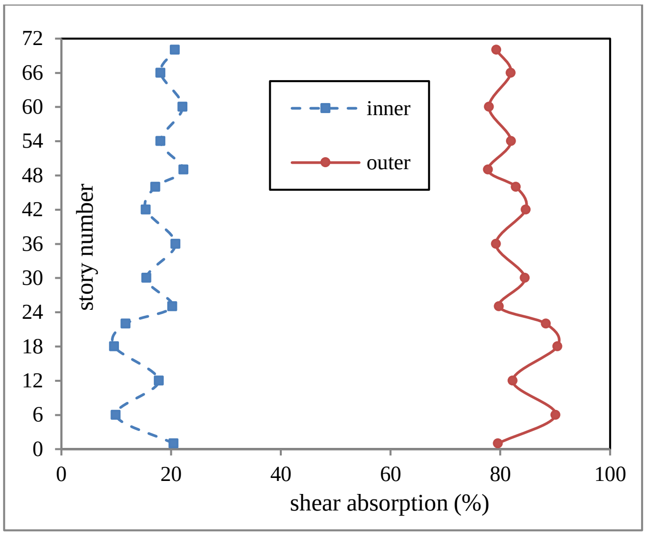

Fig. 31: Percentage of absorption of inner and outer tubes of T72TB-X.

In addition, to compare the type of bracing on the absorption rate, two types of bracings (chevron and X) were considered.

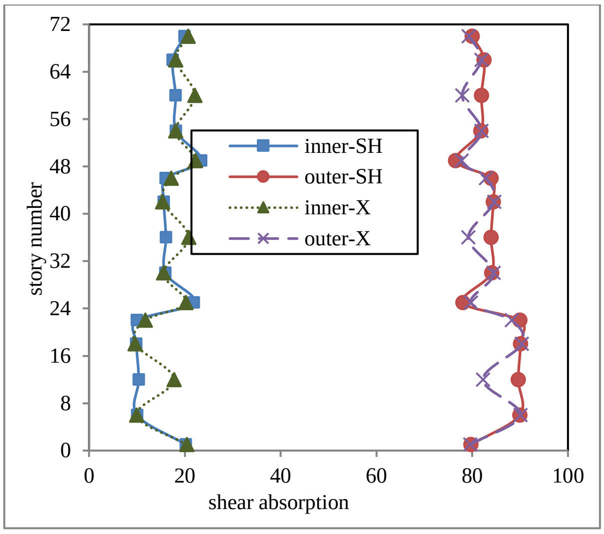

Fig. 32: Comparison of shear absorption percentage of inner and outer tubes of T72TB-X, SH.

Figure 32 shows a comparison of shear absorption percentage of 72-story building with two types of braces, X-bracing and chevron- bracing and either type of braces made a slight difference in percentage of shear absorption at most stories. Thus, the effect of types of braces could be ignored in increasing shear absorption percentage of braced tubular systems. The effects of simultaneous addition of braces and belt trusses on the outer tube were investigated.

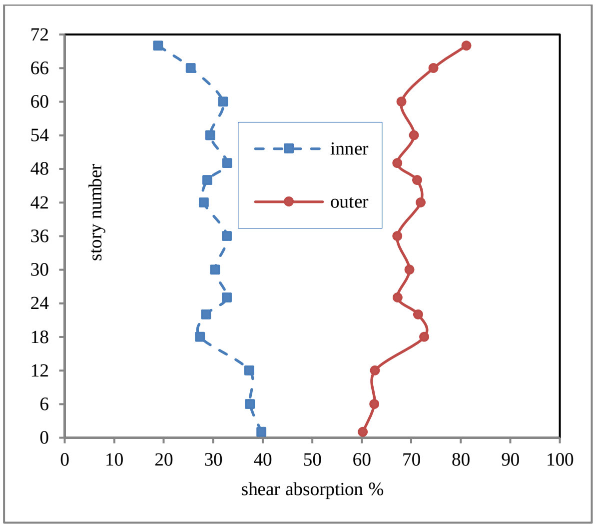

Fig. 33: Percentage of absorption of inner and outer tubes in T72TBO.

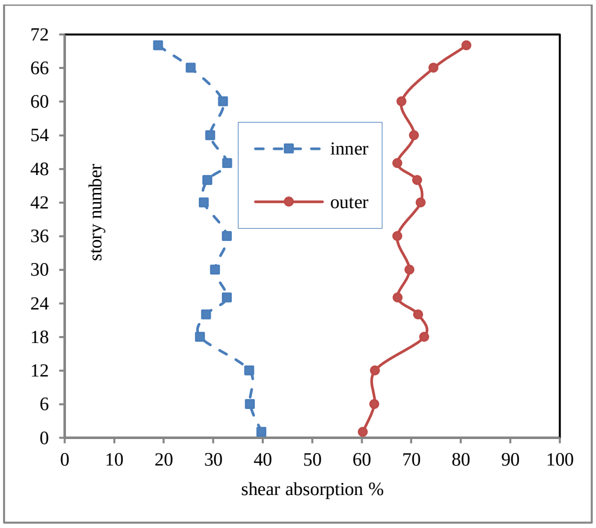

Fig. 33: Percentage of absorption of inner and outer tubes in T72TBO.

As shown in Figure 33, the absorption percentage of the inner tube in T72TBO at lower stories was higher than the absorption percentage of the inner tube of T72TB. For example, at first story, T72TBO had a decrease of 25% regarding shear absorption of outer tube in comparison with T72TB. However, by increasing height, in the inner tube of T72TBO, the contribution of shear decreased and reached 19% at upper stories. As a result, most of the shear was tolerated by the outer tube for the reason that the belt truss transferred story shear to columns of the outer tube as axial forces and caused more percentage of absorption by outer tube. Also at adjacent stories to belt trusses, the absorption percentage of the inner tube was slightly increased. In this system, the shear absorption percentage of the inner tube was higher than the shear absorption percentage in T72TB, and ranged from 40% at lower stories to 20% at upper stories.

7. Conclusion

The paper focuses on the behavior of the hybrid steel system of tube in tube with bracing and belt trusses. To this aim, some buildings were modeled with different structural systems and different number of stories and then, they were analyzed in terms of the shear lag in web and flange, lateral displacement and drift, and absorption percent of shear force under earthquake. The following results were obtained:

- In tubular buildings, by increasing height (due to decreasing story shear and reduction of effects of supports), the shear lag in the flange decreased. In addition, the indexes of shear lag in the flange were more in corner columns and columns of axes 5 and 9.
- By adding the belt truss to the tube in tube system (TnTO), the shear lag at adjacent stories to the belt truss increased at once. Therefore, the addition of belt truss did not have a favorable effect on the reduction of the shear lag in flanges. In addition, adding braces to the outer tube of the tubular system reduced the shear lag at different stories. After investigating the effect of types of bracing (X and V) on the shear lag of braced tube systems, it was concluded that X braces had a better effect on reducing shear lag in flanges except in the last six stories, but chevron braces reduced shear lag even in the last six stories. Finally, the simultaneous addition of braces and belt trusses to tubular systems (TnTBO) improved the shear lag in flange better than tubular systems with only belt truss (TnTO).
- By comparing the lateral displacement of tube in tube system, it was observed that by adding the belt truss to system, due to the addition of a hard story to the structure, the maximum value of drift of TnTO system decreased by 25% in comparison with TnT system. Meanwhile, at the position of trusses, the reduction of relative lateral displacement was greater. In addition, the lateral displacement of braced tubular system at the maximum value reduced by 52%. Finally, the simultaneous addition of braces and trusses to tubular systems compared to other systems had the greatest effect on reducing lateral displacement by 63%reduction at the maximum value in TnTBO system. As a result, the tubular systems with belt trusses and mega braces were the most effective systems in reducing lateral displacement.
- In the study of shear absorption percentage of inner and outer tubes, it was seen that most of story shear was absorbed by the outer tube, and then, by increasing height, the shear absorption of inner tube was reduced. By adding belt trusses to TnT, the absorption percentage of the inner tube increased at lower stories. By increasing height, the shear absorption percentage of the inner tube was reduced and the outer tube had a greater share in absorbing the story shear.
- Adding braces to TnT would make the outer tube harder and increase the shear absorption percentage of the outer tube. In addition, the types of braces did not affect the shear absorption percentage of the braced tube. The simultaneous addition of trusses and braces on outer tube made inner tube of T72T to be harder than the inner tube of TnTB. Therefore, the percentage of shear absorption of the inner tube in this system (TnTBO) was higher than the braced tubular system (TnTB). On one hand, the shear absorption of inner tube decreased by increasing height, and on the other hand the absorption percentage of outer tube increased. In addition, at the location of the belt truss, the percentage of shear absorption of the inner tube increased.
- Adding the belt truss to the tubular system did not have an impressive effect on improvement of shear lag in web and even caused a sudden jump at the adjacent stories to belt trusses. By increasing the depth of the peripheral beams in this system, the shear lag in the web improved to a certain extent. Comparing this system (TnTO) with a tube in tube system (TnT) with deep peripheral beams, this system did not respond well to shear lag.
- Adding braces to the outer tube of the tube in tube system would increase the axial force in columns connected to braces, therefore, adding braces would increase the shear lag in columns.
- To select a suitable system for designing a structure, application and location of structure was considered. In some cases, it was necessary to decrease drift and in other cases, it was essential to decrease shear lag. Generally, the tube in tube system with deep peripheral beams had the best performance in both terms of shear lag and drift.
- On the other hand, the braced tube system with belt trusses had the best performance in reducing lateral displacement which could be increased by adding peripheral deep beams.

7. Suggestion for further study

This paper was investigated in a hybrid system based on linear behaviour. Besides, it can be continued in non-linear behaviour by using nonlinear dynamic analysis and progressive dynamic analysis for this structure.

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