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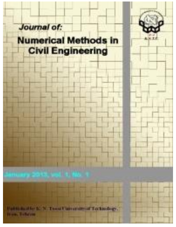

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# Selecting Optimal Dimensions of Internal Tube in Tube-in-Tube Structural Systems Based on Structural Parameters

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***Abstract:***

*Tubular structural systems are one of the most common types of systems in high-rise structures. In the early days of this system, there were imperfections in its design which were overcome over time. The most important modification to rectify these defects is the use of a series of internal frames in addition to the peripheral frames and new systems in the center of the plan to eliminate design weaknesses over time. The central frames such as the inner tube, enhance the final rigidity and durability of the system. In this paper, high-rise buildings of 30, 40 and 50 floors have been subjected to static linear analysis and resistive design and their key design parameters have been investigated. The method is in a way that several samples with real dimensions are selected and the variables of height and the inner tube dimensions are numerically compared. The results revealed that the inner tube dimensions play an important role in improving the design parameters and the best dimension of the inner tube in a square plan is equal to half of the dimension of the outer tube.*

## 1. Introduction

The main objectives of the study are the design parameters, and selection of optimal dimensions of internal tubes in tubes-in-tube structural systems, which were added to the introduction section., Almost no research has been done or there is little research to fill the gap addressed in this article. This study examines in detail the optimal dimensions of the inner tube and takes into account all the general design parameters.

Rahman Khan's innovation in the design and construction of skyscrapers was the idea of using tubular structures. This method revolutionized the design of high-rise buildings. Most of the 40-story buildings built since 1960, are now designed using tubular designs derived from Khan's structural engineering principles [1]. The configuration (of what?) short distance from each other is located in the building environment and form an environmental framework. This frame is designed to withstand lateral loads and the interior frames are designed for heavy loads based on them Availability. Pekau et al. [2] presented a static and dynamic analysis of tube-in-tube structural systems by finite-class method. This method is developed based on the previously created node displacement for approximate analysis of three-dimensional tubular high-rise structures. The central tube in each floor is modeled with a separate thin-walled beam element and is illustrated by the developed matrix. Then, the finite-class method is used to calculate the displacements, natural frequencies, and modes for two symmetric and asymmetric tube systems. The numerical results are compared with the finite element results and the mentioned method provides acceptable accuracy.

Rahgozar et al. [3] investigated the dynamic behavior of the combined shear wall tube system by the Galerkin's method. In this paper, dynamic parameters, namely natural frequencies and modal shapes, are estimated by an approximate method. The real three-dimensional structures are modeled with an equivalent cantilever and obtained on the basis of dynamic equilibrium differential equations of motion and converted to simple numerical forms. The B-Spline function method is used to approximate the numerical form and determine the final matrix of the problem. Finally,

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by applying boundary conditions, the natural frequencies and the corresponding modes are calculated. Modeling in SAP software has been used to evaluate the accuracy of the proposed method. The results of the software modeling show that the proposed method is useful and accurate enough to perform the initial design.

Mohammad Nejad and Haji Kazemi [4] proposed a new and simple method for determining the natural frequency of a tubular structural system. Their study has examined tubular system with shear wall and tube-in-tube system. The structural weight of the models is considered as a downward axial load and the effect of column shear delay is also taken into account. The main model is a non-prismatic beam whose equations of motion have been transformed into a system of linear algebraic equations and the non-trivial response of those equations has been discussed. The accuracy of this response has been confirmed by several numerical studies and previous research.

Shen et al. [5] performed a sequential nonlinear dynamic analysis on a 20-story central tube frame with a supercomputer. Sequential dynamic analysis means applying aftershocks of an earthquake record after the main earthquake record has been applied. This has been further investigated in previous research in conventional structural framework systems addressing the high-rise tubular systems. These structures have complex behavior requiring extensive and costly analysis time. The performance of the finite element model under the two main earthquake record modes and its sequential loading by floors drift, hysteretic energy and damage criterion are compared based on the Park-Ang model. The results of this comparison show that a supercomputer can be useful in solving the problem of time-consuming engineering calculations and it is recommended that the aftershock effect be taken into account. This issue should be considered especially in the structural system of the central tubular core.

Kheyroddin et al. [6] investigated the effects of a variety of peripheral tube systems, tube-in-tube, tube-in-tube with lid, braced tube and bundled tube systems in a 70-story tall structure. They studied the parameters of section cuts through internal and external tubes percentage, absolute displacement of floors, drift index, shear lag coefficient, rotation time and floor drift. The results of this study showed that the effect of each type of tube system compared to only the peripheral tube system, improves the structural behavior. They also found that the best response was related to the braced tube system, because the rate of change of the shear lag coefficient in the tensile columns was more uniform and got closer to number one as the floors increased.

Hamidi et al. [7] investigated the dynamic performance of 30- and 50-story high-rise frames with truss belt and outrigger. The two-dimensional frames were designed in SAP [8] software and analyzed under 12 different earthquake records. Most of the drifts in each model were extracted from the software under different records. The results showed that the use of truss belt system with outrigger in two-dimensional frames of 30 and 50 floors reduces the possibility of structural failure and its instability about 12 to 28 percent.

## 2. Verification

In any numerical modeling, the accuracy of the software results needs to be verified to ensure that the software performs well. In this paper, CSI ETABS [9] software has been used for numerical modeling. The selected model is a 40-story concrete tube structure with a central core shear wall tube at its full height connected to the peripheral and central tube by an outrigger. In this model, in addition to outrigger truss, belt trusses are also used and both trusses are attached to the structure on the tenth floor. The mentioned model is selected from the paper by Kamgar and Saadatpour [10] and is shown in Fig. 1. In their paper, they have presented a simple mathematical method for analyzing the free vibration of combined tube systems with shear walls, belt truss, and outriggers. The obtained natural frequency by the mathematical method is 1.855 rad/s, and it is 1.8034 rad/s by SAP [7] finite element model. The obtained natural frequency of the built model in ETABS is also equal to 1.9408. This frequency has a 4.6 percent difference with Kamgar and Saadatpour's method and a 7.6 percent difference with the SAP [7] finite element model.

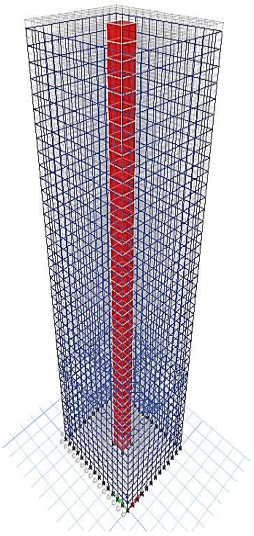

**Fig. 1:** Three-dimensional view of the selected model built into ETABS

The modeling process is that initially the axes of the columns are drawn at 2.5 m intervals, and since the plan dimensions are 35 by 30 meters, 15×13 axes should be drawn. The column sections from the 1st to 21st and from 22$^{nd}$ to 40$^{th}$ floors are 80×80 and 60×60, respectively, and the beam

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sections are the same. The central shear wall box with dimensions of 5×5 meters is also from the 1st to 21st floor and from 22nd to 40th with thickness of 25 and 20 cm, respectively. Belt truss and outriggers also have 80×80 sections. According to the paper, material characteristics are defined based on concrete with a modulus elasticity of $2\times10^4$ MPa. The model was built in real dimensions in ETABS software, and the only modeling assumption was that the mass of the structure was distributed linearly over the peripheral beams.

## 3. Design and Modeling

Before any structural modeling, it is necessary to ensure the appropriateness of dimensions, plan size, its height and sections. The book *Principles of Design of High-Rise Buildings* by Mahmoud Golabchi [11] states that, from an architectural point of view, the height-to-diameter ratio is greater than π. This is also mentioned by Derakhshande Nejad [12] in the book of high-rise buildings with tube systems. Therefore, this criterion is used to select the dimensions of the plan and the height of the building. The assumed three-dimensional building has a 30 m square plan that has been studied at 3 different heights of 30, 40 and 50 floors. The floor height is 3.5 meters and the axis spacing is 2.5 meters. In addition to the height, the dimensions of the inner tube are also included as criteria of this study. The inner square tube is modeled in 20, 15, 10 and 5 m dimensions and a non-inner tube model is included as the reference model, which is briefly referred to as No tube in the results. The overall view of the mentioned plan is shown in Fig. 2 and Fig .3.

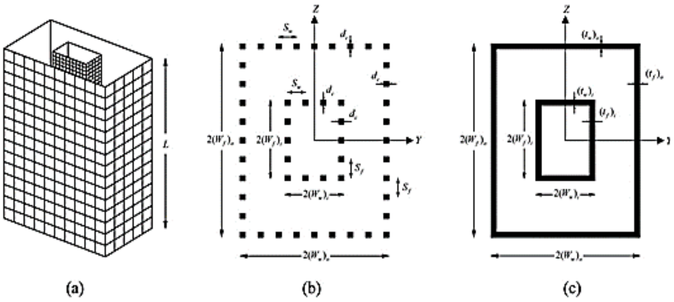
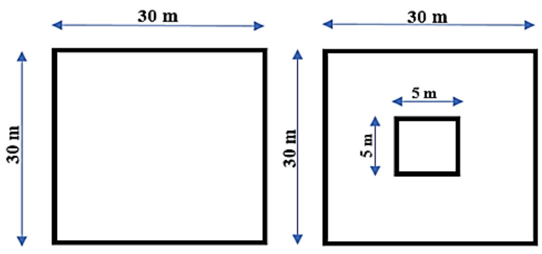


**Fig. 2:** Tube-in-tube structure: (a) actual structure, (b) structural plan of the tube-in-tube structure, and (c) structural plan of the equivalent structure



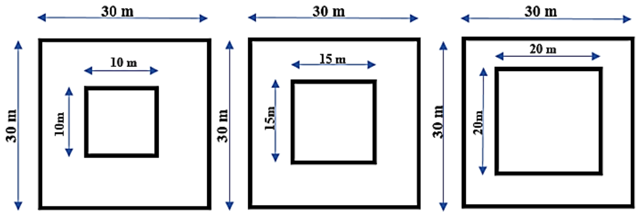


**Fig. 3:** Plan models of the tube-in-tube structure (No tube inner tube, tubes inner 5×5,10×10,15×15,20m×20m)

The modeling process is similar to the one that was mentioned in the validation part. Therefore, all the design steps, including drawing the members, allocating loads and controlling the sections, have been performed in the ETABS software. The gravity loads are calculated according to the sixth issue of the National Building Regulations, where dead and live loads are defined as 500 and 200 kg/m$^2$, respectively. The seismic mass is equal to the total dead load and 20% of the live load [13]. Wind and earthquake lateral loads are automatically calculated and applied in accordance with ASCE 7-10 [14] software. AISC Design Code 360-10 [15] has been selected because the tenth issue of National Building Regulations was obtained based on that, and the seismic design criteria are controlled by AISC 341 - 10 [16]. A special flexural frame structure is chosen. The material used to design the towers is St52 steel. The shear and elastic modulus of this type of steel are 200,000 and 77,000 MPa, respectively. The sections used for beams and columns are made of plate girder and square boxes in the software, respectively. The table of structural sections is presented in Table 1.

**Table 1:** Structural sections

| No. | Model | Member | Story | Sections(cm) |
|---|---|---|---|---|
| 1 | 30 story | column box | 1-10 | 55×5 |
| 2 | | | 11-20 | 50×4 |
| 3 | | | 21-30 | 45×3 |
| 4 | | plate beam | 1-10 | 55×30 |
| 5 | | | 11-20 | 50×25 |
| 6 | | | 21-30 | 45×20 |
| 7 | 40 story | column box | 1-10 | 60×6 |
| 8 | | | 11-20 | 55×5 |
| 9 | | | 21-30 | 50×4 |
| 10 | | | 31-40 | 45×3 |
| 11 | | plate beam | 1-10 | 60×35 |
| 12 | | | 11-20 | 55×30 |
| 13 | | | 21-30 | 50×25 |
| 14 | | | 31-40 | 45×20 |
| 15 | 50 story | column box | 1-10 | 70×70 |
| 16 | | | 11-20 | 60×6 |
| 17 | | | 21-30 | 55×5 |
| 18 | | | 31-40 | 50×4 |
| 19 | | | 41-50 | 45×3 |
| 20 | | plate beam | 1-10 | 70×40 |
| 21 | | | 11-20 | 60×35 |
| 22 | | | 21-30 | 55×30 |
| 23 | | | 31-40 | 50×25 |
| 24 | | | 41-50 | 45×20 |

## 4. Numerical Analysis Results

To obtain the output of modeling results from the software, an effort was made to address key structural design parameters. One of the most important considerations in any design is the main periodicity of the structure because, according to the spectrum of seismic response, the acceleration, and then the force on the structure, are strongly influenced by the period of that structure. Therefore, in the first step of examining the results, the first mode period of the study models is presented in Table 2.

**Table 2:** The first mode period of the study models

| No | model | Tube inner | Period (s) | Different/ No tube (%) |
|---|---|---|---|---|
| 1 | 30 story | 20x20 inner box | 2.79 | 23 |
| 2 | | 15x15 inner box | 2.82 | 22 |
| 3 | | 10x10 inner box | 3.08 | 15 |
| 4 | | 5x5 inner box | 3.41 | 5.5 |
| 5 | | No tube inner box | 3.61 | 0 |
| 6 | 40 story | 20x20 inner box | 3.4 | 21 |
| 7 | | 15x15 inner box | 3.43 | 20 |
| 8 | | 10x10 inner box | 3.73 | 14 |
| 9 | | 5x5 inner box | 4.09 | 5 |
| 10 | | No tube inner box | 4.32 | 0 |
| 11 | 50 story | 20x20 inner box | 3.96 | 18.5 |
| 12 | | 15x15 inner box | 3.96 | 18.5 |
| 13 | | 10x10 inner box | 4.29 | 11.5 |
| 14 | | 5x5 inner box | 4.65 | 4.5 |
| 15 | | No tube inner box | 4.86 | 0 |

It shows that the period increases with decreasing dimension of the inner tube. The percentage of periodicity increase in each model compared to the non-inner-tubing model is indicated in the last column. The percentages show that the 30 and 40-story models are not significantly different in terms of periodic increase, and their largest percentage of periodic increase with 20-m tubes is equal to 23 and 21 percent, respectively. The 50-story model is not very similar to the other two models, with a maximum increase of 18.5%. Increasing the number of floors, adds to the period. For example, the period of 40-story model with a 20-m tube has increased about 22 percent compared to the similar 30-story model.

## 5. Shear lag coefficient

Shear lag is a phenomenon that results from the formation of a neutral axis somewhere in the wing and structure of the tube system (usually in the middle) and a difference in the axial forces of the system columns. In other words, the tubing system treats as cantilever against lateral load, so the parallel side acts as the structure of beam and the perpendicular side acts as the beam wing. The cantilever has a neutral axis, and the further it gets, the greater the axial force of the columns gets, as shown in Fig. 4. This issue considers system optimization and plays a key role in its design.

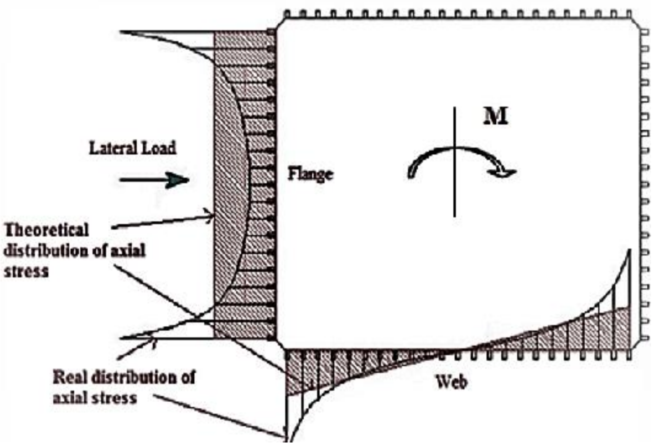
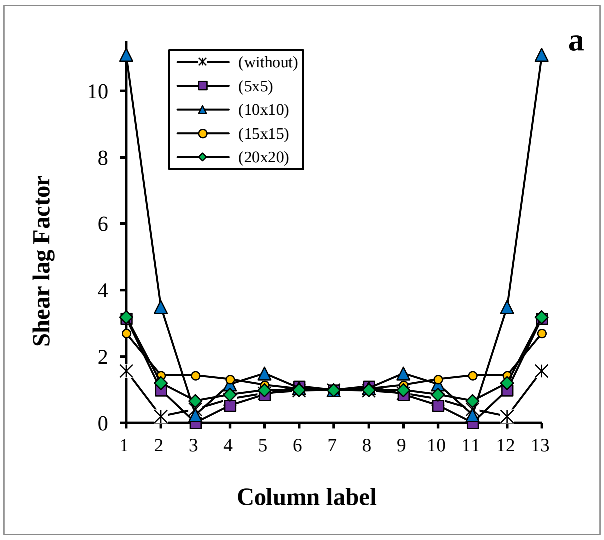


**Fig. 4:** Non-uniform axial force distribution in the tube system columns and the formation of shear lag [17]

As stated, each column has a shear lag coefficient (SLF), which is the axial force of the lateral columns to the middle ones.

The shear lag coefficients of the tensile columns of all the models investigated in this paper are calculated and their rate of change is shown in the diagrams of Figures 5 to 13. The horizontal axis of these graphs represents the column number. Since there are 13 columns on each side of the plan, the numbers of this axis are 1 to 13. Column 7 is the middle column used as the SLF coefficient reference.



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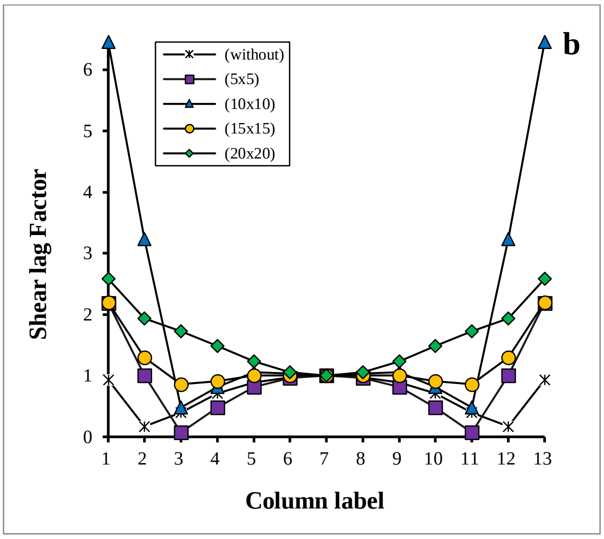

**Fig. 5:** The shear lag coefficients of models 30 story: (a) story 1 - (b) story 6

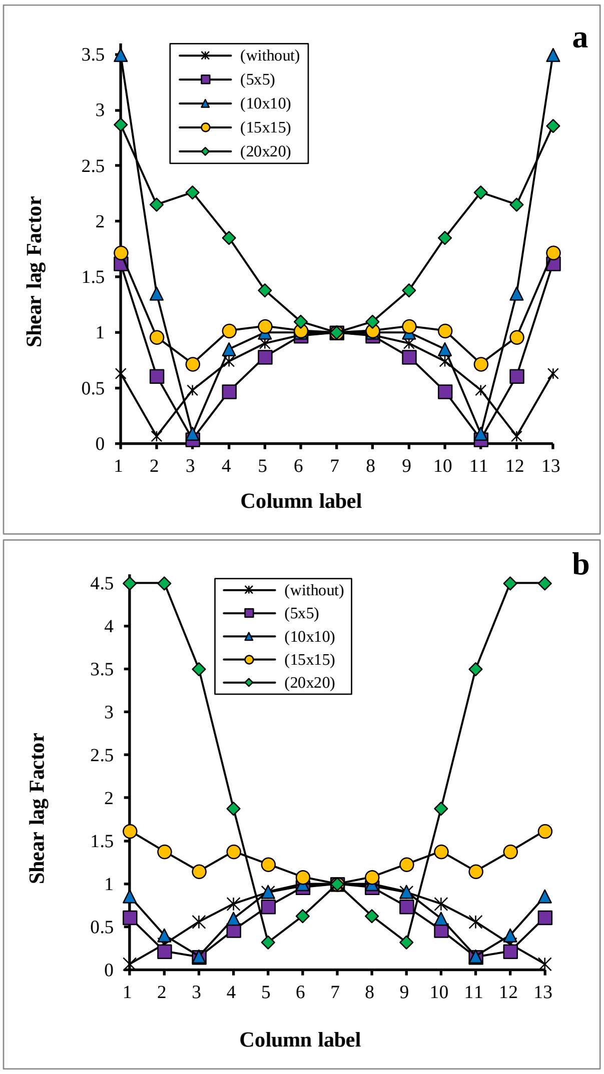

**Fig. 6:** The shear lag coefficients of models 30 story: (a) story 12 - (b) story 18

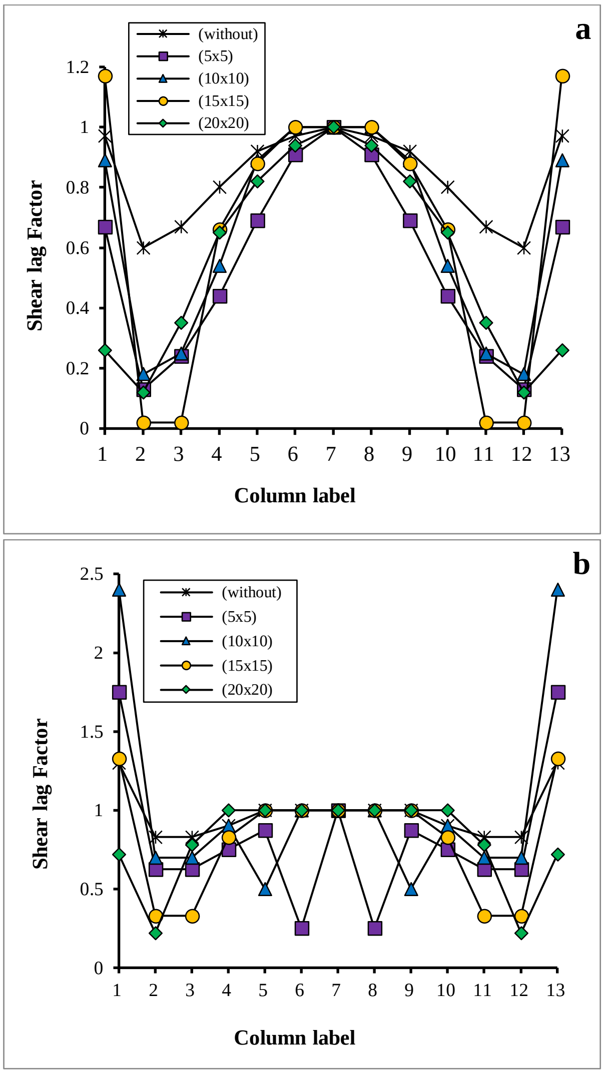

**Fig. 7:** The shear lag coefficients of 30-story models: (a) story 24 - (b) story 30

According to Figures 5, 6 and 7, on the first floor of all 30-story models, the maximum shear lag coefficient corresponds to the model with a 10-meter inner tube and the lowest one relates to the model with 15-meter tube. On the sixth floor, the highest shear lag coefficient occurred in the model with 5 m inner tube and the 15-meter tube model had the lowest shear lag coefficient. The 12th floor had the same behavior as the 6th one, but the 18th floor behaved slightly different. On the 24th and 30th floors, the results were quite different. The highest coefficient was devoted to the model with a 15-meter tube and the lowest one was related to the models no tube inner tube.

Therefore, the behavior of the 24th and 30th floors is quite the opposite of that of the 18th floor So, it can be said that the inner tube in the upper floors of the 30th floor model does not have any effect in terms of shear lag.

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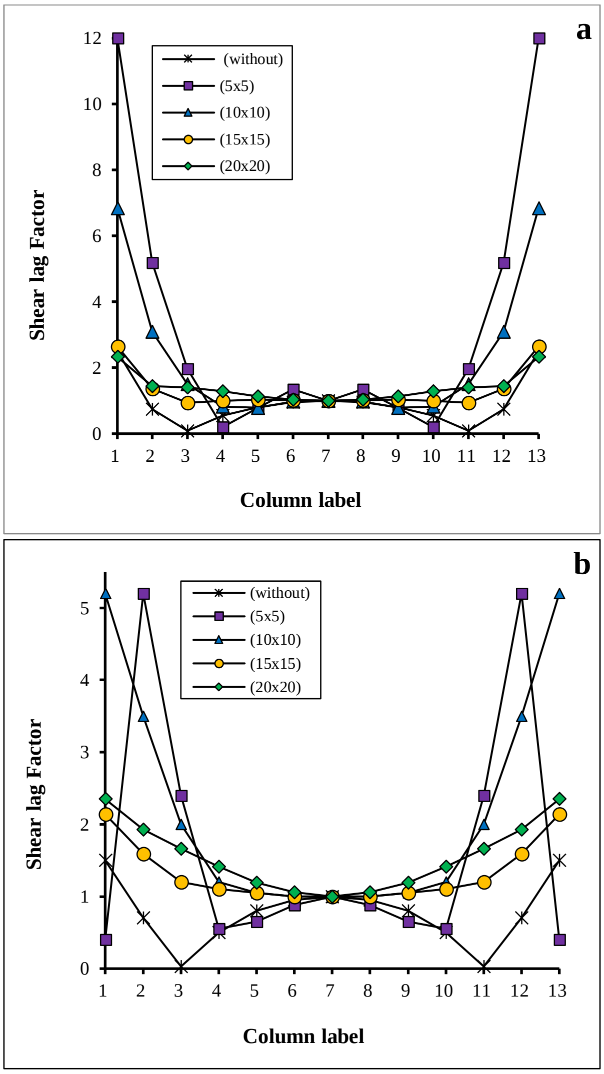
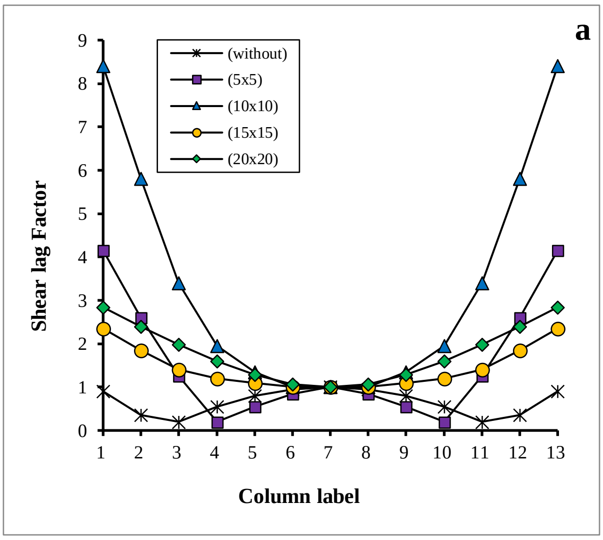


**Fig. 8:** The shear lag coefficients of models 40 story: (a) story 1 - (b) story 8



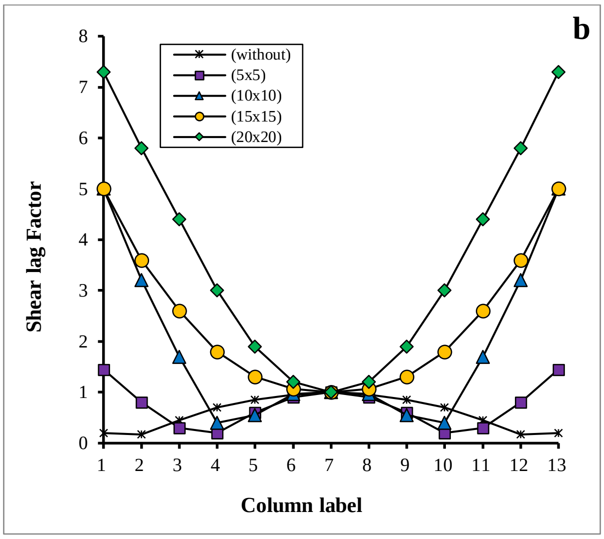


**Fig. 9:** The shear lag coefficients of 40 story models: (a) story 16 - (b) story 24

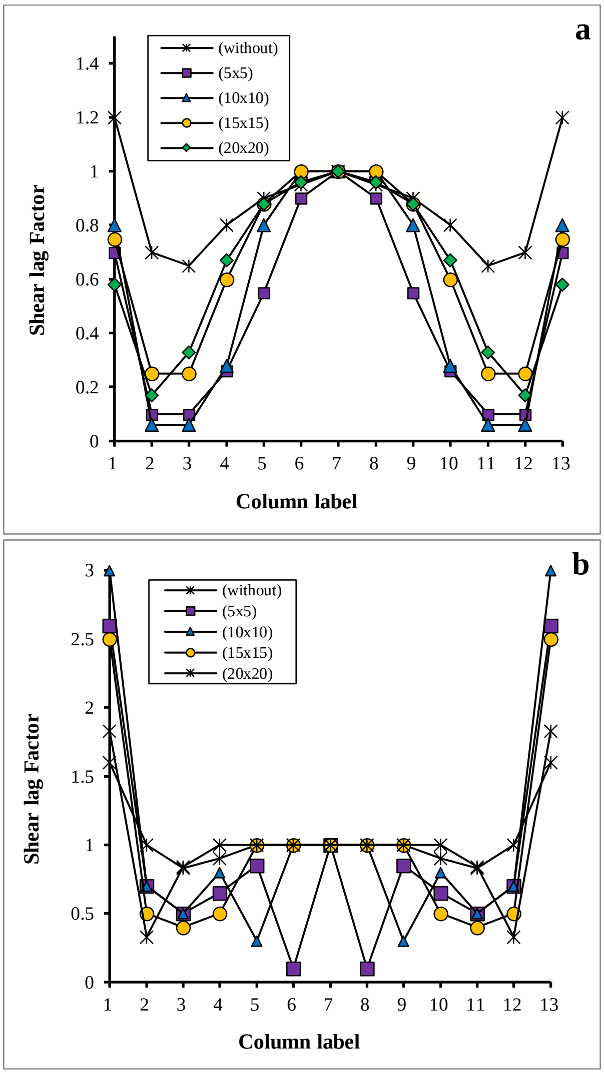


**Fig. 10:** The shear lag coefficients of 40 story models: (a) story 32 - (b) story 40

Figures 8, 9 and 10 show the rate of change of shear coefficients of columns of floors 1, 8, 16, 24, 32 and 40 for 40-story samples. It is apparent from the diagrams that in floors 1 and 8, the effect of the inner tube of 20 meters and especially 15 meters reduces the shear lag coefficient. In these floors, most of the shear lag occurred in no tube as an inner tube.

The rate of changes in shear lag coefficients in the 16th and 24th floors are similar to those in the 1st and 8th floors. But in floors 32 and 40, the shear lag coefficient of no tube model is less than that of the other models, and, like the 30-story model, the inner tube at heights has no particular effect on the system. The diagram of the shear coefficient changes of the 50-story model is illustrated in three Figures of 11, 12 and 13 below.

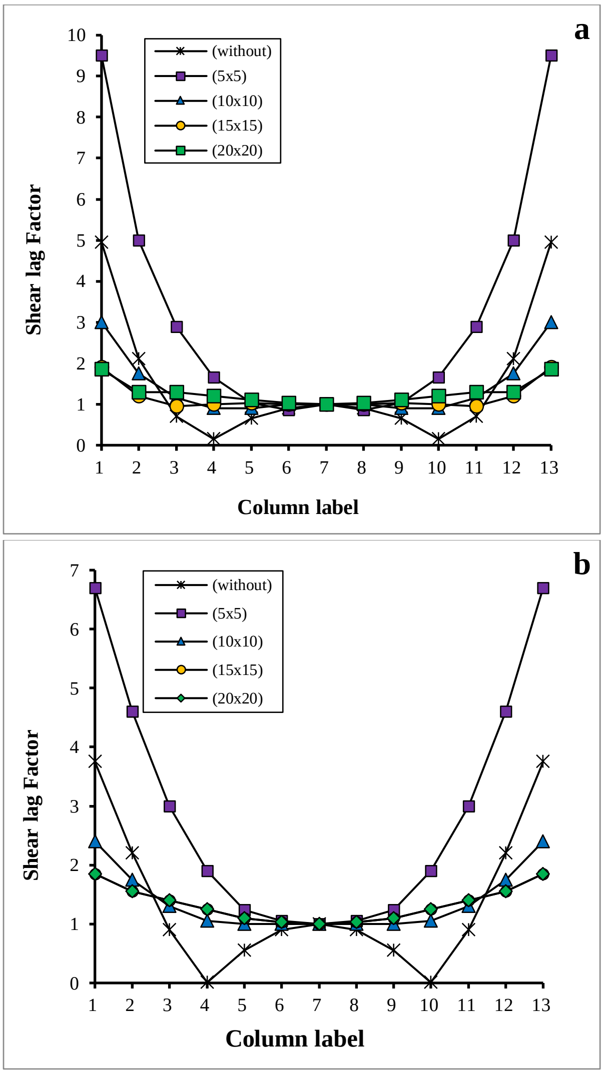


**Fig. 11:** The shear lag coefficients of 50 story models: (a) story 1 - (b) story 10

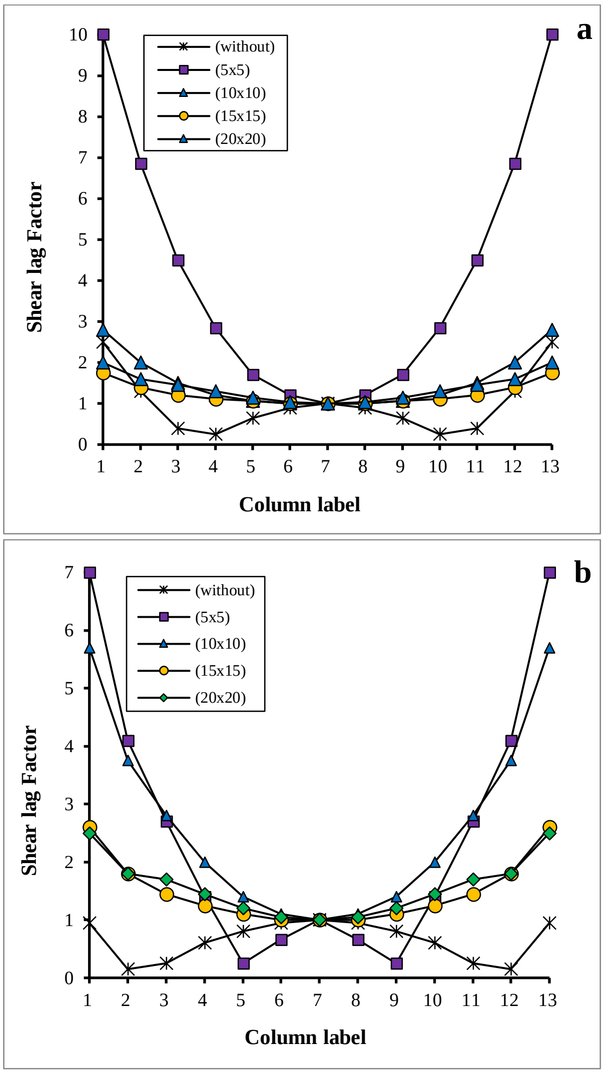
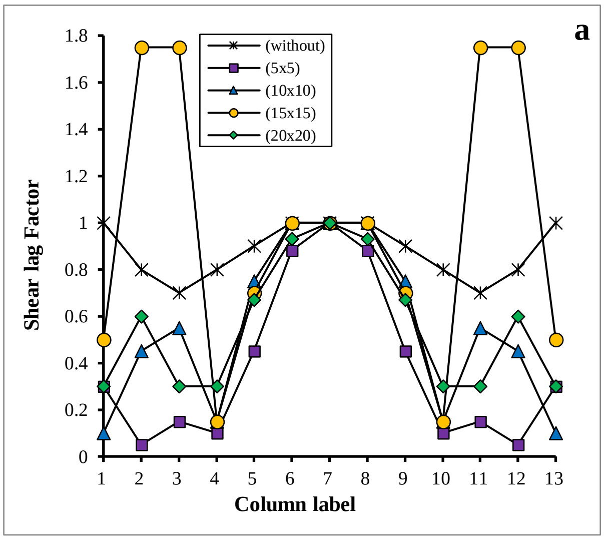


**Fig. 12:** The shear lag coefficients of 50 story models: (a) story 20 - (b) story 30



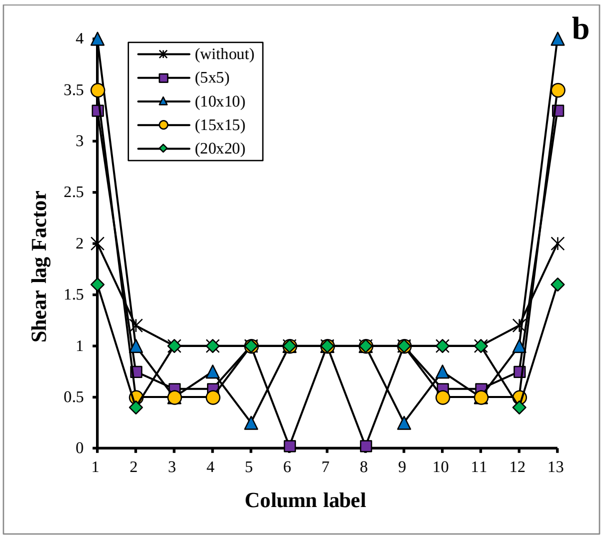


**Fig. 13:** The shear lag coefficients of 50 story models: (a) story 40 - (b) story 50

It can be seen from Fig. 11 that in floors 1 and 10, most of the shear lag changes are related to the models with 5-meter tube and no tube models. On the other hand, the lowest shear lag coefficient was obtained for models with inner tube of 20 and 15 meters. The 20th and 30th floors of the 50-story model are similar to those of the 1st and 10th floors and the highest and lowest coefficients are for the models with 15-meter tube and no tube models, respectively. But in floors 40 and 50 of Fig. 13, different results have been obtained. In these floors, the least rate of change of the shear lag coefficient is given to the no tube model. The models with the 15 and 20-meter tubes are then followed, and generally in the 50-story models, as in the 30 and 40-story models, the inner tubes have no effect on reducing the shear lag of the upper floors.

## 6. Percentage of shear force absorption

Shear force absorption percentage is the ratio of shear force absorbed by members of the structural system to the shear force applied to the floor [18]. This parameter helps to understand the extent of the inner tube's involvement in different dimensions and heights. Therefore, in Figures 14, 15 and 16, the rate of change of absorption percentages of the shear forces of 30, 40, and 50-story models are listed separately for each outer and inner tube, respectively.

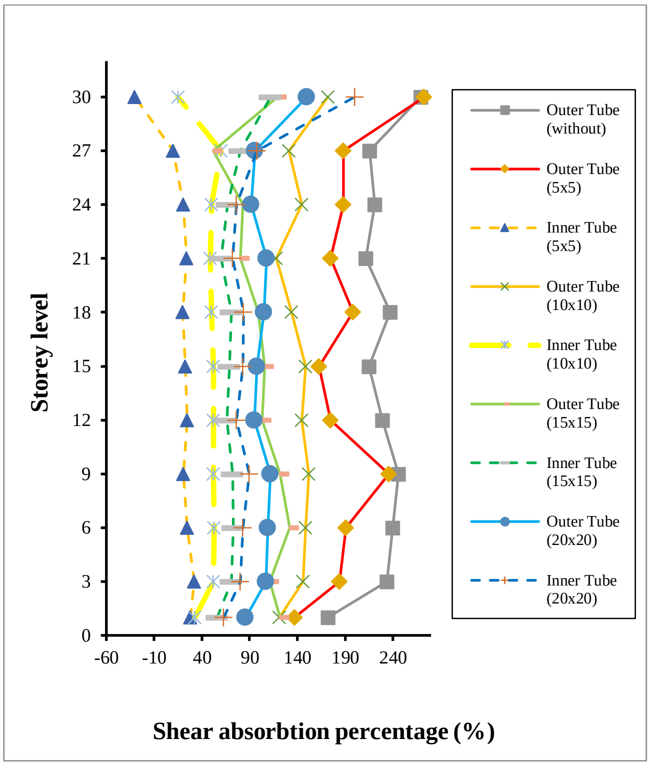


**Fig. 14:** Absorption percentages of the shear forces of 30 story models are listed separately for each outer and inner tube, respectively

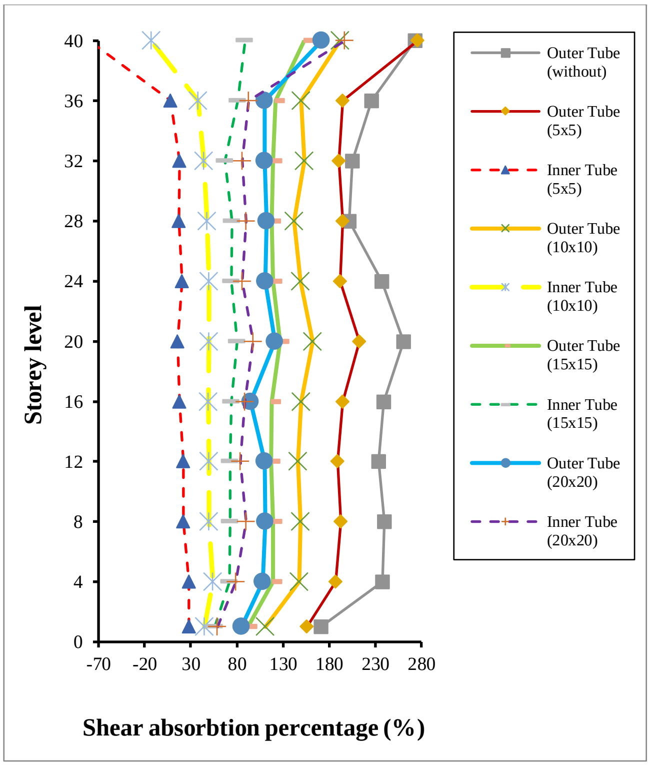


**Fig. 15:** Absorption percentages of the shear forces of 40-story models listed separately for each outer and inner tube, respectively

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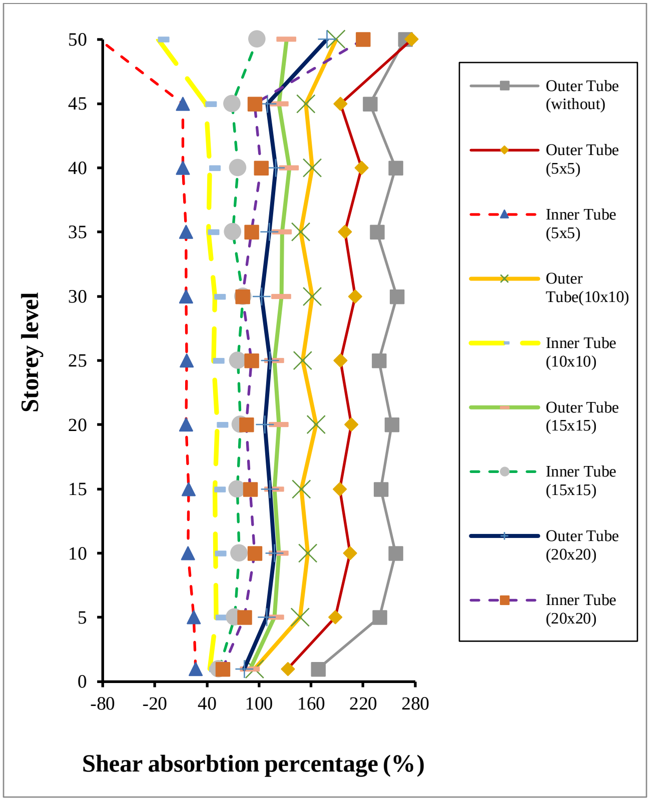

**Fig. 16:** Absorption percentages of the shear forces of 50-story models listed separately for each outer and inner tube, respectively

It can be seen from Fig. 14 that the highest percentage of section cuts through internal and external tubes relates to no tube model, because no inner tube helps it withstand lateral load. The model with 5-meter inner tube has less shear force than the no tube model, and in general, when the inner tube size increases, the absorption rate of the outer tube decreases, since the number of inner tube members increases and becomes more involved in bearing lateral loads. The point that should be taken into account is the negative absorption rate of the 5-meter inner tube shear that occurred on the top floor. This amount increases the sheer force of the outer tube on the last floor [18]. This sharp decline in the percentage of internal tube participation is also observed in 10-meter inner tube. The percentage of participation from the 60th floor decreases from 60 to 15 percent to 30th floor. But this is not the case with a 15-meter tube. The percentage of participation of this model on the top floor has not decreased but increased instead. Interestingly, the percentage of this model's participation on the 15th floor is more than that of the model with 20-meter tube. It can be seen in Fig. 15 that the overall behavior of the 40-story model is similar to the 30-story section cuts through internal and external tubes percentage, and with the increase of the inner tube dimensions, the section cuts through internal and external tubes percentage is reduced in outer tube. According to the diagram in this figure, on the last floors of the inner tubes of 5 and 10 meters, the negative section cutting through internal and external tubes is about 70 and 20 percent. This is contrary to our expectation, and nothing can be done to (improve?) the external tube of these models [18]. The 15-meter inner tube has the highest normal diagram of the rate of changes. Its outer tube is also not much different from the 20-meter inner tube model. The mentioned factors for 30 and 40-story models also apply to the 50-story model. In Fig. 16, the 5 and 10-meter inner tubes have negative section cuts through internal and external tubes. Models with 15 and 20-meter inner tubes do not differ much. The 20-meter inner tube on the top floor tolerates high shears and, therefore, the 15-meter tube has a more uniform diagram.

## 7. Relative drift of floors

Story Drift: Lateral displacement of one level relative to the next lower level. Each floor is examined compared to the floor beneath it. This ratio is defined in terms of percentage and is a criterion for controlling the operating conditions of non-structural members. According to clause 3-5-2 of Standard 2800 Fourth Edition [19], the relative drift of floors of buildings over 5 floors shall not exceed 2%. The relative drift of all floors of all the models examined in this study is shown in Figures 17, 18 and 19.

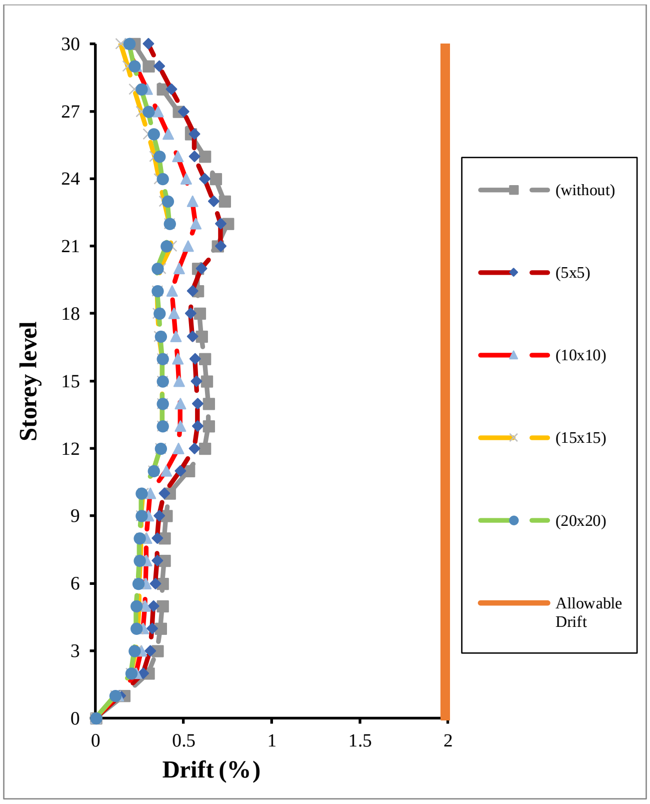

**Fig. 17:** Drift floors of the 30-story models

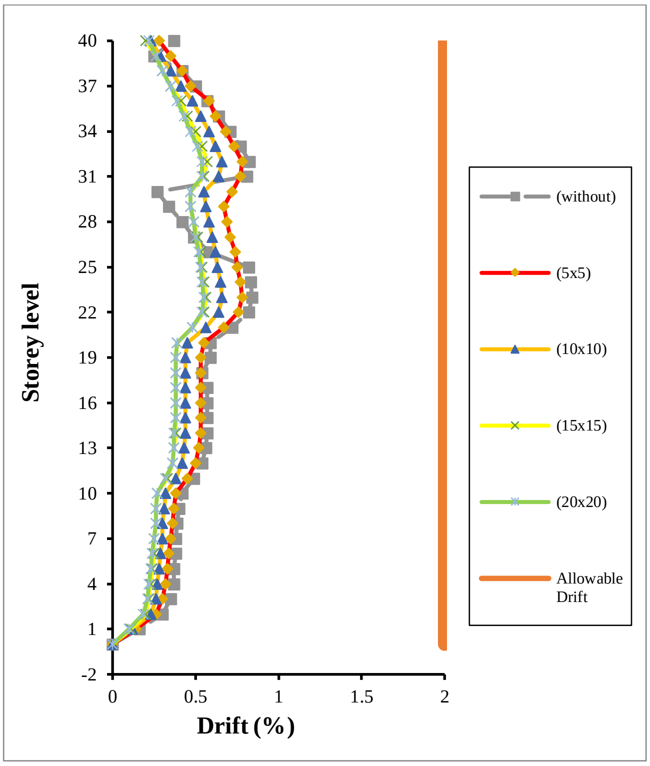

**Fig. 18:** Drift floors of the 40-story models

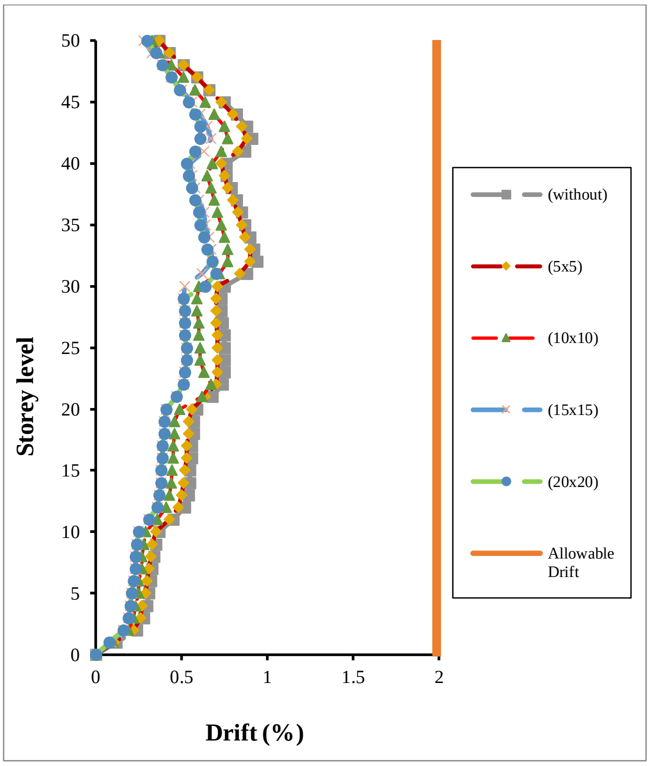

**Fig. 19:** Drift floors of the 50-story models

As can be seen in all three Figures above, the relative drift of all 30, 40, and 50-story models is less than the norm. Therefore, the design of the sample structures of this study is justified and appropriate operating conditions are followed. In the graphs of the drift changes of the floors, the no tube model has the highest drift and with the increase of the inner tube dimensions, the drift decreases. Drift reduction is not unexpected, because when the size of the inner tube increases, the number of structural elements and stiffness increases and the displacement decreases. But this is not the case with the 20-meter tube model, whose floor drift is not much different from models with 15-meter inner tube.

## 8. Conclusion

In this study, the design of high-rise buildings of 30, 40 and 50 floors with tubular and tube-in-tube systems with different dimensions was investigated. The effects of inner tube dimensions and height were investigated with periodic design parameters, shear lag coefficient, section cuts through internal and external tubes percentage, and relative drift of the floors. The results of this study can be summed up as:

1. Increasing the dimensions of the inner tube raises the stiffness and reduces the period. The no tube structure of the inner tube is softer and has a longer period. In order to select the appropriate dimensions to optimize the design, knowledge of the soil type of the site is also required. But empirically, the more the natural period of the structure, the less acceleration it has under an earthquake. Therefore, regardless of the type of site and the predominant period of the earthquake, the no tube model would be the optimal one.
2. In order to optimally select the structure, the periodicity criterion is not sufficient and another key parameter should be considered. The rate of change of shear lag coefficient shows that the effect of the inner tube of 15 m is better at 2.3 height of all three structures of 30, 40 and 50 stories.
3. Regarding the investigation of shear force absorption amount in floors, it can be concluded that the models with 5 and 10 m tube have poor performance, because their participation percentage of lateral load tolerance tends to be negative on the last floor. Participation percentage of the model with the inner tube of 15 m, although weaker than the model with the 20 m tube, is not much different.
4. Structural design is performed in the correct strength. The reason is that the relative drift of the floors is not exceeded by norms.
5. The no tube model of the inner tube is less weak than the rest of the models, and therefore it has a higher relative drift on floors. The models with the 15 and 20 m tubes are identical in terms of drift.
6. According to the above-mentioned results, it can be claimed that the dimensions of the inner tube have a great influence on the design parameters of the tube-in-tube system. The smaller dimensions of the inner tube do not yield the desired results, and among the examined cases, the best responses are for the models with 15-meter inner tube.

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