The Effect of Geometry of Plan on Shear Lag of Framed Tube Tall Buildings Subjected to the Earthquake Load

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***Abstract*—Framed tube structural system, proposed by "Fazlur khan" is one of the most influential systems in design and construction of skyscraper. The tubular system in its simplest form, consists of closely spaced exterior columns linked at each floor level with relatively deep spandrel beams. Axial force in exterior columns is unequally distributed due to the flexibility of circumferential beams. This phenomenon is called shear lag which reduces the efficiency of the above system. In this research the earthquake behavior of reinforced concrete framed tube structures in three different plan shapes, including Rectangular as the control model, Triangular and Hexagonal, is investigated. Also Iranian code was used to reload structures in this paper. It is observed that, structures with Rectangular plan shape had the maximum amount of shear lag and the Hexagonal ones had the minimum.**

***Index Terms*—tall building, framed tube, plan shape, shear lag, structural behavior**

I. Introduction

Framed tube structure is an effective structural system for both concrete and steel tall buildings. This kind of system is mainly comprised of closely spaced exterior columns, which are connected by a deep spandrel beam at each floor. These constituents create an effect of "hollow tube" [1]. The framed tube system combines the behavior of a true cantilever, such as a shear wall, with that of a beam-column frame. The overturning moment under lateral load is resisted by tube form causing compression and tension in the columns, while the resulted shear force due to the lateral loads is resisted by bending in columns and beams primarily located at two sides of the building parallel to the direction of the lateral load [2]. Gravity loads are resisted partly by exterior frames and partly by interior columns [3]. In a tubular system, exterior columns and beams connected together (Fig. 1 and Fig. 2), considered as walls of a hollow tube cantilevering from the ground with a basic stress distribution as shown in Fig. 3.

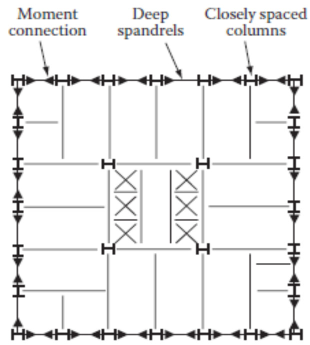

Figure 1. Framed tube, Schematic plan [2]

Although the above structure has a tubular form, its behavior is more complicated than the behavior of a solid tube. In a framed tube structure, the axial force in the columns toward the middle of the flange frames lag behind those near the corner due (Fig. 3) to the nature of a framed tube which is different from a solid tube [4]. This phenomenon is called "shear lag" which reduces the cantilever efficiency in under lateral load framed tube [5]. Fouth and Chang [6] found out a new phenomenon in lateral behavior of framed tube which is called negative shear lag. This anomaly unlike its positive form, will occur when column forces near web panel is smaller than that near center of flange frame. There have been many

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researchers who have focused to understand this type of shear lag (Chang and Zheng [7]; Kwan [8]; Shushkewich [9]; Singh and Nagpal [10]). This phenomenon, is maximum at the top of the buildings and occurs only after positive shear lag has occurred. An optimized framed tube should have a minimum of shear lag effect and acts such as a cantilever as much as possible. There are many studies which have been doing since 1961 (the first year of proposition of tubular system concept [11]), to reduce shear lag effect and increase the efficiency of tubular systems.

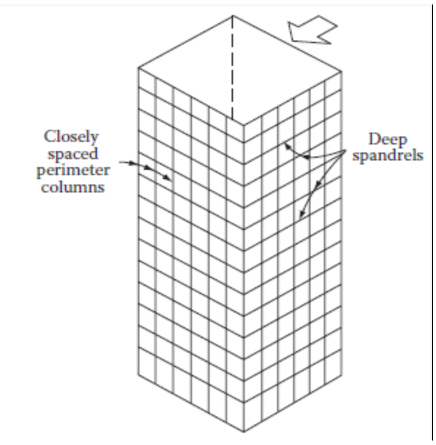

Figure 2. Framed tube, Isometric plan [2]

II. Specifications of the Tube Structures

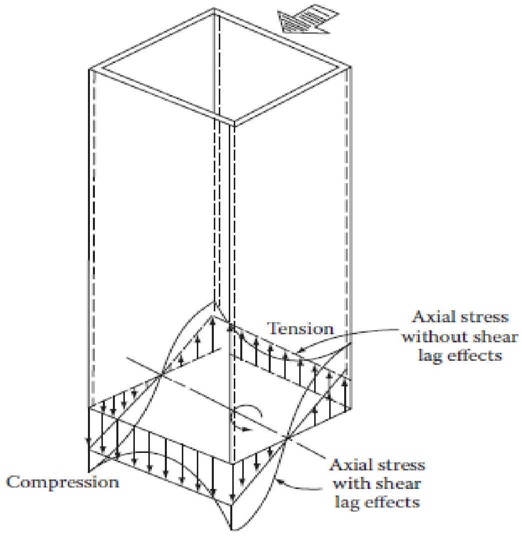

Figure 3. Axial stress distribution in a square hollow tube, with and without shear lag [3]

In this paper, six reinforced concrete framed tube are modeled and analyzed. In terms of structure's height, they consist of two main groups: the first one has 40 stories and the second group has 60 stories tube frames. Tall buildings of each groups included three different plan shapes: a) Rectangular, b) Triangular, c) Hexagonal (Fig. 4). The table below (Table I) shows the Terminology which are employed for each model in this paper.

TABLE I. Terminology of Models

No. Story	Rectangular	Triangular	Hexagonal
40	40R	40T	4H0
60	60R	60T	60H

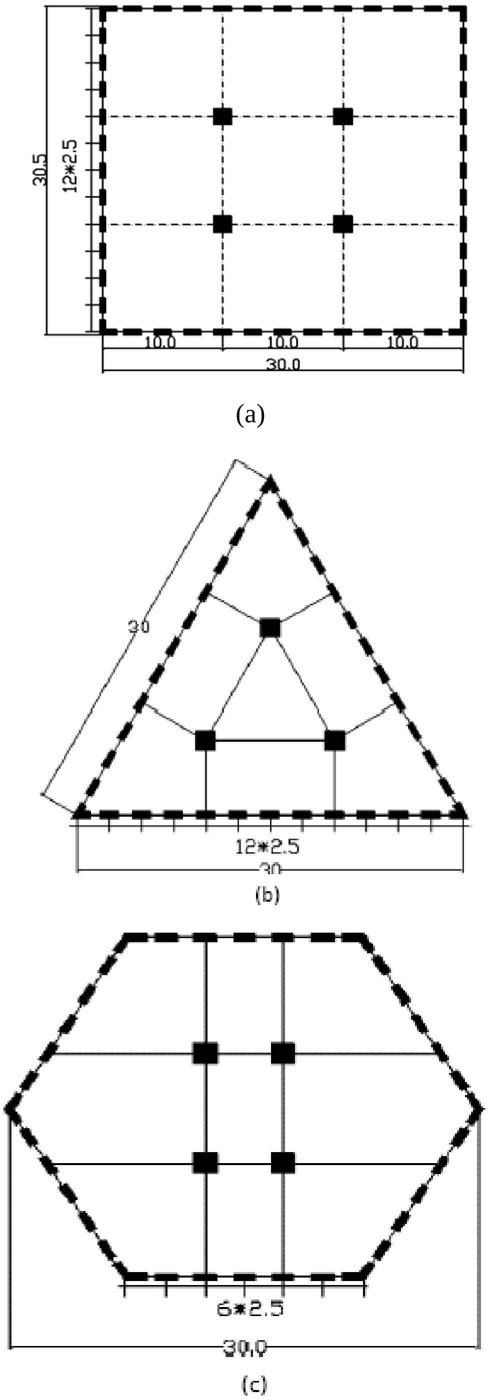

Figure 4. Three different plan shapes:

a) Rectangular; b) Triangular; c) Hexagonal
Note: All dimensions are in meter

The close spacing of columns in tubular structures could be problematic for entrance at the first floor. Therefore, to solve this problem we considered the columns with normal axis to axis distance without any beam in the first floor and also the second story is isolated by deep beams as a solid story. In fact the tubular form of the structure starts from third story. To achieve a better analogy, the equivalent length of 30 m for each side of rectangular and triangular plans is ass umed which is equal to the hexagonal plan diameter. Each side of hexagonal plan is obtained 15 m**.** The distances between columns which are located in the first floor are 10 m in rectangular and triangular plan shapes and 5 m for hexagonal plan shape.

Circumferential columns have 2.5 m distance in all structures. The dimensions of circumferential and also gravitational columns and beams for the models are shown in Tables II to VII for both 40 and 60 story buildings. These dimensions are obtained through initial analysis and final design which is explained in section 3. Slab floor's thicknesses are 0.2 m for structures type 'a' and 'b', and 0.3 m for structures type 'c'.20lumns The story's height is 3.8 m each and the total height of 40 story and 60 story buildings are 152 m and 228 m respectively.

TABLE II. 40 STORY, RECTANGULAR PLAN SHAPE STRUCTURES (R4)

storey	Columns Dim	Beams Dim	Gravitional Columns Dim	Gravitional Beams Dim
1	2x2	0.75x0.6	2x2	0.7x0.5
2	-------	-------	2x2	0.7x0.5
3-10	1.4x0.5	1.4x0.5	2x2	0.7x0.5
11-20	1.4x0.4	1.4x0.4	1.5x1.5	0.7x0.5
21-30	1.4x0.3	1.4x0.3	1.3x1.3	0.7x0.5
31-40	1.4x0.2	1.4x0.2	1x1	0.75x0.6

TABLE III. 60 STORY, RECTANGULAR PLAN SHAPE STRUCTURES (R6)

storey	Columns Dim	Beams Dim	Gravitional Columns Dim	Gravitional Beams Dim
1	2x2	0.75x0.6	3x3	0.75x0.6
2	-------	-------	3x3	0.75x0.6
3-10	1.4x0.7	1.4x0.7	3x3	0.75x0.6
11-20	1.4x0.6	1.4x0.6	2.5x2.5	0.75x0.6
21-30	1.4x0.5	1.4x0.5	2x2	0.75x0.6
31-40	1.4x0.4	1.4x0.4	1.7x1.7	0.75x0.6
41-50	1.4x0.3	1.4x0.3	1.3x1.3	0.75x0.6
51-60	1.4x0.2	1.4x0.2	1.3x1.3	0.75x0.6

TABLE IV. 40 STORY, TRIANGULAR PLAN SHAPE STRUCTURES (T4)

storey	Columns Dim	Beams Dim	Gravitional Columns Dim	Gravitional Beams Dim
1	2x2	0.75x0.6	2x2	0.65x0.45
2	-------	-------	2x2	0.65x0.45
3-10	1.4x0.5	1.4x0.5	2x2	0.65x0.45
11-20	1.4x0.4	1.4x0.4	1.5x1.5	0.65x0.45
21-30	1.4x0.3	1.4x0.3	1.3x1.3	0.65x0.45
31-40	1.4x0.2	1.4x0.2	1x1	0.65x0.45

TABLE V. 60 STORY, TRIANGULAR PLAN SHAPE STRUCTURES (T6)

storey	Columns Dim	Beams Dim	Gravitional Columns Dim	Gravitional Beams Dim
1	2.7x2.7	0.75x0.6	2.7x2.7	0.65x0.45
2	-------	-------	2.7x2.7	0.65x0.45
3-10	1.4x0.7	1.4x0.7	2.7x2.7	0.65x0.45
11-20	1.4x0.6	1.4x0.6	2.5x2.5	0.65x0.45
21-30	1.4x0.5	1.4x0.5	2x2	0.65x0.45
31-40	1.4x0.4	1.4x0.4	1.5x1.5	0.65x0.45
41-50	1.4x0.3	1.4x0.3	1.3x1.3	0.65x0.45
51-60	1.4x0.2	1.4x0.2	1x1	0.65x0.45

TABLE VI. 40 STORY, HEXAGONAL PLAN SHAPE STRUCTURES (H4)

storey	Columns Dim	Beams Dim	Gravitional Columns Dim	Gravitional Beams Dim
1	2x2	0.75x0.6	2x2	0.75x0.6
2	-------	-------	2x2	0.75x0.6
3-10	1.4x0.5	1.4x0.5	2x2	0.75x0.6
11-20	1.4x0.4	1.4x0.4	1.5x1.5	0.75x0.6
21-30	1.4x0.3	1.4x0.3	1.3x1.3	0.75x0.6
31-40	1.4x0.2	1.4x0.2	1x1	0.75x0.6

TABLE VII. 60 STORY, TRIANGULAR PLAN SHAPE STRUCTURES (H6)

storey	Columns Dim	Beams Dim	Gravitional Columns Dim	Gravitional Beams Dim
1	2.7x2.7	0.75x0.6	3x3	0.75x0.6
2	-------	-------	3x3	0.75x0.6
3-10	1.4x0.7	1.4x0.7	3x3	0.75x0.6
11-20	1.4x0.6	1.4x0.6	2.5x2.5	0.75x0.6
21-30	1.4x0.5	1.4x0.5	2x2	0.75x0.6
31-40	1.4x0.4	1.4x0.4	1.5x1.5	0.75x0.6
41-50	1.4x0.3	1.4x0.3	1.3x1.3	0.75x0.6
51-60	1.4x0.2	1.4x0.2	1x1	0.75x0.6

III. LOADING, STRUCTURAL ANALYSIS AND FINAL DESIGN

A. Loading

The loads applied on the structures obtained from Iranian loading code [12]. The total dead load for each model is assumed 308 $^{kg}/_{m^2}$ which includes 63 $^{kg}/_{m^2}$ as floors weight and 245 $^{kg}/_{m^2}$ as partitions weight. It is noticeable that ETABS automatically calculates result loads from beams, columns and slabs weights. And also 250 $^{kg}/_{m^2}$ is assumed for live load.

To achieve a real structural design, earthquake load is applied on every six structures according to Iranian code [13]. The models are dynamically analyzed to obtain the shear lag amounts due to this load. The information about spectrum used in dynamic analysis is shown in Fig. 5.

B. Initial analysis

The main model of structures is a framed tube with a rectangular plan shape. It is approximately designed as the two other plan shapes (Triangular and hexagonal) by non-dimensional curves which is provided for preliminary design which are proposed by khan [2]. The dimensions of circumferences columns and beams is assumed equal respectively in width and depth due to the aesthetic considerations in tall buildings architecture.

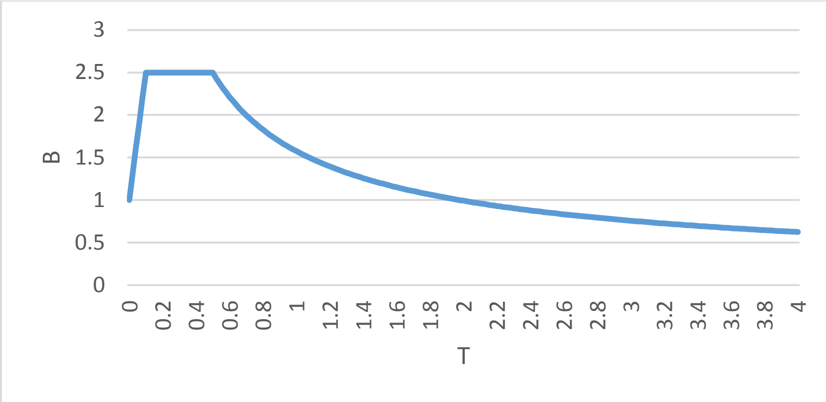

Figure5. Response spectra intended for dynamic analysis

C. Finial Analysis and Design of Framed Tubes

ETABS vr.9.7.3 software program is used to evaluate and analysis all six models of tube framed structures under the earthquake load. This software which is developed specially for analysis and design of building structures, has a good ability for static and dynamic analysis regardless to the numbers of nodes and stories. Also it can design structures according to famous international codes [14].

Models are analyzed and designed for applying described loads in section III-A. In this study we obtained the shear lag factor caused only by the axial forces, without considering the interference of structure's deformations. Thus the linear elastic method was chosen to calculate the factor.

The structures are checked by ETABS to have the minimum requirements of CSA94 code [15]. Columns and beams dimensions are lessened after every ten stories as buildings get higher due to the economical targets.

D. The Effect of Geometry of Plan on the Behavior of Tube Framed Structures

To observe the shear lag phenomenon in mentioned structures, shear lag diagrams is drawn for some stories. A factor named "shear lag factor" is defined due to achieve a precise comparison between different types of structures. This factor is a ratio of corner column axial force to the middle column axial force. It shows a good vision of shear lag in each story.

Shear lag factor with an amount of more than one is considered as positive shear lag and of course amount of less than one is considered as negative shear lag. In Tables VIII and IX, the average of shear lag factor in some stories for 40 and 60 story structures are shown respectively and columns are selected in every ten story from the 5th story. According to these tables it is observed that framed tube with rectangular plan shapes have the most amount of shear lag while the structures with triangular and hexagonal plans have a better behavior in case of shear lag.

TABLE VIII. SHEAR LAG FACTOR FOR 40-STORY STRUCTURES

Story / Type of structure	R4	T4	H4
5	1.38	1.36	1.04
15	1.13	1.11	1.01
25	1.06	1.06	1.01
35	0.65	0.7	0.84

TABLE IX. SHEAR LAG FACTOR FOR 60-STORY STRUCTURES

Story / Type of structure	R6	T6	H6
5	1.24	1.25	1.04
15	1.07	1.07	1.01
25	1.04	1.04	1
35	1.04	1.02	1
45	0.94	0.97	0.99
55	0.52	0.59	0.78

To have a better view, shear lag factor is shown for 40 and 60 stories framed tube structures in Figures 6 and 7 respectively. It is obvious that shear lag has a poor attendance in the middle stories of all structures. The noticeable point is that structures with hexagonal plan shape have low range of shear lag in most stories in comparison with to other plans.

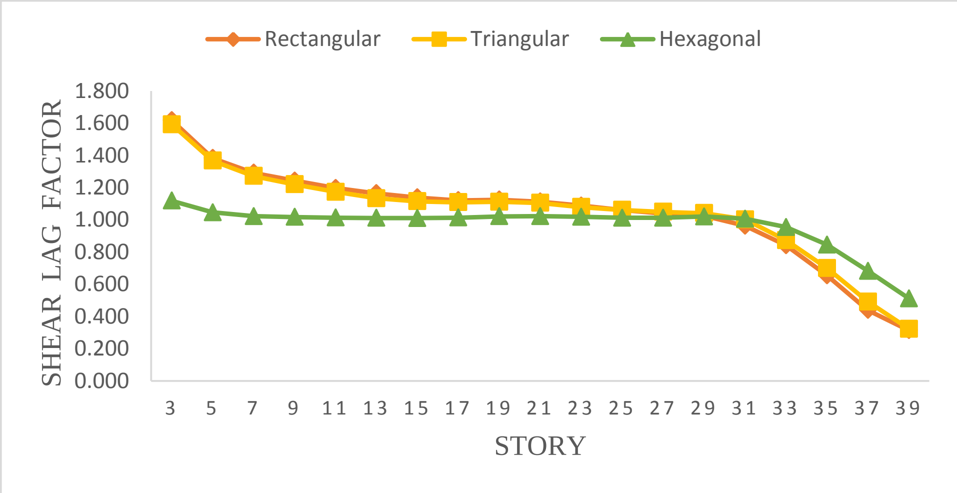

Figure 6. 40-Story structures

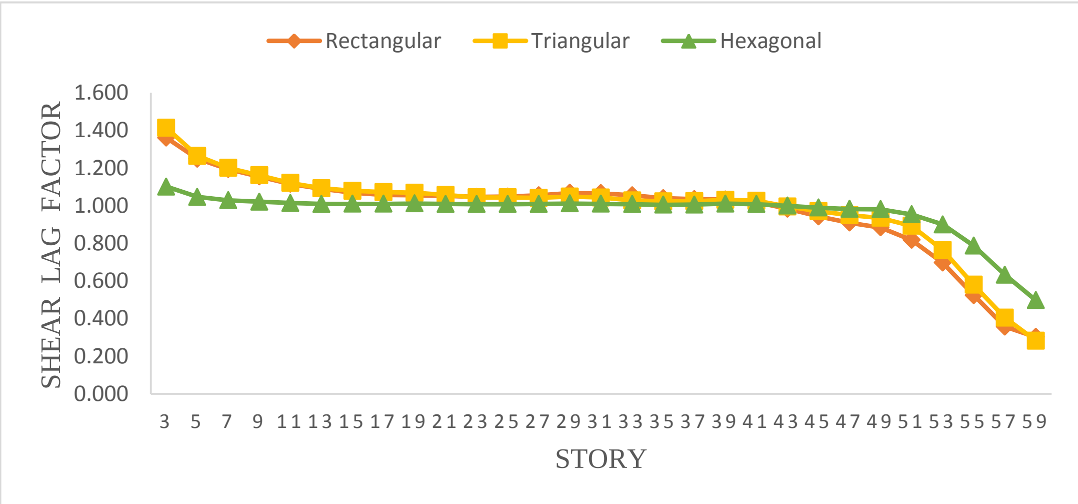

Figure 7. 60-Story structures

IV. Conclusion

1. Geometry of plan in framed tube structures, plays a fundamental role in the amount of shear lag factor and structural behavior.
2. The structures with rectangular plan shape had the worse distribution of axial force in their columns and also the maximum amount of shear lag.
3. The amount of shear lag factor in the structures with rectangular plan shape and triangular plan shape were almost the same in lower and middle stories. But this amount was decreased for structures with triangular plan shape in the upper stories.
4. Hexagonal plan shape structures had the minimum amount of shear lag, among all the other structures.

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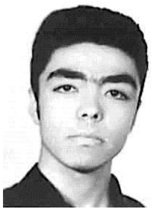

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