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Optimum Design of Tall Tube-Type Building: An Approach to Structural Height Premium

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Abstract**—**In last decades, tubular systems employed for tall buildings were efficient structural systems. However, increasing the height of a building leads to an increase in structural material corresponding to the loads imposed by lateral loads. Based on this approach, new structural systems are emerging to provide strength and stiffness with the minimum premium for height. In this research, selected tube-type structural systems such as framed tubes, braced tubes, diagrids and hexagrid systems were applied as a single tube, tubular structures combined with braced core and outrigger trusses on a set of 48, 72, and 96-story, respectively, to improve integrated structural systems. This paper investigated structural material consumption by model structures focusing on the premium for height. Compared analytical results indicated that as the height of the building increased, combination of the structural systems caused the framed tube, hexagrid and braced tube system to pay fewer premiums to material tonnage while in diagrid system, combining the structural system reduced insignificantly the steel material consumption.

Keywords**—**Braced tube, diagrid, framed tube, hexagrid.

I. Introduction

Construction of high-rise structures using tubular structural system started from the concept that lateral stiffness is the governing design criterion, and the strength requirement is automatically satisfied. Meeting the stiffness requirements causes the structural engineering to apply the efficient structural system with consideration of material-saving design. Recent studies demonstrate that the design criterion in tall buildings depends on the configuration of the structural system and in some structural systems (diagrid structures), it may be changed to strength requirement [1]. Thus, providing both stiffness and strength requirements concurrently leads to the optimum design of a tall building. Over the last decades, for design optimization of high-rise structures, a combination of two or more structural systems to push the limit height of the buildings has developed. Khan [2] demonstrated for the first time that, as the height of a building increases, the difference between the amount of material required to account for the effect of lateral loads to that needed for only gravity loads increases. This differential was called the structural height premium [3]. This reveals that the structural engineering community needs the number of studies into the investigation of structural systems considering structural height premium.

Khan developed tubular structural system in the early 1960s. Tubular structures use less material than the braced rigid frame of the early 1930s. He first proposed the framed tube system as the ideal structural system that would be a frame with closely spaced columns connected to deep beams at the perimeter of the building that behaves like a box girder [4]. In order to improve lateral stiffness, several modifications of the framed tube system have been emerged to reduce lateral displacement. Among various tube type structures, braced tubes have more structural efficiency. In this system, the diagonal elements cause the structure to resist lateral more effectively than the structures with orthogonal members [5]. Architectural functional and structural efficiency of diagrid system due to the use of triangular diagonal configuration have caught the attention of architectural and structural designers of tall buildings [6]. Another efficient structural system is outrigger system. It is composed of two structural systems – typically a core system and a perimeter system [7]. Recently, a structural system called hexagrid is used for tall buildings with the composing the old space-truss concept and tubular action [8]. Multiple hexagonal grids are located at the perimeter of the building form its configuration. In order to achieve a comprehensive understanding of the structural behavior, more research has been done on it [9]-[11].

Besides the structural performance of a structural system in tall buildings, saving materials also plays a key role in the efficiency of the structure. The following publications summarize that this factor is very important in the design of tall buildings. Moon studied the stiffness-based design methodologies for the impact of different geometric configurations of the braced tube and diagrid structural members on the material-saving economic design [12]. Moon [13] proposed a simple methodology for determining preliminary member sizes of diagrid system, which used the least amount of structural material to meet the stiffness requirements. Moon [14] studied optimal stiffness distribution between the building core and perimeter structure in diagrid, braced tube, and outrigger systems with less amount of structural material to meet design requirements. Moon [15] compared the efficiency of common structural systems of braced tubes, diagrids and outrigger structures for tall buildings, depending on building heights and height-to-width aspect ratios and discussed the material-saving design of the candidate structures.

Taller buildings should be able to compete economically with shorter buildings. Thus, the structural height premium should be controlled in tall buildings.

This paper evaluates the material consumption of tube type structural systems focusing on the premium for height. Based on this, material consumption of common tube-type structures such as framed tube, braced tube, diagrid and hexagrid is

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compared. In order to evaluate the structural material for various heights of the building, a set of 48-,72-, and 96- story structures are modeled in case of a single tube, tubular structures combined with the braced core and combined with outrigger trusses, respectively.

II. Premium for Height

In design of tall buildings, the governing factor is usually the lateral loads. As the height of the building increases, the lateral load resisting system becomes more important than gravity load resisting system. Khan classified structural systems for tall buildings based on their heights with considerations for efficiency [2]. He recognized that the amount of required material for resisting lateral load is related to the building height and increases nonlinearly and drastically with height, while the material quantity corresponding to gravity load only depends upon the floor framing and it increases constantly for the same floor framing in the stories. The differential between the materials corresponding to these loads is named the "premium for height"(Fig. 1). Based on the strength and stiffness design, by an increase in the height of the building, the lateral loads become significant. Thus, selecting an efficient structural system for a tall building affects the quantity of structural material. This is due to the premium for height [16], [17].

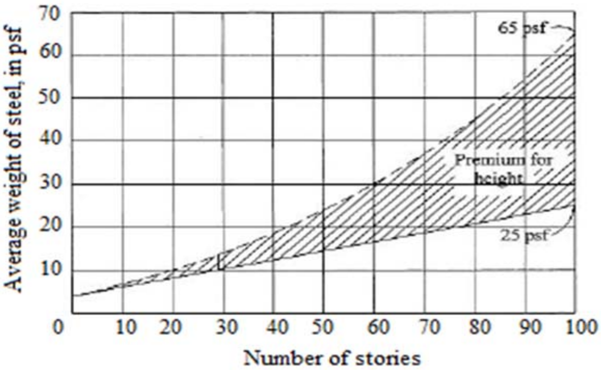

Fig. 1 Premium for height [23]

III. Analytical Models

To conduct a parametric study of common steel structural system for tall buildings, framed tube, braced tube, diagrid and hexagrid systems were chosen as tube-type structural systems. For all chosen structural systems, the following analysis models were prepared: 48-story single perimeter tube, 72-story perimeter tube combined with braced core and 96-story perimeter tube combined with outrigger trusses (Figs. 2 and 3). The diagonal trusses were applied in outrigger structures with consideration for the existence of corner mega columns in the model structures [18]. Table I summarizes the geometric characteristics for the analytical models.

The computer software SAP2000 [19] was used to design the structural models. The buildings were designed to resist wind load with the consideration of the document SEI/ASCE 7-10 (minimum design loads for Building and other structures) [20]. The models were assumed to be in an exposure B and within category III. Based on the guidelines, the basic wind speed has been considered 110 mph. The structural models were designed according to AISC code requirements [21] to control stress ratio of structural members. The designs satisfy an allowable lateral displacement limit of (H/400).

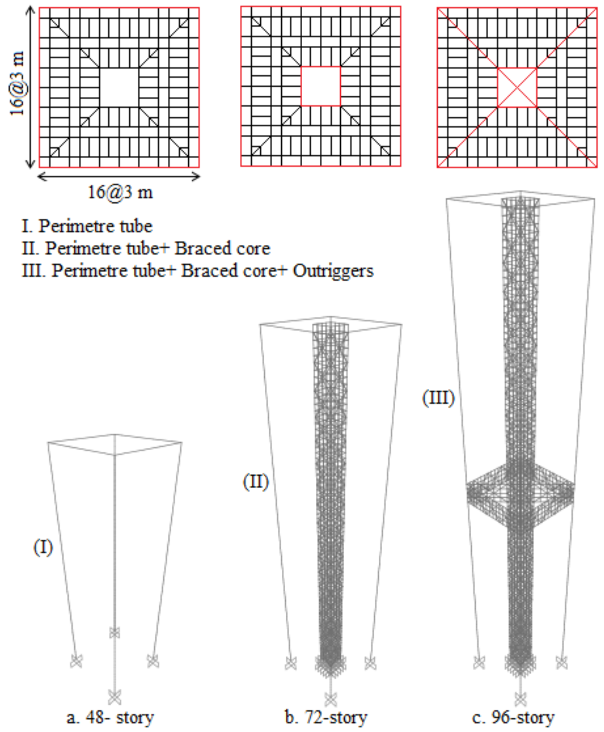

Fig. 2 Plan view of the models

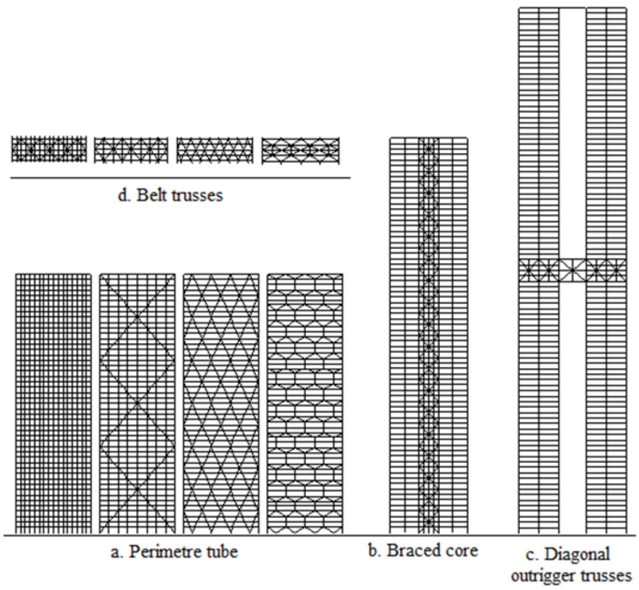

Fig. 3 (a) 48-story model structures (perimeter tube), (b) 72-story combined model structures (perimeter tube and braced core) and (c) 96-story combined model structures (perimeter tube, braced core and outrigger trusses)

TABLE I
GEOMETRIC PARAMETERS OF MODEL

Description	Value
Story height	4m typical
Floor live load	500 kg/m^2
Floor dead load	600 kg/m^2

Candidate structures were considered to be symmetric in all directions. The diagonal angle for diagrid system was considered according to previous conclusions [7]-[22] which illustrated that the optimal angle is between 65 and 75 degrees and based on the architectural configuration, the angle of 73° has been chosen for diagrid structures. For all systems, in the buildings with similar height, the internal members were considered to be similar. This is because they were assumed to carry only gravity loads. In the models, for the structural members of the diagonal elements, columns and beams, tube-shape sections, box shape and W sections were applied.

IV. DESIGN STUDIES

A. Lateral Stiffness

In this study, in order to design the model structures optimally, as the height of the candidate buildings increases the example tube-type structural systems are combined with the other structural systems. Fig. 4 shows the maximum lateral displacements of the models.

As analytical results illustrate diagrid system has the most lateral stiffness and the framed tube has the least. In fact, by increasing the height, the design of diagrid system is governed by strength requirement and in the framed tube system, it is governed by stiffness requirement. In design of braced tube structures, the portion of strength requirement is more than stiffness requirement and in hexagrid that is vice versa. This refers to inherent stiffness of structural systems. However, all the structures have been designed to satisfy the allowable maximum displacement. Results indicate that the combination of the structural systems to meet stiffness requirements is more effective for framed tube and hexagrid than braced tube and diagrid.

B. Structural Steel Material

In tube type buildings, the steel material corresponding to the lateral loads depends on the perimeter structure, while the material corresponding to gravity loads depends on the internal elements. In this study, in order to control the structural height premium, various tube type structural systems are combined with other structural systems. To this end, the material consumption is evaluated in the case of designed models with and without lateral loads. Table II summarizes the material usage for the internal member of model structures when they are designed only for gravity loads.

Table III provides the steel material for the lateral resistant structural systems of 48-story model buildings. In these models, the steel material corresponds to the perimeter tubular system. Results of structures indicate that hexagrid system applied the least steel material and framed tube applies the most material. The results show that the high lateral stiffness can affect the steel material in diagrid and braced tube systems and the low lateral stiffness in framed tube make the most consumption of steel material. Thus, the lateral stiffness should be enough.

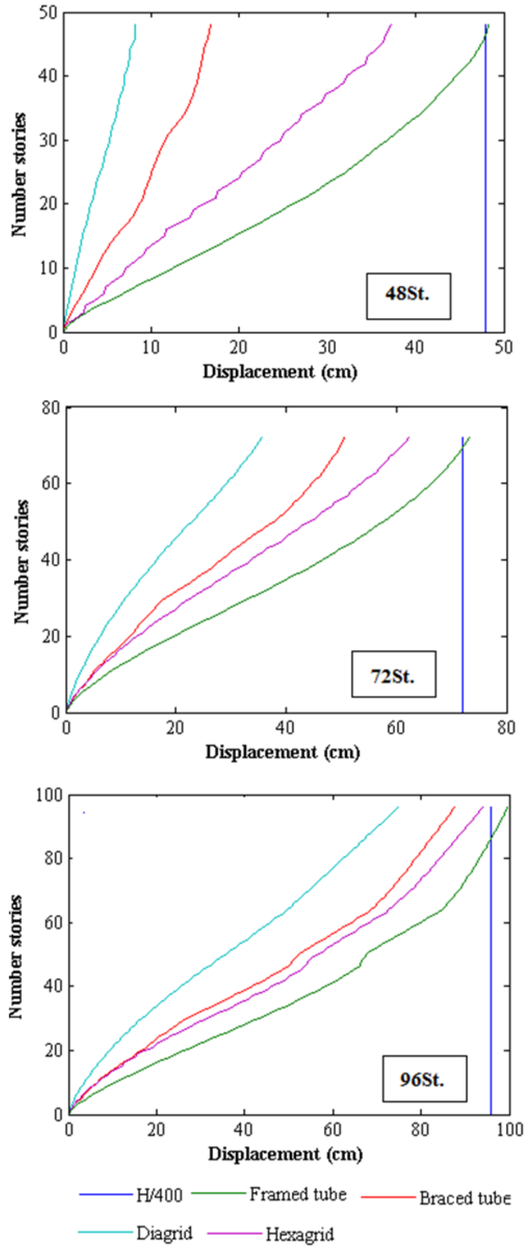

Fig. 4 Lateral displacement profile of model structures

TABLE II
STEEL MATERIAL FOR GRAVITY LOAD RESISTANCE

Model	Gravity frame system (psf)
48 Story	10.8
72 Story	15.7
96 Story	20.8

TABLE III
STEEL MATERIAL FOR 48-STORY STRUCTURE FOR LATERAL LOAD RESISTANCE

Structural system	H/B	Perimeter tube (psf)
Framed tube	4	14.8
Braced tube	4	11.6
Diagrid	4	10.8
Hexagrid	4	9.1

Table IV summarizes the results of the steel material consumption in 72-story models. These results correspond to the perimeter structure combined with the braced core. Analytical results state that, as the braced core is added to perimeter system, hexagrid system requires the least steel material, and framed tube requires the most material. This is due to the flexibility of the hexagrid reacting to the braced core. As the stiffness of system increases, its sensitivity to combination with other structural systems decreases [7]. As shown, the braced core material is more in hexagrid than diagrid and braced tube systems.

TABLE IV
STEEL MATERIAL FOR 48-STORY STRUCTURE FOR LATERAL LOAD RESISTANCE

Structural system	H/B	Perimeter (psf)	Braced core (psf)	Total weight (psf)
Framed tube	6	22.2	5	27.2
Braced tube	6	12.7	2.8	15.5
Diagrid	6	12.7	3.9	16.6
Hexagrid	6	11.8	3.7	15.5

Table V summarizes the results of the steel material consumption in 96-story models. These results correspond to the perimeter structure combined with braced core and outriggers. The comparison of the steel material quantity illustrates that composing the structural systems in hexagrid and braced tube systems are much more effective. As can be seen from the results, they behave efficiently with the outrigger trusses and the steel material distributions state that the braced core and outrigger trusses are applied properly. In fact, in diagrid system, diagrids provide the most lateral stiffness and using other systems might not be necessary. Thus, by increasing the height of the building, without composing system, concentrating the steel material on the façade increases and it decreases architectural function.

TABLE V
STEEL MATERIAL FOR 48-STORY STRUCTURE FOR LATERAL LOAD RESISTANCE

Structural system	H/B	Perimeter (psf)	Braced core (psf)	Outrigger (psf)	Total weight (psf)
Framed tube	8	36.7	6.0	1.4	44.1
Braced tube	8	13.9	5.1	0.7	19.7
Diagrid	8	15.1	7.9	0.9	23.9
Hexagrid	8	13.9	5.2	1.1	20.2

In order to have a comparison study, considering premium for height, a diagram provided similar to Ali's and Moon's diagram [19] in which the horizontal and vertical axis represented the number of stories and the weight steel material respectively (Fig. 5). It can be concluded that as the height of the building increases, composing the structural systems when it is effective (it depends on the structural system), would be a good choice to keep balance and reduce the steel material consumption. This effect is more significant for the hexagrid and braced tube structures than the diagrid and framed tube structures.

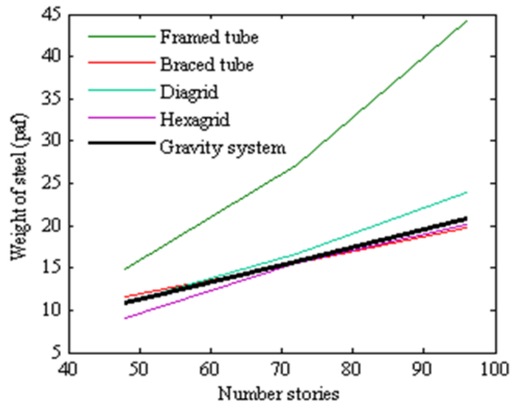

Fig. 5 Premium for height for various tube type structures

V. CONCLUSION

In tall buildings, as the height of the buildings increases, the lateral resistant structural system becomes more important than gravity. This is because selecting a structural system affects the quantity of material. By an increase in the height, the structural material corresponding to the lateral loads increases drastically while the material corresponding to the gravity loads increases constantly. This differential was called the structural height premium.

In this study, the steel material consumption of four tube type structural system such as framed tube, braced tube, diagrid and hexagrid system is evaluated. In order to investigate structural height premium of the candidate systems, the building models were prepared for different heights in case of 48-story single tubular structures, 72- story tubular structures combined with braced core and 96-story tubular structures combined with outrigger trusses. For optimal design, by increasing the height of the model buildings, the structural systems were combined to reduce the premium for height.

The lateral displacement profile indicated that the structural system became stiffer in diagrid, braced tube, hexagrid, and framed tube, respectively. However, the models were designed to satisfy the allowable displacement. The strength requirement governed the design and in the framed tube, the stiffness requirement governed it. In the braced tube and hexagrid system, both stiffness and strength requirement contribute to the design. From the results, framed tube and diagrid model structures paid a higher premium for height to meet the stiffness and strength requirements respectively than the braced tube and hexagrid system. Combination of the structural system in braced tube and hexagrid system was more effective to reduce structural height premium. In fact, composing the structural systems by increasing the height of the building balanced the density of steel material in the structures to have an optimum design.

Results illustrated that, in 48-story structures with the single tube, the steel material consumption increased drastically from hexagrid, diagrid, braced tube to the framed tube, respectively. Results of 72-story buildings indicated that the hexagrid, braced tube and framed tube systems had a good reaction to the composed braced core, while in diagrid system, due to its inherent stiffness, use of braced core was not effective and increased steel material. Results of 96-story buildings stated that by increasing the height of the structures, the use of outrigger trusses on the distribution of steel material, in hexagrid and braced tube was effective to reduce premium for height, in framed tube it was necessary to meet allowable displacement, and in diagrid it was insignificant.

The quest for an innovative structural system is in direction of limiting the lateral displacement to allowable limits without paying a high premium in material tonnage. Based on the results of structural material, by increase in the height of the building, from least to greatest, hexagrid, braced tube, diagrids, and framed tube system pay premium for height.

REFERENCES

[1] G. M. Montuori, E. Mele, G. Brandonisio, and A. De Luca, “Design criteria for diagrid tall buildings: stiffness versus strength”. Struct. Design Tall Spec. Build, 2014, vol 23, pp.1294–1314.
[2] F. R. Khan, “Recent structural systems in steel for high-rise buildings”, In Proceedings of the British Constructional Steelwork Association Conference on Steel in Architecture, London: British Constructional Steelwork Association. 1969.
[3] M. M. Ali, Art of the Skyscraper: The Genius of Fazlur Khan. New York: Rizzoli. 2001.
[4] C. C. Pouangare, and J. J. Connor, “New structural systems for tall buildings: the space- truss concept”, Struct. Design Tall Spec. Build, 1995, vol 4, pp. 155-168.
[5] K. S. Moon, “Sustainable structural engineering strategies for tall buildings”, Struct. Design Tall Spec. Build, 2008, vol 17, pp. 895–914.
[6] K. S. Moon, J. J. Connor, and J. E. Fernandez, Diagrid structural systems for tall buildings: characteristics and methodology for preliminary design. Struct. Design Tall Spec. Build., 2007, vol 16: pp. 205–230.
[7] K. S. Moon, “Sustainable structural engineering strategies for tall buildings”, Struct. Design Tall Spec. Build, 2008, vol 17, pp. 895–914.
[8] N. Mashhadiali, and A. Kheyroddin, “Proposing the hexagrid system as a new structural system for tall buildings”, Struct. Design Tall Spec. Build, 2013, vol 22, pp. 1310–1329.
[9] G. M. Montuori, M. Fadda, G. Perrella, and E. Mele, “Hexagrid – hexagonal tube structures for tall buildings: patterns, modeling, and design”. Struct. Design Tall Spec. Build., 2015, vol 24: pp. 912–940.
[10] N. Mashhadiali and A. Kheyroddin. “Progressive collapse assessment of new hexagrid structural system for tall buildings”. Struct. Design Tall Spec. Build, 2014, vol 23: 947–961.
[11] N. Mashhadiali, A. Kheyroddin, and R. Zahiri-Hashemi, “Dynamic increase factor for investigation of progressive collapse potential in tall tube-type buildings”, J. Perform. Constr. Facil., 2016, vol 30
[12] K. S. Moon, “Stiffness-based design methodology for steel braced tube structures: a sustainable approach”, Eng. Struct., 2010, vol 32, pp. 3163–3170.
[13] K. S. Moon, “Sustainable design of braced tube structures: The role of geometric configuration”, Int. J. Sustain. Build. Technol. Urban Dev., 2011, vol 2, pp. 229-236.
[14] K. S. Moon, “Sustainable structural systems and configurations for tall buildings,” Archit. Eng. Conf., 2011, pp. 196-203
[15] K. S. Moon, “Comparative efficiency of structural systems for steel tall buildings”. Int. J. Sustain. Build. Technol. Urban Dev., 2014, vol 5, 230-237.
[16] Taranath, Structural Analysis and Design of Tall Buildings: Steel and Composite Construction, New York: McGraw-Hill. 1998.
[17] K. Al-Kodmany, Eco-Towers: Sustainable Cities in the Sky. WIT Press. 2015.
[18] K., Kwon, M. Jung, and J. Kim, “Collapse behavior of mega-frame buildings”, EUROSTEEL. 2011.
[19] SAP2000 (Computer software), Berkeley, CA, Computers and Structures. 2009.
[20] ASCE/SEI 7-10, Minimum Design Loads for Buildings and other Structures. American Society of Civil Engineers, Reston, VA. 2010.
[21] AISC, Manual of steel construction, load and resistance factor design, 14th Ed., Chicago. 2010.
[22] J. Kim, and Y. H. Lee, “Seismic performance evaluation of diagrid system buildings”, Struct. Design Tall Spec. Build, 2012, vol 21, 736–749.
[23] M. M. Ali and K. S. Moon, “Structural development in tall buildings: currents trends and future prospects”, Archit. Sci. Rev, 2007, vol 50, 205–223.