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OPTIMAL STRUCTURAL CONFIGURATIONS FOR TALL BUILDINGS

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ABSTRACT

The efficiency of a structural system is significantly influenced by its configurations such as geometric configurations and stiffness distribution between the components. This paper investigates optimal configurations of today's prevalent structural systems for tall buildings. When the primary lateral load resisting system is located over the building perimeter, the system's efficiency can be maximized because the entire building depth can be used to resist lateral loads. Among various structural systems developed for tall buildings, the systems with diagonals are generally more efficient because they carry lateral loads by their primary structural members' axial actions. Tall building structural systems with perimeter diagonals include braced tubes and more recently developed diagrids. Diagrid structures of various angle configurations are studied to determine optimal geometric configurations. Braced tubes of various column and diagonal configurations are comparatively studied. Another very efficient structural system widely used today is outriggers structures. Optimal stiffness distribution between the building core and perimeter mega-columns is investigated for outrigger structures.

Keywords: Tall buildings, structures, diagrids, braced tubes, outrigger structures.

1. INTRODUCTION

Lateral shear forces and overturning moments due to wind significantly influence the structural design of tall buildings. These forces can be carried very efficiently by primary structural members located on the building perimeter and configured to work in axial actions. Braced tubes and diagrids are two typical examples developed based on this concept.

Since its application for the John Hancock Center of 1969 in Chicago, braced tubes have continuously been used for tall buildings. This paper studies optimal configuration of braced tubes. Various column spacings are studied comparatively to determine more efficient alternatives. Structural efficiency of different geometric configurations of perimeter bracings is investigated.

Recently developed diagrid structures are widely used for major tall buildings throughout the world. Diagrids, with their unique architectural potentials, are very often expressed on the building facades, as are the cases with the Swiss Re Building in London and Hearst Headquarters Tower in New York. Diagrid structures of various angle configurations are studied to determine more efficient geometric configurations.

Outrigger structures are another prevalently used structural system for today's tall buildings. Unlike braced tubes and diagrids, which carry lateral loads primarily by perimeter structural members,

outrigger structures use stiff core structures and perimeter mega-columns connected to the core through outrigger trusses. Optimal stiffness distribution between the core and mega-columns is studied for outrigger structures of various heights.

2. BRACED TUBES

2.1. Braced Tubes of Various Column Configurations

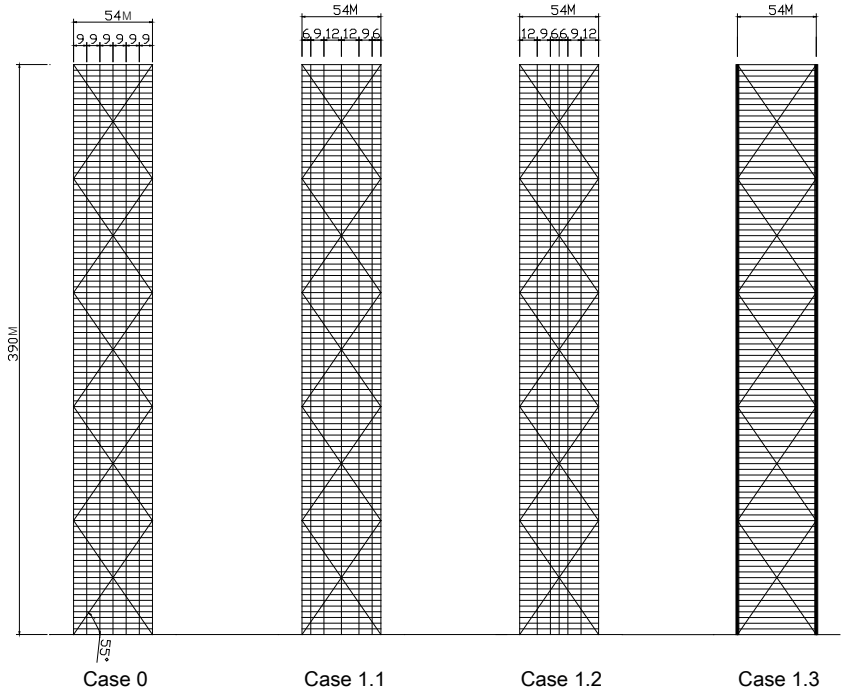

Figure 1: 100-story braced tubes of various column spacings.

Braced tube structural systems are configured with perimeter diagonal bracings and vertical columns typically spaced evenly. Different column configuration strategies are investigated to improve structural performance of the braced tube. Figure 1 shows four different cases of 100-story braced tube structures. Each building's plan dimensions are 54 meters by 54 meters, and its typical story height is 3.9 meters. Case 0 is the structure with all the perimeter columns spaced evenly at every 9 meters. In Case 1.1, the column spacing is gradually reduced from 12 m at the mid-width of each façade plane to 6 m at the building corner, with 9 m between them. In Case 1.2, the column spacing is gradually increased from 6 m at the mid-width of each façade plane to 12 m at the building corner, with 9 m between them. In Case 1.3, four large perimeter columns are located at four building corners. Structural design of the braced tube is performed for Case 0 first using the stiffness based design methodology developed by Moon (2009) to resist the code-defined wind loads in Chicago. The maximum lateral displacement is limited to a five hundredth of the building height. The member sizes used for Case 0 are also used for Case 1.1 and 1.2. The sectional areas of

the perimeter columns of Case 1.3 are six times larger than those of Case 0, and the diagonal member sizes of Case 1.3 are the same. Therefore, Cases 0, 1.1, 1.2 and 1.3 use the same amount of structural steel for the braced tubes.

Equation 1 expresses a typical braced tube module's bending stiffness based on the perimeter columns on both the flange and web planes. The bending stiffness of each case shown in Figure 1 is different because the different column spacing influences the value of δ, which represents the contribution of columns on the web planes to the bending stiffness.

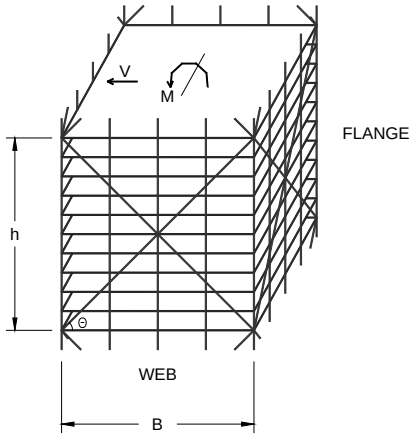

Figure 2: Typical braced tube module.

$$K_b = (N_f + \delta)\frac{B^2 A_c E}{2h} \quad (1)$$

A_d is area of each diagonal; A_c is area of each column; V is shear force; M is moment; E is modulus of elasticity of steel; θ is angle of diagonal member; N_f is number of columns on each flange plane; δ : contribution of web columns for bending rigidity; B is building width.

As the column spacing becomes denser toward the building corners, the web columns' contribution to the bending rigidity increases, and vice versa. This phenomenon directly impacts the lateral displacement of each tower. The maximum displacement at the top of Case 0, 1.1, 1.2 and 1.3 are 76.0 cm, 73.4 cm, 78.2 cm and 61.8 cm respectively.

2.2. Braced Tubes of Various Diagonal Configurations

Equation 2, which expresses the transverse shear stiffness of the braced tube as a function of $\cos^2\theta \sin\theta$, suggests that an angle of about 35 degrees produces the maximum shear rigidity. Therefore, diagonal member sizes can be smaller as the diagonal angle becomes closer to about 35 degrees. However, smaller member sizes at each level do not guarantee the most efficient design. While the diagonal member sizes become smaller as the angle nears 35 degrees, the total length of

all diagonals decreases as the angle becomes steeper. Therefore, the optimal angle in terms of material use cannot be determined by Equation 2 alone.

$$K_t = \frac{4A_d E \cos^2\theta \sin\theta}{h} \quad (2)$$

Design studies have been carried out with braced tubes having X diagonals placed at 35, 45 and 55 degrees. As the angle deviates more from the optimal value of 35 degrees, the member size becomes larger. The required sectional areas of diagonal members placed at 55 degrees is larger by 43% than those placed at 35 degrees. However, the case with diagonals placed at 55 degrees requires 0.6% less steel because the total length of the diagonals is much shorter. In fact, the influence of the diagonal angle changes between 35 and 55 degrees is minimal on structural material savings.

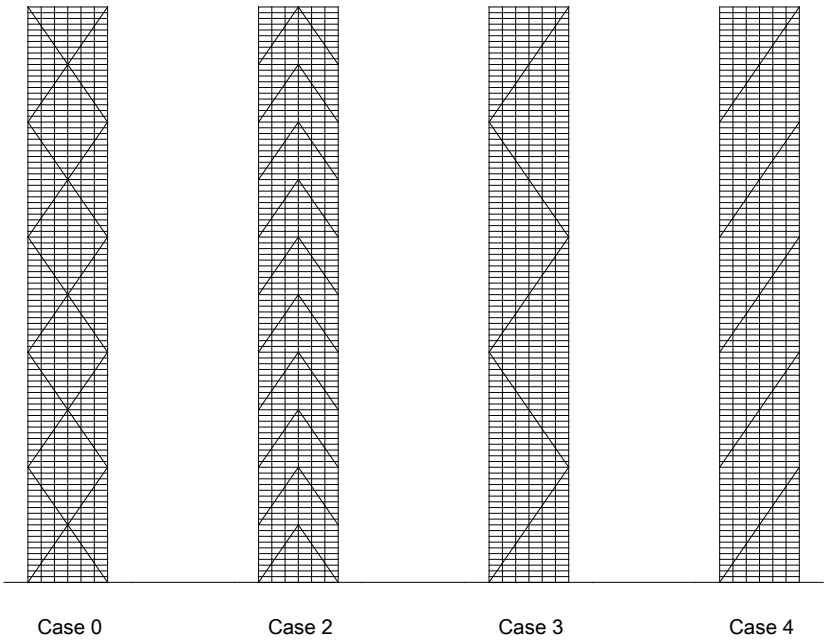

Figure 3: Braced tubes with chevron and single diagonal bracings.

Not only X but also other types of bracings are used for tall building structures. Figure 3 shows four different bracing types. Identical member sizes are used for Cases 0 and 2, while two times larger member sizes in terms of the sectional area are used for Cases 3 and 4. Therefore, the same amounts of structural materials are used for these structures regardless of the shape of the bracings. Case 0 with X bracings, which are continuously connected over the entire building height, provides the greatest lateral stiffness among the four cases. The structural performances of Case 2 with chevron bracings and Case 3 with alternate direction single diagonal bracings are not much different. The

lateral stiffness of Case 4 with single direction single diagonal bracings is substantially smaller than that of the other three cases. The maximum lateral displacements of the braced tubes of Cases 0, 2, 3 and 4 are 76.0, 77.8, 78.4 and 82.2 cm respectively.

3. DIAGRIDS

3.1. Diagrids of Uniform Angles

Diagrid structural systems can be configured with diagonals placed at various uniform angles. The optimal diagrid angle is dependent on the height-to-width aspect ratio of the building. As a diagrid building becomes taller, its optimal diagrid angle becomes steeper, and vice versa, because a taller structure behaves more like a bending beam and a shorter structure behaves more like a shear beam.

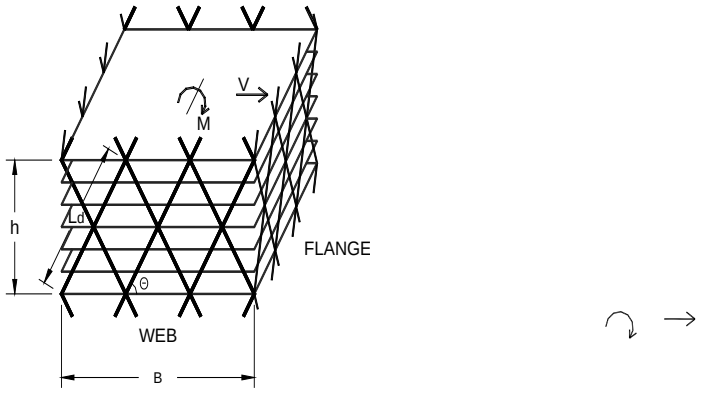

Figure 4: Typical diagrid module.

Figure 4 shows a 6-story tall typical diagrid module. Equations 3 and 4 express bending and shear stiffness of the module. $A_{d,w}$ is area of each diagonal on the web; $A_{d,f}$ is area of each diagonal on the flange; V is shear force; M is moment; E is modulus of elasticity of steel; θ is angle of diagonal member; B is building width; L_d is length of diagonal; N_w is number of diagonals on each web plane; N_f is number of diagonals on each flange plane; δ : contribution of web diagonals for bending rigidity.

$$K_b = (N_f + \delta)\frac{B^2 A_{d,w} E}{2L_d}\sin^2\theta \qquad (3)$$

$$K_t = 2N_w \frac{A_{d,w} E}{L_d}\cos^2\theta \quad (4)$$

Optimal angles for the uniform diagrids range from about 60 degrees for the building with a height to width ratio of about 4 to 70 degrees for the building with the ratio of about 10.

3.2. Diagrids of Varying Angles

Appropriately designed uniform angle diagrids are a very efficient structural system for tall buildings. By varying the diagrid angles, the system's efficiency can be further increased. Figure 5 shows 100-story diagrid structures of five different angle configurations. Each building's plan dimensions are 54 meters by 54 meters, and its typical story height is 3.9 meters. Case I is a uniform angle diagrid structure. Cases II and III are diagrid structures of horizontal angle variations. Cases IV is a diagrid structure of vertical angle variation with steeper angles towards the base. Case V combines horizontal and vertical angle variations of Case III and IV respectively. Structural design is performed for Case I first using the stiffness based design methodology developed by Moon et al. (2007) to resist the code-defined wind loads in Chicago. The maximum lateral displacement is limited to a five hundredth of the building height.

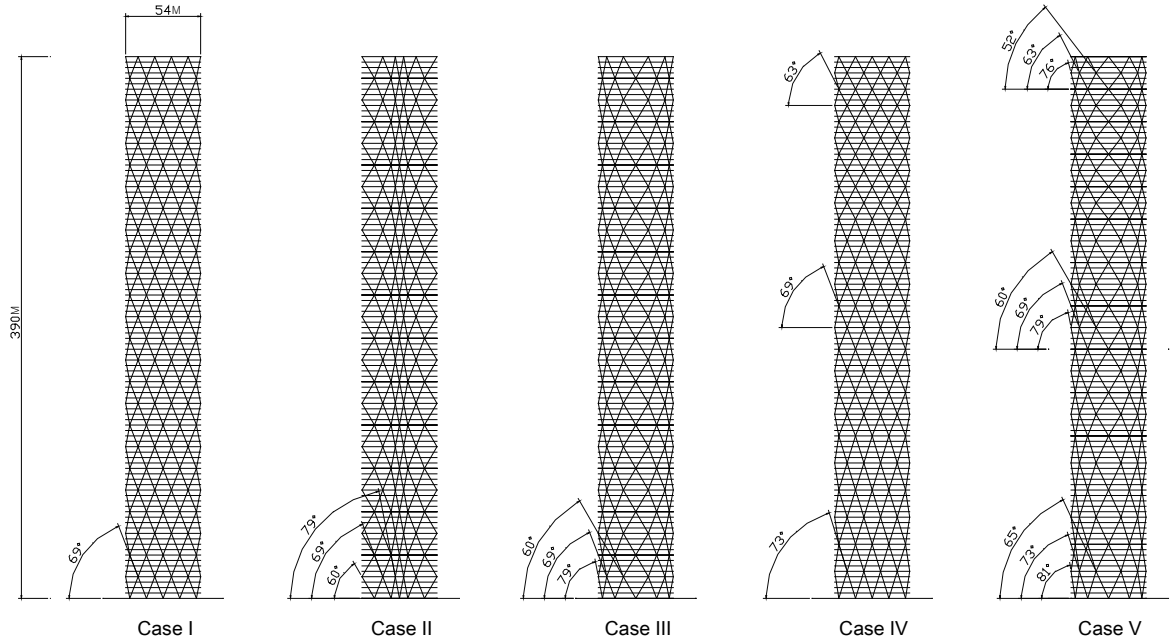

Figure 5: Diagrids of various angle configurations.

As the diagonal angle becomes stiffer toward the building corner, the web diagonals' contribution to the bending rigidity increases, and vice versa. Therefore, the lateral stiffness of Case III is larger than Case I, while that of Case II is smaller than Case I. Since the design of lower and upper level diagrid members is governed by overturning moments and shear forces respectively, diagrids configured with steeper angle diagonals toward the base of the building, such as Case IV, can be more efficient than uniform angle diagrids. By combining angle configurations of Cases III and IV, the lateral stiffness of the diagrids can be maximized. Maximum lateral displacements of Cases I, II, III, IV and V are 76.0, 90.1, 74.6, 72.7 and 71.9 cm respectively. Steel masses used for the five diagrid structures are very similar. In fact, Case V which produces the greatest lateral stiffness uses 0.6% less steel than Case I.

4. OUTRIGGER STRUCTURES

Outrigger structures carry wind-induced overturning moments very efficiently by connecting perimeter mega-columns to stiff building cores through outrigger trusses. This section studies structural efficiency of outrigger structures depending on the lateral bending stiffness distribution between the braced core and perimeter mega-columns. Tall buildings of 60, 80 and 100 stories are designed with outrigger structures as shown in Figure 6. The aspect ratios of 60-, 80- and 100-story outrigger structures are 6.5, 8.7 and 10.8 respectively. In the 60-story structures, outrigger trusses are located at one third and two third heights. In the 80-story structures, outrigger trusses are located at one fourth, mid and three fourth heights. In the 100-story structures, outrigger trusses are located at one fifth, two fifth, three fifth and four fifth heights.

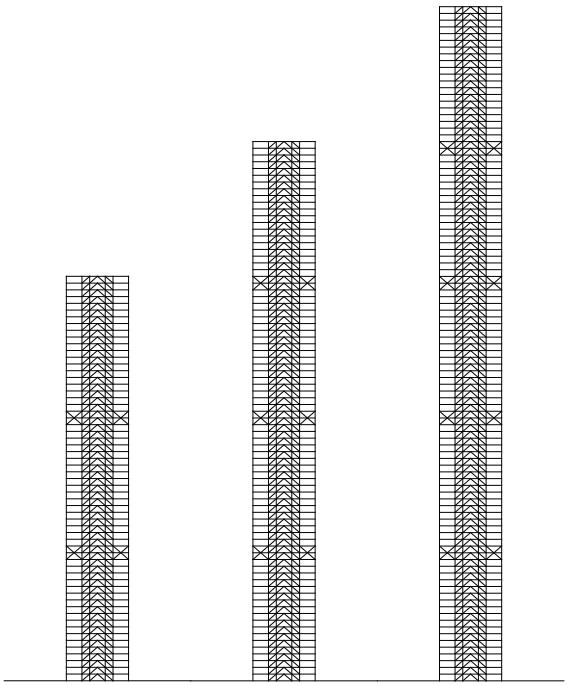

Figure 6: Outrigger Structures of 60, 80 and 100 Stories.

Three different lateral bending stiffness distribution cases are studied. The studied bending stiffness distribution ratios between the braced core and perimeter mega-columns are 3:7, 4:6 and 5:5. Depending on the height-to-width aspect ratio of the building, the optimal stiffness distribution ratio is different. For the 60- and 80-story outrigger structures, stiffness distribution ratio of 4:6 produces the most efficient design, while for the 100-story outrigger structures, 3.7. The impact of different stiffness distribution on structural steel use becomes greater as the building height increases. The 100-story outrigger structure with the stiffness distribution ratio of 3:7 uses about 10 % less steel than that with the stiffness distribution ration ratio of 5:5, in order to satisfy the same target

displacement requirement. For the 60-story outrigger structures, the maximum percentile difference between the three cases is less than 2%, and that for the 80-story outrigger structures is about 5%.

5. CONCLUSIONS

Tall buildings are a worldwide architectural phenomenon. Selecting an appropriate and efficient structural system for a tall building is a very important step toward successful project execution. The efficiency of a particular structural system selected for a tall building is substantially influenced by its configuration. Considering abundant emergence of tall buildings all over the world, the importance of the studies on optimal configuration of tall building structural systems cannot be overemphasized to save our limited resources and construct more sustainable built environments.

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