Braced tube Structural System: A Review

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Abstract: The advanced construction technologies, evolution of efficient structural system, necessity of vertical growth because of scarcity of urban land and rapidly increasing population caused the development of the high rise buildings all over the world. Lateral loads i.e. earthquake loads and wind loads requires special attention in design of high rise buildings along with gravitational loading. Lateral loads can be taken care by interior structural system or exterior structural system. Generally shear wall core, braced frame and their combination with other frames are interior structural systems where lateral load is borne by centrally located structural elements. While framed tube, braced tube structural system bear lateral loads by the elements provided on periphery of the buildings. It is very much important that the selected structural system must be optimized and should utilize structural elements effectively while satisfying design requirements.

In the past decades, the Braced tube structural system is widely adopted and used for the construction of tall steel buildings due to its structural efficiency and aesthetic potential provided by the unique geometric configuration of the system. Compared to closely-spaced vertical columns in framed tube, Braced tube structural system consists of widely spaced column with inclined X- brace members on the exterior surface of building. Due to inclined brace members, lateral loads are resisted by axial action of the diagonals, compared to bending of vertical columns in framed tubular structure. Braced tube structures generally do not require gravity core because lateral shear can be managed by the diagonals on the periphery of building. The aim of study is to optimize the variable angle of X-Braced pattern under gravity and lateral loading and applying best suitable X- bracing angle on different configuration of column.

Keywords: Skyscrapers, Tall and High-Rise Buildings, Braced tube, diagrid, optimum angle of braced tube, wind tunnel effect, seismic effect, material consumption

1. Introduction

The advanced construction technologies, evolution of efficient structural system, necessity of vertical growth because of scarcity of urban land and rapidly increasing population caused the development of the high rise buildings all over the world. Lateral loads i.e. earthquake loads and wind loads requires special attention in design of high rise buildings along with gravitational loading. Lateral loads can be taken care by interior structural system or exterior structural system. Generally shear wall core, braced frame and their combination with other frames are interior structural systems where lateral load is borne by centrally located structural elements. While framed tube, braced tube structural system bear lateral loads by the elements provided on periphery of the buildings. It is very much important that the selected structural system must be optimized and should utilize structural elements effectively while satisfying design requirements.

Tube is a system where in order to resist lateral loads. A building is designed to act like a hollow cylinder cantilevered perpendicular to ground. This system was first introduced by Fazlur Rahman Khan. The first example of tube is 43-storey Dewitt-chestnut apartment building in Chicago.

The main idea of tubular system is to arrange the structural elements so that the system can resist the loads imposed on the structural efficiently particularly horizontal loads. In this arrangement several elements contribute to the system i.e., slabs, beams, girders, columns. Unlike most often, the walls and cores are used to resist the horizontal loads, in tubular system the horizontal loads are resisted by columns and spandrel beams at the perimeter of the tubes. First building designed using tubular concept was sears tower.

In tubular structure, interior columns are comparatively few and located at the core. The distance between the interior and the exterior is spanned with beams or trusses and intentionally left column free. This maximizes the effectiveness of the perimeter tube by transferring some of the gravity loads within the structure to it and increase its ability to resist overturning due to lateral loads. Tubular structure is a structure with closed column space between two or four meters and joined by spandrel beam at the floor level, the structure behaves as a cantilever tube. Group of column perpendicular to the horizontal load is called flanged frame and parallel to the direction of horizontal load is called web frame. Therefore, It is obvious that 75% of overturning moment is carried by flange and remaining 25% by webs.

Braced tube is formed by intersecting horizontal and vertical component. The example of braced tube structure all around the world are Bank of China Tower in Chicago, Onterie centre in Chicago, Renaissance tower in Dallas, Pearl River town in Guagzhou, The Brunswick Building. The John Hancock Building in Chicago is also one of the examples of utilization of Braced tube structural system to support the perimeter column

Braced tube is an improvement of tubular structure made by cross bracings the frame with X bracings over many stories. Diagonal of braced tube are connected to the column at each intersection, they virtually eliminate the effect of shear lag in flange and web .As a result, the structure behaves under lateral loads more like a braced frame reducing bending in the members of the frame. In braced tube structure, the braces transfer axial load from more highly stressed columns to less highly stressed columns and eliminates difference between load stresses in columns. Hence, spacing of the column can be increased and depth of girders will be less, thereby allowing large size windows than in conventional framed tube structures.

In braced tube structure, the distribution of axial forces along the flanged frame columns at one floor is not uniform and the distribution of shear forces along the web is not linear. This is mainly due to the flexibility of the tubular structures and is called shear lag effect. Along the flanges, this non-linearity can result in the corner or exterior columns experiencing greater stress than the centre or interior columns. This is known as positive shear lag. However, negative shear lag has been discovered to exist and this is opposite of positive shear lag and the corner are less stressed than the centre columns.

2. LITERATURE REVIEW

a) Braced tube Structural System

Ali and Moon[1] discussed the various structural system for tall buildings and the technological driving forces behind development of tall building. They classified the structural systems for tall buildings in to two major categories viz., interior and exterior structural systems. The most representative structural systems for tall buildings like Diagrid Structural System and Outrigger Structural System were discussed.

b) Analysis and Design Aspects and Optimal Configuration

Moon deliberated [4] the stiffness based design methodology for braced tubes have been continuously used for tall buildings. Since their emergence in the late 1960s because of their efficiency as a structural systems for high-rise buildings. The said methodology was applied to a set of braced tube buildings ranging from 40 to 80 stories tall having height to width aspect ratio ranging from 4.3 to 8.6 parameters for most economical design in terms of material usage were generated for representative design loadings. The building plan dimension was considered as 36 X 36m having 18 X 18m gravity core at the centre and the typical storey height was considered as 3.9m. The diagonals were connected at every 10 stories and created an angle of 47.3' with the horizontal axis. The structural members having "Preliminary design were analysed with the help of SAP 2000 software. He compared the targeted maximum displacement and the displacement computed by SAP 2000. He concluded that, the stiffness based methodology can be used got designing the preliminary member sizes.

Moon [5] discussed the stiffness based design methodologies for tall buildings having diagonals such as braced tubes and most recently developed diagrid structures. The said methodologies were used to carry out member sizes for structural systems. He presented the guidelines to calculate the shear and bending deformations for optimal design, which requires the least amount of structural material to meet the stiffness requirements, the difference between conventional braced tube structures and Diagrid structures was illustrated. He considered the aspect ratio's ranges starting from 4.3 to 10.8 for braced tube and diagrid structures having 40, 50, 60, 70, 80, 90 and 100 storey buildings. The square building plan having each side of 36m. The typical storey was considered as 39m. The structural analysis were carried out with the help of SAP 2000 software. He founded that for diagrid structures, as the buildings becomes taller, the optimal angle also becomes steeper within the typical range of about 60 to 70 degree.

Mazinani, Jumaat, Ismail, Chao [13] presented Comparison of shear lag in structural steel building with framed tube and braced tube. They investigated the effect of shear lag on BT and FT under wind load. They also investigated the effect of various configurations in BT on the reduction the shear lag. They used STAAD Pro software for dynamic analysis of the models. They compared the shear lag ratio of various configuration of braced tube and framed tube and concluded that the X-diagonal member not only significantly increases the stiffening of the – diagonal member that starts from the corner- to – corner was better at reducing the lateral displacement than a single diagonal brace in alternate and parallel configuration. They concluded from a comparison between the shear lag effect and lateral displacement that the shear lag effect did not correspond directly to lateral displacement and the deformation caused by bending was much higher than the shear in taller structures.

Moon [24] presented Comparative Evaluation of structural systems for tilted tall buildings. He studied structural system design options for tilted tall buildings with various structural system such as braced tube, diagrids and outrigger systems and their performance. He also studied the impact of tilting tall buildings on the gravity and lateral load resisting systems. He presented 60 story parametric model of tilted braced tube structures of 0, 4, 7 9, 13 degree of tilting in SAP 2000 respectively. He showed less combined (gravity and wind induced) maximum lateral displacement in straight braced tube compared to tilted. From his parametric model study, He concluded that torsional stiffness was greater in the perimeter tube structures than in the outrigger structures. Thus, the tube type tilted structures were less twisted.

Moon [18] discussed Structural Design and Construction of Complex- Shaped Tall building. He presented comparative lateral performance of braced tube, diagrid and outrigger system, employed of twisted, tilted, tapered and freeform tall building. He studied conventional box- form buildings' plan dimensions 36 X 36 m² with an 18 X 18 m² core at the centre and storey height of 3.9 m with height to width aspect ratio of 60-80 and 100 storey were 6.5, 8.7 and 10.9 in SAP 2000.Fianlly, He concluded that lateral stiffness of diagrids, braced tube and outrigger structures were reduced when they employed for twisted. Lateral stiffness of outrigger structure was increased as they were tilted. Lateral displacement of tapered tall building decreased. Lateral stiffness of diagrid structural system was decreased as the degree of fluctuation increased.

c) Case Study of Braced tube System

Fazlur R. Khan [19] presented the 100 storey John Hancock Centre in Chicago played a dominant role and become the apparent architectural expression. Total height of the building is 330 m. The braced tube system takes advantage of the structural aesthetics of double tapered truncated pyramid shape form to reduce overall required steel quantity about 13.5kg per m² for 100 storey to keep unit product, when compared to a traditional frame building of 30 to 40 storey. The base dimension of 48 X 78 m² tapering upward to 30 X 48 m² at top floor level. This paper described the structural design of braced tube at perimeter and the unique sustainable features incorporated in to the buildings.

Andy, Nigel, Smith and Butler [22] presented a case study for the leaden hall building, London. The leaden hall project is piloting the application of radio frequency identification software to track components through manufacture, supply and installation. This will enable preventive action in the event of any delays downstream. At 47 stories and 225 meters high, the leaden hall building would contain the highest office floors in the city of London on completion. From a structural perspective tall and light building has no central core and make use of "tube" structural perimeter with an external support core that allows for open floor plates. The leaden hall building comprises a tapering perimeter braced-diagrid structure containing a connected to the structural tube, termed the mega-framed at every floor without the need for further Perimeter column. In leaden hall building, rectangular office floor plan 48 meters wide and up to 43 meter deep is column free and six internal columns are required on the largest floors. The stability of structures integrated into the external mega frame. The building's triangular geometry in profile and the layout of the mega frame enable seven floors to fit within a 28 meter high section, with each floor 750 millimetres narrower in plan than the one below. In Leaden hall building, the office floor beams are connected to the mega- frame via sliding bearings which allow small horizontal movement to occur freely. So that mega- frame can expand and contract without transferring forces in to the floor structure behind.

W. Barker, C. Besjak, B.McElhattem and X.Li [28] presented a case study of Pear River Tower: Design integration towards sustainability. It is a 71-storey, 309m office building located in Guangzhou, china. The main goal for the project was to create the most energy efficient buildings. To meet the demand of sustainability, initiatives and seismic requirements, structural concept utilizes a highly integrated series of systems including reinforced concrete core wall , composite mega X- bracing, Outrigger and belt truss. Structural steel columns and composite floor framing. Construction was completed in 2012. A four pronged strategy consist of reduction, reclamation, absorption and generation were presented to reduce the amount of energy required by the building and reach the zero energy goal.

Jain and Mandal [29] discussed A Case study on Shear lag Effect in Tubular structures under Wind load. They analysed 40 story RC tubular framed building using STAAD Pro to understand the shear lag phenomenon in high-rise framed tube structure. They considered size, beam and column as 0.8 X 0.8m and storey height is 3.0 m. The presented the graph of axial force in flange Panel and web panel for every 4 story. Finally, they concluded that from graph that as the height of the building increase point of maximum axial force shifts towards the centre of the web from either ends. In other words, column which are under compression gets tensile forces as the height increases. They noted that axial force in corner column which are maximum at the base reduces and axial force in adjacent columns increase with height but after a certain height axial forces in corner columns increases and axial forces in adjacent columns reduces up to top of the building.

D.C. RA and S.C.Goel [31] studied Seismic evaluation and upgrading of chevron braced frames. They selected a building in the North Hollywood area that suffered major damage in the 1994 Northridge earthquake. They compared Response spectrum, nonlinear static (pushover) and nonlinear dynamic (time history) analysis for a ground motion recorded at a nearby site with observed damage. Seismic performance of CBFs can be improved by delaying the fracture of braces. This was achieved by preventing the local buckling of brace members. The instability and plastic hinging of floor beams can be avoided by changing the popular chevron bracing configuration to 2- storey X. If the fracture of braces was prevented with the use of ductile braces, the 2- storey X configuration was a great improvement over the chevron system.

Kim, Shin, Park and Min [32] presented Seismic Performance of tubular Structures with buckling restrained braces. They designed 36 and 72 storey framed and braced tubular structures and their seismic performance by nonlinear static and dynamic analysis using ICC (International building code) in MIDAS and SAP 2000.According to the analysis result, the tubular structures showed high earthquake resisting capability. The framed tube structures showed lower stiffness and strength compared with tube structures with diagonal braces. The braced tube structures showed greater strength but lower overall ductility compared with framed tube structures. When buckling restrained braces were used instead of conventional braces, strength increased significantly compared with the framed tube, and ductility was enhanced compared with braced tube structures.

d) Across Wind Loading

Quan and Gu [45] presented the across wind loads for typical tall buildings. In this paper, 15 tall building models with different cross-sections and aspect ratios from 4 to 9 were tested with high-frequency force balance. Technique in a wind tunnel to obtain their first-mode generalized across-wind dynamic forces. They derived the formulas of the power spectra of the across wind dynamic forces, the coefficients of base moment and shear force. Comparison was done between present formulas and literature for verification.

e) Non-Linear Analysis

Peter C. Chang and D.A. Foutch [35] studied static and dynamic modelling and analysis of tube frame by the finite element method. These model considered shear and flexural deformation as well as shear lag effect. They represented a model by a set of first-order differential equations and solved numerically using a fourth order approximation technique and compared their result with the result of finite element code. They analyses that their predicted deflection, frequency and mode shape in a model showed excellent comparison to the finite element results. Finally, they reached a conclusion that, after analysing a building as a thin walled tube, the tube model allowed for shear lag in flange as well as flexural and shear deformation. They found differential equation for static loading and equation of motion through minimum potential energy principle and Hamilton's principle and deflection, frequency and mode shape of the model through Rayleigh-Ritz method and compared these result withy result of finite element program.

Jun Jin., Sherif El-Tawil [36], discussed a paper that contain a formulation for a beam-column element used to simulate the inelastic cyclic behaviour of steel braces. In this paper, the model was implemented in a computer analysis program-DYNAMIX and verified by comparing analytical calculations to experimental data for individual steel braces and a three story braced steel frame. Finally, they concluded that the proposed model employed stress resultant plasticity concept that focus on forces and corresponding generalized strain and was computationally efficient. The model had no restrictions on brace boundary conditions and accounted for gradual spread of plasticity through the cross section and along the member length as well as degradation of axial strength and stiffness with cycling. This developed model was well suited for conducting analysis of large multi-storey braced steel frame subjected to seismic loading

Farshid Nouri, Mohammad Yassmi and Payam Ashtari [19] presented evaluating optimum topology of braced-tube tall steel structures using non-linear time-history analysis in Open Sees and MATLAB. He provided massive lateral stiffness and enable the engineers to design structures with considerable heights. In these paper, optimum angle of diagrids was investigated and would yield the minimum lateral displacement and inter-storey drift. He considered minimization of shear lag phenomenon. He presented the graph of shear lag having 20, 30 and 40 storey braced tube system. Result of non-linear response history analysis showed that

I. Tall buildings insist existence of shear lag after reaching higher levels.
II. The design which was appropriate for serviceability constraint not necessarily minimizes the effects of shear lag.

Yoo, Lehman and Roeder [38] presented influence of connection design parameters on the seismic performance of braced frames. The braces are connected to the beams and columns by gusset plate connections and inelastic deformation is developed through tensile yielding and inelastic post-buckling deformation of the braces. They studied to examine the influence of the gusset plate and framing elements on the seismic performance of SCBFs and to develop improved design models with the finite element program ANSYS. They also explored the impact of the frame details including the beam to column connections, the brace angles and their inelastic deformation demands.

3. CONCLUSION

From the literature study based on braced tube structural system following conclusions are made:

[1] The optimum value of 's' is higher (ratio of the displacement at the top of the structure due to bending and the displacement due to shear) at H/B is equal or greater than 4 respectively.[4]
[2] For more than 40 story having aspect ratio is greater than 4, the optimum angle is from about 40° to 50°[4].
[3] Material percentage usage difference between Braced tube and Diagrid for 40, 50, 60, 70, 80, 90 and 100 story is 20.5, 14.7, 7.6, 5.9, 2.4, 0.7 and -1.5.[5]
[4] Shear lag ratio of 40 story 3.8m high structure for Braced tube system for 10 story module is 2.38 as compared to framed tube system having 5.94.[13]
[5] Lateral stiffness of braced tube is reduced when it is employed for twisted tall buildings.[18]
[6] Most of the lateral load is resisted by the Diagonals on the periphery, while gravity load is resisted by both the

internal columns and peripheral diagonals. So, internal columns need to be designed for vertical loads only.[1]

[7] Overall, Braced tube as a structural system demonstrates high efficiency in carrying lateral load in high-rises. It performs better than the framed tube system. Braced tube system is the ideal structural system for high-rise buildings.[1]

[8] behaviour of the systems having vertical irregularity and/or horizontal irregularities in the plan and elevation can be carry out[18]

[9] Soil-Structure interaction can be carry out

[10] Foundation Design of this system for various height of Brace tube Structures can be study.[19]

[11] Analysis and Design of the whole system considering Thermal expansion and contraction can be carry out[24]

[12] Other geometric shapes like rectangular, circular, pentagonal, hexagonal, diamond, etc. can be carry out by applying Braced tube Structural System.[19]

[13] Shear Lag effect for Braced tube Structural system can be study.[13]

[14] Non-prismatic sections can be carry out for the same system to check its' performance under the cyclic behaviour.[19]

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