Pak. J. Engg. & Appl. Sci. Vol. 14, Jan., 2014 (*p.* 17-26)

Comparison of Different Bracing Systems for Tall Buildings

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Abstract

When a tall building is subjected to lateral or torsional deflections under the action of fluctuating wind loads, the resulting oscillatory movement can induce a wide range of responses in the building's occupants from mild discomfort to acute nausea. As a result, lateral stiffness is a major consideration in the design of tall buildings. Bracing is a highly efficient and economical method of resisting lateral forces in a frame structure because the diagonals work in axial stress and therefore call for minimum member sizes in providing the stiffness and strength against horizontal shear. In this research study, five different types of bracing systems have been investigated for the use in tall building in order to provide lateral stiffness and finally the optimized design in terms of lesser structural weight and lesser lateral displacement has been exposed. For this purpose a sixty storey regular shaped building is selected and analyzed for wind and gravity load combinations along both major and minor axes.

Key Words: Bracing System; Tall Buildings; structural weight; lateral displacement

1. Introduction

The high cost of land, the desire to avoid a continuous urban sprawl and need to preserve important agricultural production have all contributed to drive the residential buildings upward or in other words, have promoted height zoning in Pakistan's big cities. To accommodate the continuous urban sprawl, there is a need to construct tall buildings. A tall building may be defined as a building whose design is governed by the lateral forces induced due to wind and earthquake [1].

When a tall building is subjected to lateral or torsional deflections under the action of fluctuating wind loads, the resulting oscillatory movement can induce a wide range of responses in the building's occupants from mild discomfort to acute nausea. As far as the ultimate limit state is concerned, lateral deflections must be limited to prevent second-order p-delta effect due to gravity loading being of such a magnitude which may be sufficient to precipitate collapse. In terms of serviceability limit states deflection is required to be maintained at a sufficient low level for following reasons;

- To allow proper functioning of nonstructural components such as elevators and doors.
- To avoid the distress in the structure, to prevent excessive cracking and consequent loss of stiffness and to avoid any redistribution of the load to non-load-bearing partitions, infill, cladding or glazing.
- The structure must be sufficiently stiff to prevent dynamic motions becoming large enough to cause discomfort to occupants or affect sensitive equipment.

To satisfy strength and serviceability limit stares, lateral stiffness is a major consideration in the design of tall buildings. The simple parameter that is used to estimate the lateral stiffness of a building is the drift index defined as the ratio of the maximum deflections at the top of the building to the total height. Different structural forms of tall buildings can be used to improve the lateral stiffness and to reduce the drift index [2]. In this research the study is conducted for braced frame structures.

Bracing is a highly efficient and economical method to laterally stiffen the frame structures against wind loads. A braced bent consists of usual columns and girders whose primary purpose is to support the gravity loading, and diagonal bracing members that are connected so that total set of members forms a vertical cantilever truss to resist the horizontal forces. Bracing is efficient because the diagonals work in axial stress and therefore call for

minimum member sizes in providing the stiffness and strength against horizontal shear [3].

With the increase in trend of constructing tall buildings, there is need to find cost effective structural forms of bracing system to be used in tall buildings against lateral loads. This research study aims to find the most suitable bracing system out of five investigated bracing systems in terms of lesser weight of the structure and smaller value of lateral displacement. For this purpose, a regular shape tall building has been selected and analyzed for wind loads acting along the minor axis of bending of column and then acting along the major axis of bending of column. Similarly, in first case (wind loads along the minor axis), building is braced in minor direction of bending and in second case (wind loads along the major axis), building is braced in minor direction of bending. Moreover, various options of bracing provision in different bays of the building at same level have also been investigated.

2. Tall Buildings and Structural Form

Tallness is considered as relative term which cannot be defined in terms of height. From structural engineer's point of view, tall building is defined as the building whose structural design is governed by the lateral forces induced due to wind and earthquake.

The structural form of a tall building depends on a number of factors, some are given below;

- Internal planning
- Material and method of construction
- External architectural treatment
- Location and routing of service system
- Nature and magnitude of horizontal loading
- Height and proportion of building

Following are some structural forms of the tall buildings:

2.1 Braced frame system

Such systems consist of frames with vertical trusses. Both fixed and pinned frames are usually used in conjunction with the vertical trusses.

In some bays of frame, diagonal members are provided within the story height and this pattern is repeated throughout the height of the building forming a vertical truss type structure as shown in Fig.1. These vertical trusses increase the strength and stability of the buildings against lateral loads.

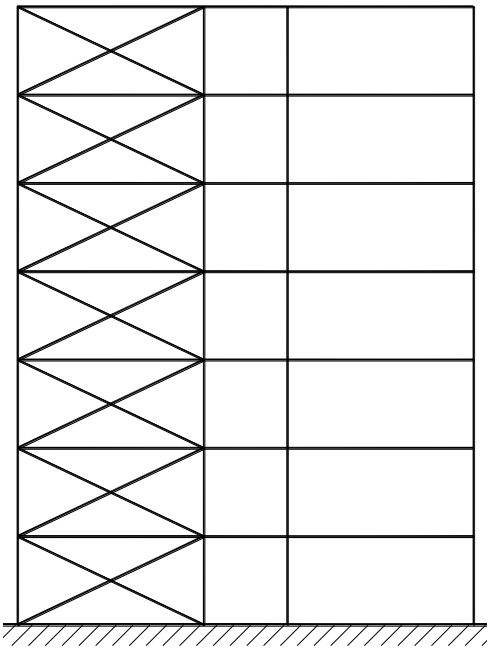

Fig.1 Braced frame

2.2 Rigid frames

In these structures, the lateral stability is provided by the moment resisting connections of the beams and columns as shown in Fig.2. These forms are only used up to 25 stories [4] as for the more high buildings, the demand of the lateral forces increases and can result in larger size of beams and columns. Such forms are normally preferred for the concrete buildings.

2.3 In-filled frame structures

In these structures space between the columns and beams is filled with the brick masonry or block masonry as shown in Fig.3. Such forms are used for tall buildings up to 30 stories [4].

2.4 Flat slab structures

In such systems a slab of uniform thickness is used to connect all the columns and there are no beams spanning between columns. Slabs are considered as rigid diaphragms in such forms that transfer the lateral load to the columns. These types of structures are used only for the tall buildings upto 25 stories [4].

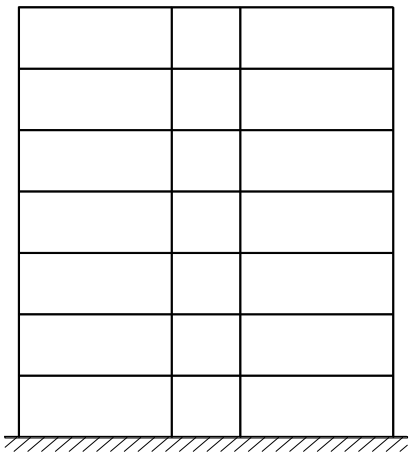

Fig.2 Rigid frame

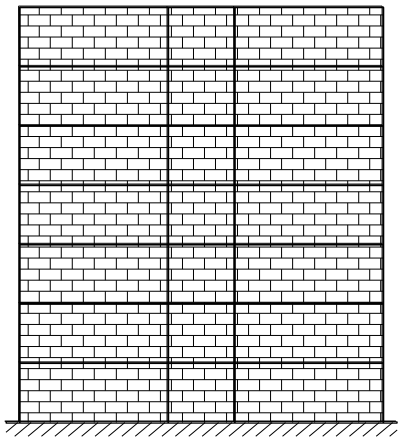

Fig.3 In-filled frame

2.5 Shear wall structures

These include the vertical walls of concrete or masonry. Sometimes these are also used in combination with the rigid frames. These walls are considered effective in resisting the horizontal shear acting along their length due to the lateral loading of wind or earthquake as a result of large in-plane stiffness.

2.6 Tube structures

In these structures lateral resistance is provided by the moment resisting frame (tube) present at the periphery of the building. Tube consists of closely spaced columns that are joined with deep beams. The gravity loading is shared by both inner columns and tube whereas lateral load is resisted by the exterior tube. The structures can be constructed for tall buildings ranging from 40 to more than 100 stories [4].

2.7 Suspended structures

The suspended structures, shown in Fig.4, consist of a central core with the cantilevers at roof level to which the vertical hangers of steel cable are attached. The roof slabs are suspended from the hangers. These are used for relatively less high buildings.

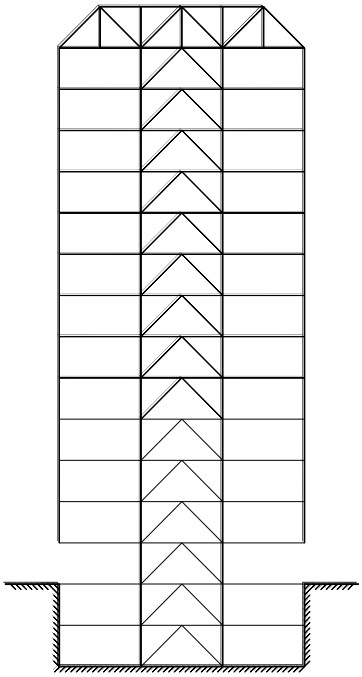

Fig.4 Suspended structure

3. TYPES OF BRACINGS

Bracing can be categorized into the following types;

3.1 Diagonal bracing

This type of bracing is preferred when the availability of the opening spaces in a bay of frame are required. Diagonal bracing is obstructive in nature as it blocks the location of opening which ultimately affects the esthetic of the building elevation. It also sometimes hinders the passage for use.

Diagonal bracing can be single diagonal or double diagonal as shown in Fig.5. If there is no

architectural limitation, diagonal bracings are considered to be the most efficient in resisting the lateral forces due to wind as these form a fully triangular vertical truss. The beams and columns are designed to take the gravity loads only.

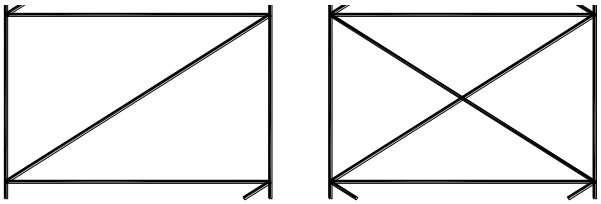

Fig.5 Diagonal bracings

3.2 K-bracing

The full diagonal bracing is not used in areas where a passage is required. In such cases, k-bracings are preferred over diagonal bracing because there is a room to provide opening for doors and windows etc. as shown in Fig.6.

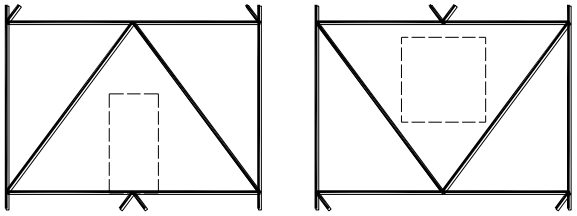

Fig.6 K-bracing

3.3 Eccentric bracing

Besides K-bracing, there is another type in which door and window openings can be allowed known as eccentric bracing as shown in Fig.7. Such type of bracing arrangement cause the bending of the horizontal members of the web of braced bent. Generally these types of braced bents resist the lateral forces by bending action of beams and columns. These provide less lateral stiffness hence less efficient as compared to diagonal bracing.

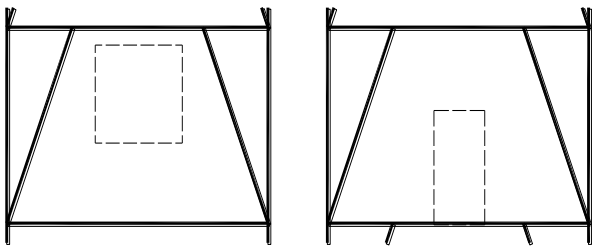

Fig.7 Eccentric bracing

4. Structural Mechanism of Bracing System

Various bracing systems perform differently under lateral and gravity loads. The mechanism of action of each type of bracing systems against the two loading cases (gravity and lateral) is explained below:

4.1 Behavior of bracing under lateral loads

The design of tall buildings is governed by the lateral forces induced due to wind. Braced frames are considered to be the most efficient to resist these lateral forces in either direction. The primary purpose of bracing is to resist horizontal shear induced due to the lateral forces. The mechanism to resist horizontal shear can be understood by following the path of horizontal shear along the frame. It can be explained by considering the four types of bracings subjected to lateral loading as shown in the Fig.8.

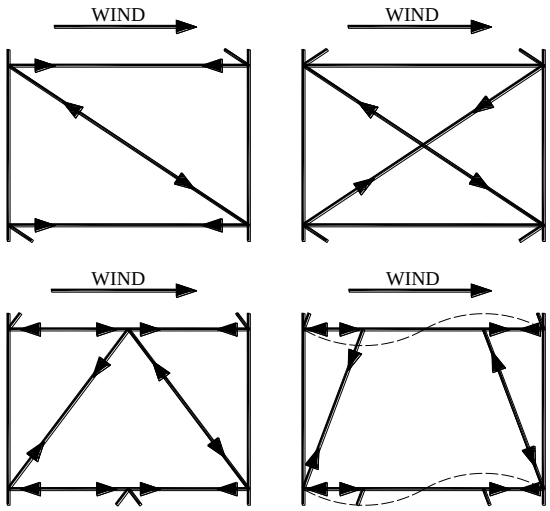

Fig.8 Path of horizontal force

It is clear from the Fig.8 that when diagonals are subjected to compression, the horizontal web members will undergo axial tension for equilibrium in lateral direction. This will result in shear deformation of braced bent. In case of k-bracing half of the web members and both horizontal and inclined will be subjected to tension and compression simultaneously. Forces and deformations in each member of braced bent will be reversed as the building is subjected to lateral loading in opposite direction.

4.2 Behavior of bracing under gravity load

Under the action of gravity loads, columns shorten axially due to the compressive loads. As a result the diagonals are subjected to compression and beam will undergo axial tension due to the tying action as shown in Fig.9. In the cases where diagonals are not connected at the ends of the beams, the diagonal members will not carry any force because no restraint is provided by the beams to develop force. Therefore, such bracing will not take part in resisting the gravity loads.

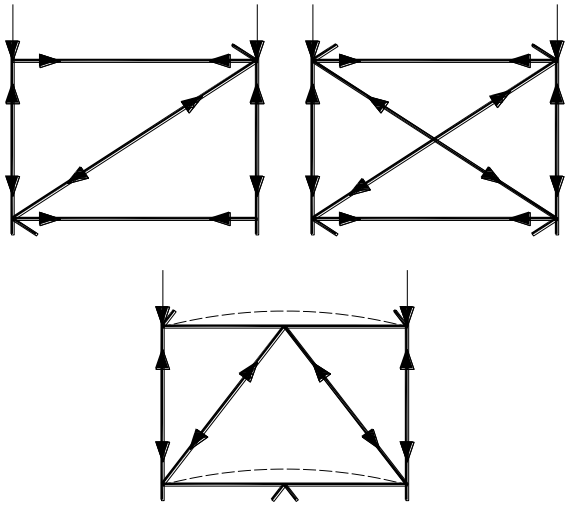

Fig.9 Path of gravity load

5. Methodology of research study

In order to compare different bracing systems and to get the most economical one among them, a regular building subjected to both gravity and wind loadings was selected. The building along with different bracing configurations was analyzed and designed in STAAD Pro [5]. The non-linear static analysis was performed so that the bracing members are effective only in tension.

Five different types of bracing systems were studied by placing them along the major axis first and then along the minor axis. Moreover, bracings were distributed in different bays in both cases as described above.

The following sections will further explain in detail the methodology adopted with reference to making the computer models.

5.1 Structural Details

Buildings with a fundamental natural frequency of less than 1 Hz are known as flexible buildings [6]. In this study, a flexible tall building was selected. The structural form adopted for the study was braced steel frame structure. Plan of the selected tall building is shown in Fig.10. Following are the parameters of the building:

No. of bays in X-direction	=	8
No. of bays in Y-direction	=	8
Width of bay in X-direction	=	18 ft.
Width of bay in Y-direction	=	18 ft.
No. of stories	=	60
Height of each story	=	12 ft.
L/W ratio	=	1
H/W ratio	=	5

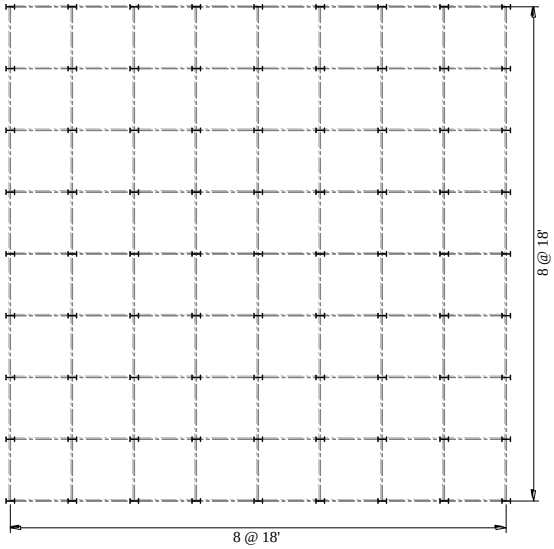

Fig.10 Plan of the selected tall building for computer model

5.2 Bracings

Five different types of bracing systems studied in this research program are single diagonal bracing, double diagonal bracing, k/chevron bracing, v bracing and story-height knee bracing. All five types of bracing types are shown in Fig.11.

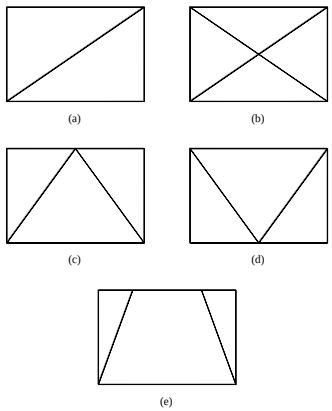

Fig.11 Bracing types. (a) Single diagonal bracing (b) Double diagonal bracing (c) K/Chevron bracing (d) V-bracing (e) Story-height knee bracing

The bracing members were selected automatically using SELECT OPTIMIZED option in STAAD.

5.2.1 Bracing Configurations Used in Building

The wind loading was considered only in one direction at a time; therefore, two different arrangements of columns were used: 1) Major axis of the columns parallel to the wind; and 2) minor axis of all columns parallel to the wind as shown in Fig.12 and Fig.13, respectively. For both arrangements of columns, the effect of different bracing types was studied by changing the locations of the braced bays as shown in the Fig.14 to Fig.17.

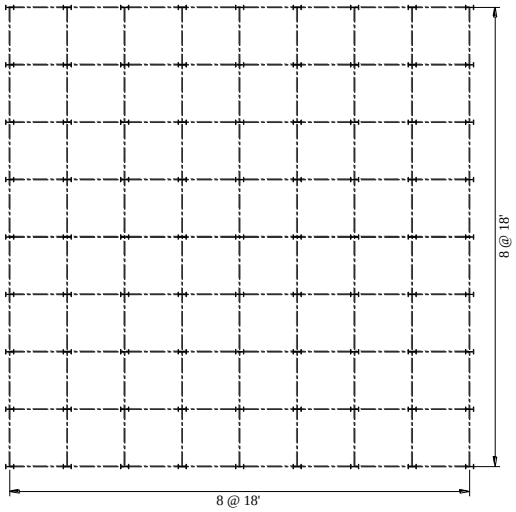

Fig.12 Columns with minor axis parallel to wind

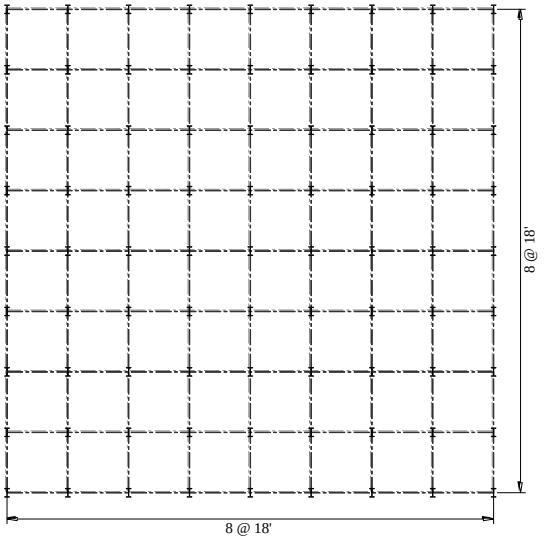

Fig.13 Columns with major axis parallel to wind

5.2.1 Bracing Configurations Used in Building

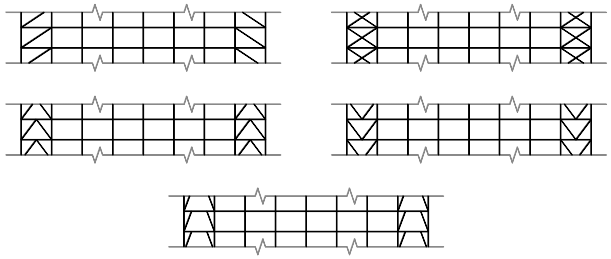

Fig.14 Option 1: 1st and 8th bay braced

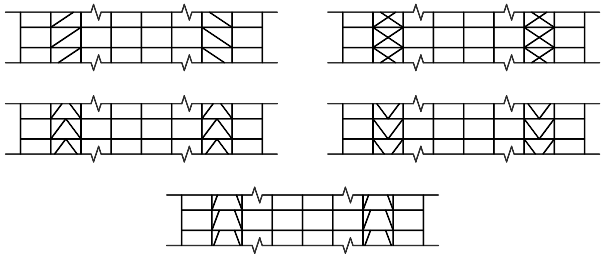

Fig.15 Option 2: 2nd and 7th bay braced

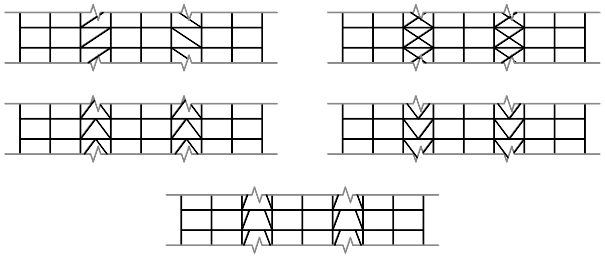

Fig.16 Option 3: 3rd and 6th bay braced

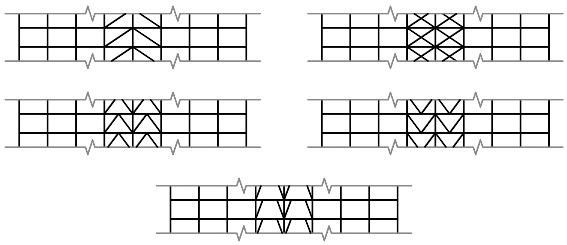

Fig.17 Option 4: 4th and 5th bay braced

6. Results and Discussion

Results obtained by analysis and design of the selected building with five different types of bracing system provided at different bays level were analyzed and are discussed in this section. Main focus of the discussion is the following points:

- Comparison of structural weight obtained in two cases [(1) bracing along the minor axis of bending and (2) bracing along the major axis].
- Comparison of lateral deflection under service wind loads at different levels of the building with different option of bracing system.

Total weight of the structural steel corresponding to bracing along the minor axis and major axis with different four options of bracing location (refer to figures 14 to 17) are given in Table 1 and Table 2 respectively. Comparison of different types of bracings along minor axis and major axis is graphically shown in Fig.18 and Fig.19, respectively. It is clear in the Fig.18 that when bracing is provided along the minor axis of columns, minimum weight of the structural steel is obtained by using double bracing

Table 1: Total weight of structural steel corresponding to bracing along minor axis

Bracing Type	Weight (Kips)			
	Option 1	Option 2	Option 3	Option 4
Single Diagonal	27646	27626	27678	27553
Double diagonal	26562	26335	26351	25789
K/Chevron	27415	27549	27834	27774
V	27328	27234	27507	27333
Knee	27625	28006	28415	28585

Table 2: Total weight of structural steel corresponding to bracing along major axis

Bracing Type	Weight (Kips)			
	Option 1	Option 2	Option 3	Option 4
Single Diagonal	31134	31749	32371	32195
Double diagonal	28848	28895	29177	28148
K/Chevron	30620	30697	31473	31384
V	30512	30173	30739	30607
Knee	31320	31794	32465	32780

system and among different options of bracing at different levels, option 4 produces less weight. It is obvious in Fig.19 that similar results are obtained in case when bracings are provided along the major axis of bending of columns as obtained in case when bracings are provided along minor axis of bending of columns.

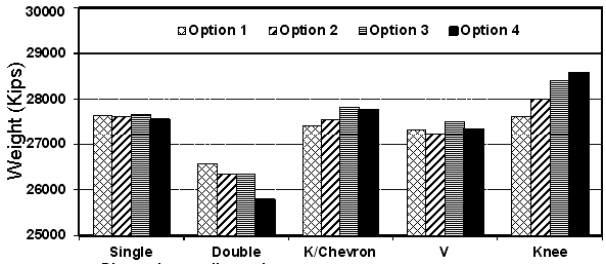

Fig.18 Comparison of structural weight (bracing along minor axis)

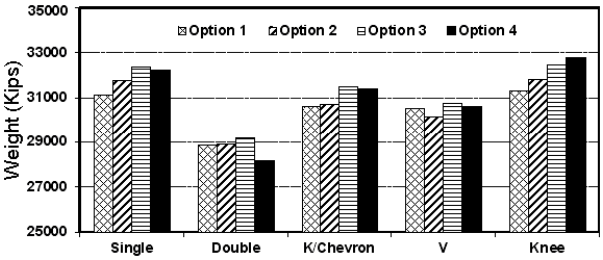

Fig.19 Comparison of structural weight (bracing along major axis)

Percentage increase in the weight of the structure with double bracing provided along the minor and major axis of bending of columns in options 1, 2 and 3 in comparison of option 4 is shown in Fig.20. In case of bracing provided along the minor axis of bending of columns, it is clear in Fig.20 that option 1 is 3% heavier, option 2 is 2.12% heavier and option 3 is 2.18 % heavier than option 4. In case

of bracing provided along the major axis of bending of columns, option 1 is 2.49% heavier, option 2 is 2.65% heavier and option 3 is 3.66 % heavier than option 4.

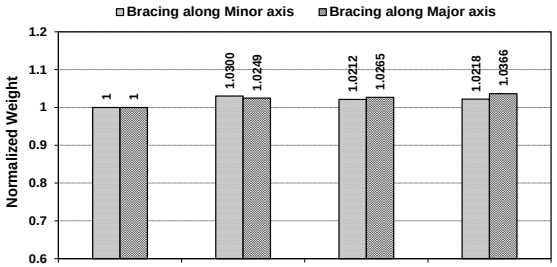

Fig.20 Double bracing system along minor and major axis: Increase in weight of structure in option 1, 2 and 3 in comparison of option 4

Magnitude of lateral displacement along the height of the building braced with different bracing systems in minor direction of bending of columns is shown in Fig.21 to Fig.25. ASCE-7-05 [7] recommends maximum sway of H/500 and storey drift of H/500 to H/400. A value of H/400 is selected in this study. In these figures, the values of lateral displacement obtained with four different options of bracing provision (refer to Fig.14 to Fig.17) are also compared with permissible limit of lateral displacement which is H/400, where H is building height in feet. In Fig. 21 to Fig.25, it is clear that in all the four options of bracing provision, lateral displacement is within the acceptable limit and minimum lateral displacement is obtained in option 4. Among different types of bracing systems used in this study along the minor axis bending of columns as shown in Fig, K bracing system produced minimum lateral displacement as shown in Fig.26.

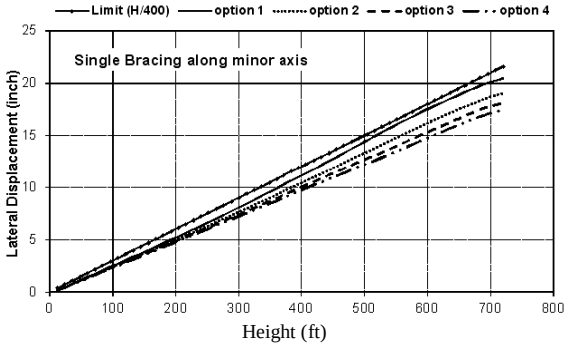

Fig.21 Lateral displacement of building with single diagonal bracing along minor axis

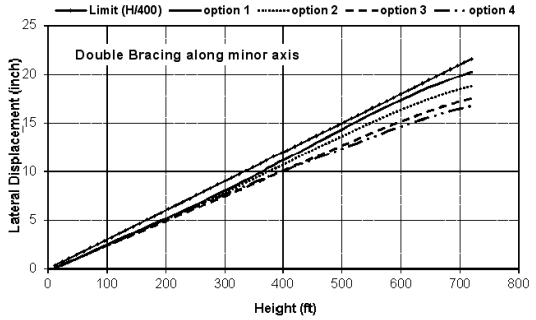

Fig.22 Lateral displacement of building with double diagonal bracing along minor axis

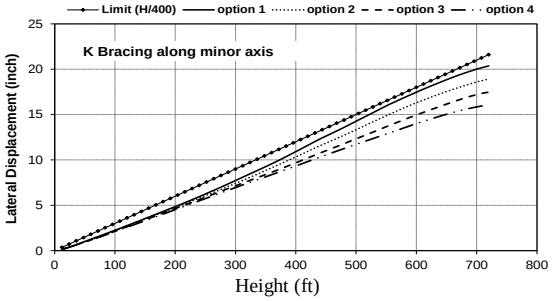

Fig.23 Lateral displacement of building with K bracing along minor axis

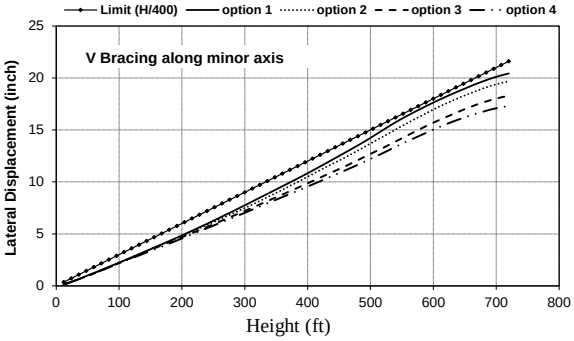

Fig.24 Lateral displacement of building with V bracing along minor axis

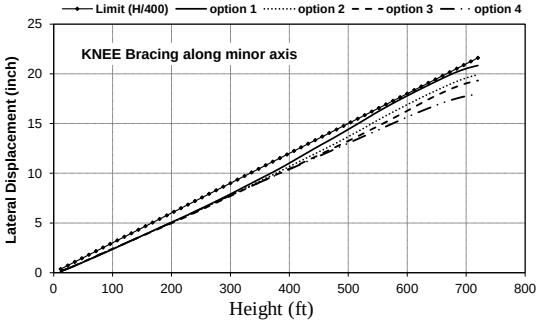

Fig.25 Lateral displacement of building with KNEE bracing along minor axis

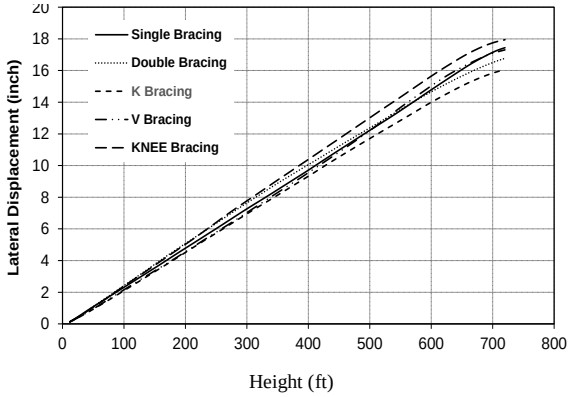

Fig.26 Comparison of lateral displacement with different bracings along minor axis of bending of columns in Option 4

In Fig.27 to Fig.28, the values of lateral displacement along the height of the building obtained with four different options of five types of bracing (refer to Fig.14 to Fig.17) along the major axis of bending of columns have been compared with permissible limit of lateral displacement which is H/400 [7]. In all these figures, it is observed that lateral displacement in option 1 with all types of bracing exceeds the permissible limit of H/400. In case of V bracing, lateral displacement values were higher than permissible limits in option 1 and option 2 while for option 3 and 4, displacement were within limits. Similarly, for KNEE bracing system, lateral displacement values were found to be higher than the limit for option 1, 2 and 3 while for option 4, these were within limits. It is to be noted here that for all types of bracings along the major axis, only option 1 produced satisfactory results in all four option of bracing provision in terms of lateral displacement. Among different types of bracing systems used in this study along the major axis bending of columns, K bracing system produced minimum lateral displacement for option 4 as shown in Fig.32.

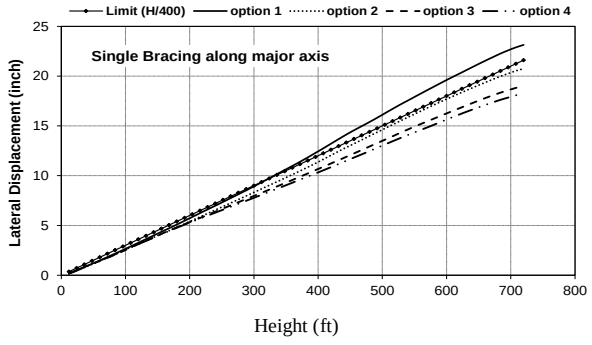

Fig.27 Lateral displacement of building with single diagonal bracing along major axis

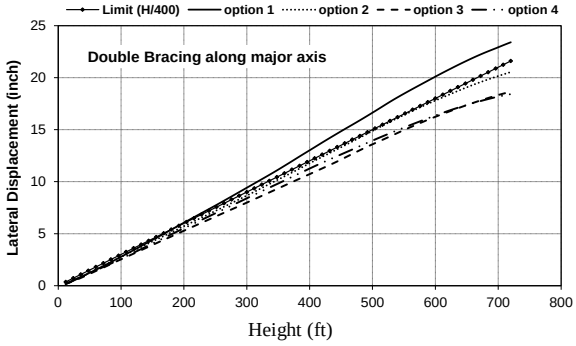

Fig.28 Lateral displacement of building with double diagonal bracing along major axis

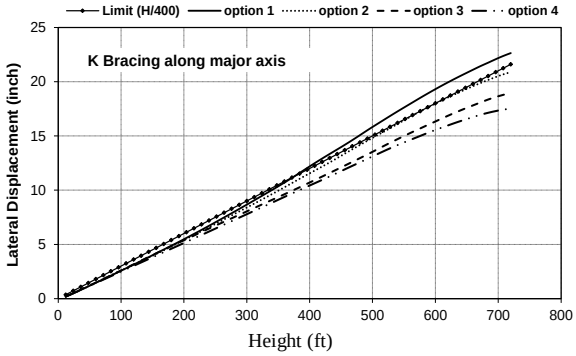

Fig.29 Lateral displacement of building with K bracing along major axis

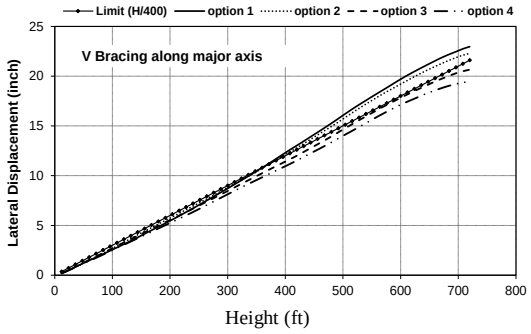

Fig.30 Lateral displacement of building with V bracing along major axis

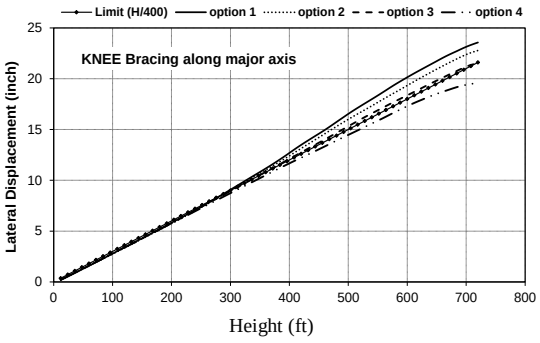

Fig.31 Lateral displacement of building with KNEE bracing along major axis

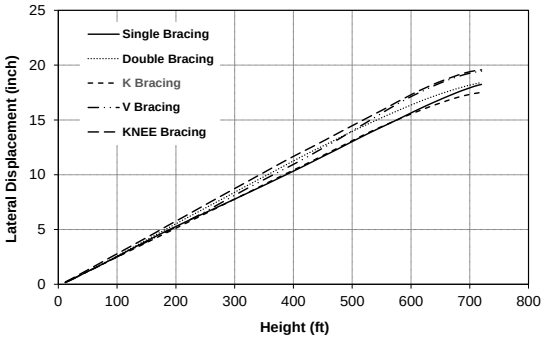

Fig.32 Comparison of lateral displacement with different bracings along major axis of bending of columns in Option 4

7. Conclusions

From the results obtained in this study, it is possible to draw the following conclusions:

- Lesser structural steel weight of a tall building is obtained when it is braced along the minor axis of bending of columns in comparison of the situation when same building is braced along the major axis of bending.
- Among five different investigated bracing systems, double bracing system yields minimum weight of structural steel. Moreover, minimum weight is obtained when central two bays of the tall building are braced against lateral loads (4^{th} and 5^{th} bays in the present study).
- Lateral displacements are within the permissible limit of H/400 for all five bracing systems used in this study are provided along the minor axis of bending of columns and also for all four options of bracing provision in different bays at one story level. However, when columns are braced along their major axis of bending, only in option 4 (where central bays are braced), lateral displacements remain within permissible limits for all types of bracing system investigated here.
- When columns are braced along their minor axis of bending, provision of K bracing results in minimum value of lateral displacement compared to other four types of bracing systems.
- When columns are braced along major axis, although lateral displacement values go beyond the permissible limits but among five types of bracing systems, which similar to the case when columns are braced along their minor axis of bending, K type bracing results in smaller lateral displacement compared to other types.
- Double bracing provided in the central bays along the minor axis of bending of columns of a tall building yields minimum weight of the structural but minimum value of lateral displacement is obtained in case of K bracing. Since the values of lateral displacement in the presence of double bracing system is also within permissible limits of H/400, it can be suggested to use double bracing system in tall buildings to enhance the lateral stiffness against wind load.

8. Acknowledgement

Financial support from the University of Engineering and Technology Lahore for this study is highly acknowledged.

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