Influence of Design Parameters on Performance of SMRF Installed with Buckling Restrained Brace

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Abstract : Buckling restrained brace (BRB) has been a popular earthquake resistant component due to ductility, stable hysteretic behavior, yielding in tension and compression and ease of post disaster assessment. In this paper, effects of core length of BRB on its performance, as an individual component, are studied using finite element model of BRB. Ansys Workbench 18.0 is used for modeling and analysis of the component. Microsoft Excel program for Design procedure of BRB is prepared and BRB capacities variation regarding variable aspect ratio (width to thickness ratio) is observed. Further, comparative study of G+9 storey RC frame (without infill walls) performance is conducted before and after installation of BRBs. Moreover, influence of BRB inclination is also studied. Seismic Performance of the building concerning time period of vibration and storey response is contemplated. Modeling and analysis of the structure is done using ETABS 2016. Study depicts that core length; aspect ratio and inclination are the most important design parameters governing BRB contribution in structural damping. Moreover, it is found that SMRF installed with BRBs show efficient performance concerning time period of vibration, besides storey responses, when subjected to dynamic loading and thus proving it to be an efficient lateral load resisting system.

IndexTerms - Buckling Restrained Brace, Non-Linear Dynamic Analysis, SMRF, Storey Response

I. INTRODUCTION

Over conventional bracing systems, Buckling Restrained Brace (BRB) is getting more popular as it has got many more advantages such as: stable hysteretic behavior, yielding in tension as well as compression, ease of post earthquake assessments due to concentrated damage, economy of construction, etc. Buckling restrained brace consists of a central steel core which is subjected to direct axial loading due to lateral earthquake loads, concrete restraining member which is subjected to flexural stresses generated because of restrain provided to the buckling of steel core. A de-bonding layer is provided between steel core and concrete member in order to avoid friction. Whole assembly is encased in a steel casing and can be placed in position with the help of end stiffeners. Typical configuration of BRB is shown in Fig. 1.

Santiago and Larry [1] study employed the FEMA P695 framework to evaluate the response of BRBFs designed according to current codes in the United States and to study the effect on seismic stability of three additional parameters: BRBF column orientation, gravity column continuity, and dual systems. T. Albensi et al. [2] have proposed that design of Buckling restrained brace is mainly based on the basic concept valid for all ductile seismic design that Buckling restrained braces are yielding elements which are designed to deform with considerable inelastic deformation during DBE level earthquakes they are designed for and remaining structural elements are capacity based designed so that they remain elastic till expected strength of BRB is reached. In Performance based design procedure, performance criteria is selected initially as target displacement to be within permissible limits as given by limit states. Effective damping required for the corresponding maximum displacement of the structure within its permissible limits is computed and inherent damping of the structure itself is deducted from the overall effective damping to get the additional damping required to be provided by BRB. Ziqin et al. [3] employed a refined finite element (FE) model to evaluate the contact force between the core and external restraining members and to investigate the BRB performance. Moreover, the influences of strength and stiffness of external restraining member, core length, and other geometric parameters on the BRB performance were also studied.

This study aims to evaluate effect of core length, aspect ratio, inclination of brace with respect to horizontal, installation of BRB in Special Moment Resisting Frame (SMRF) of on its performance, as an individual component as well as in the structure is studied governing response of the component in terms of stress functions, effective stiffness, core buckling, global flexural capacity and structure performance concerned with time period of vibration and storey responses.

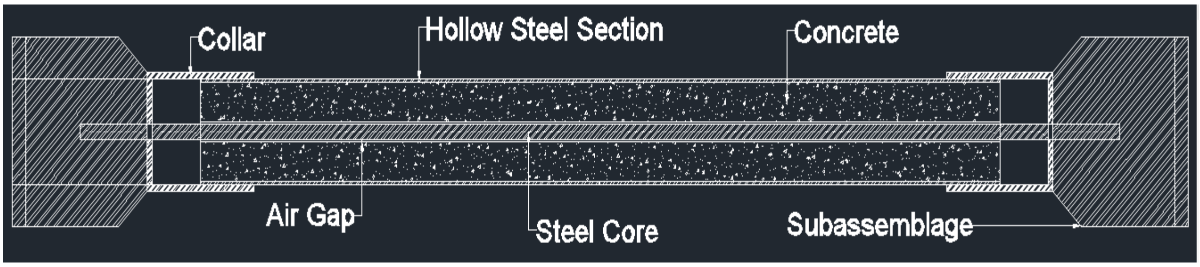

Fig. 1. Typical Configuration of buckling restrained brace

II. Proposed Work

2.1. Methodology

Initially a buckling restrained brace of presumed dimension is considered. A simplified finite element model of buckling restrained brace is prepared in Ansys Workbench 18.0. Non-linear dynamic analysis of the model is carried out using El-centro (Imperial Valley) earthquake ground motion records. Varying length of core, variation of stress functions is obtained and comparative study is carried out further in order to check the influence of core length on performance of BRB. A design procedure of BRB confirming to design guidelines given in ASCE7-2005 and FEMA 273-1997 is prepared in Microsoft Excel and effect of aspect ratio variation is studied. Later SMRF installed with BRB is modeled in SAP2000 and time history analysis of SMRF is carried out using El-centro (Imperial Valley) earthquake ground motion records. Axial force to which a brace is subjected is found out and BRB is designed for the axial load. BRB (multi-linear plastic links) are then installed in the structure at predetermined locations. Comparative study based on the performance output of SMRF installed with BRB subjected to non-linear dynamic analysis is then carried out to understand the performance of SMRF before and after installation of BRB.

2.2. Modelling and analysis of BRB

Five different refined finite element models (as shown in Fig. 2) with lengths 1.5m, 2m, 3m, 4m and 5m of buckling retrained brace prepared in Ansys Workbench 18.0 were employed for the study. Length of core and external restraining member is kept same for the ease of modeling and analysis. Mild steel (Fe250) core is decoupled from External restraining concrete (M20) member by 1mm air gap in order to avoid friction and discontinue load transfer through shear. Wing plate is provided at both ends to facilitate gradual transfer of axial load to steel core. Whole assembly is encased in a steel tube of 3mm thickness and provided with two rigid end plates at both ends. End conditions are provided to be pinned at both ends. The proposed model is then subjected to non linear dynamic analysis using ground motion records of El-centro earthquake (Imperial Valley, 05:35 UTC on May 19, 1940).

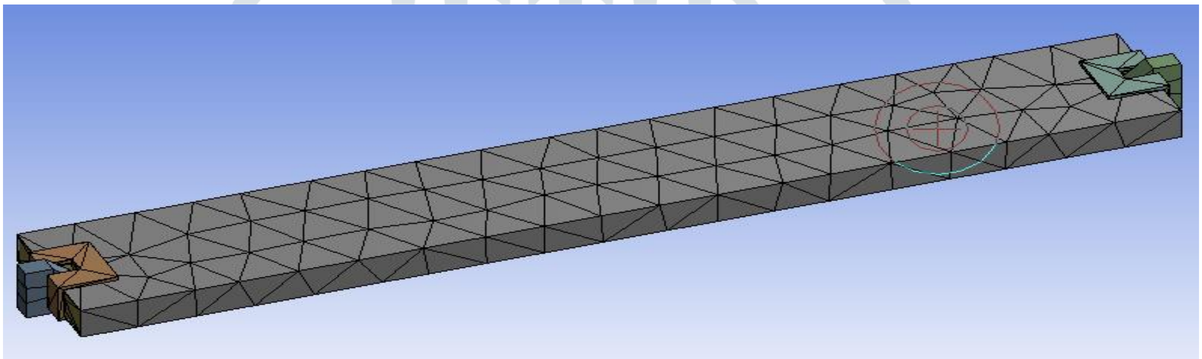

Fig. 2. Finite element model of buckling restrained brace

2.3. Modeling and analysis of SMRF installed with BRB

A bare 10 storey RC frame (SMRF) is modeled with 5 bays of 4 m width in both X and Y direction (without infill walls) as 3D multi degree of freedom system. Storey height is kept to be 3m for all stories including ground storey and bay width is kept to be 4m in each direction. Elevation and plan of SMRF locating positions of BRBFs are shown in Fig. 3 and Fig. 4 respectively. Modeling and design of structure is based on the provisions of IS 456:2000, IS 875:1987, IS 1893:2016(Part 1) and IS 13920:1993. Structure is supposed to be situated in India (Zone IV) on medium soil. Preliminary seismic analysis details are given in Table 1.

Table 1 : Preliminary seismic analysis considerations

Sr No.	Content	Description
1	Seismic zone	IV
2	Importance factors	1.5
3	Soil type	Medium
4	Response reduction factor	5

III. DESIGN PROCEDURE

Structure was first made safe for primary loading and then time history was applied to the structure to obtain design lateral load BRB will be subjected to. Design approach based on cross sectional area of core is used to design BRB under the guidelines of ASCE7-2005 and FEMA 273-1997 as discussed here:

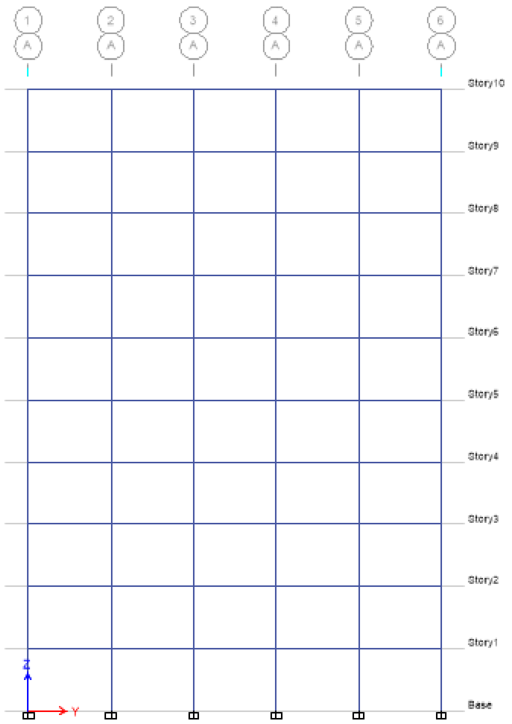

Fig. 4. Elevation of proposed structure

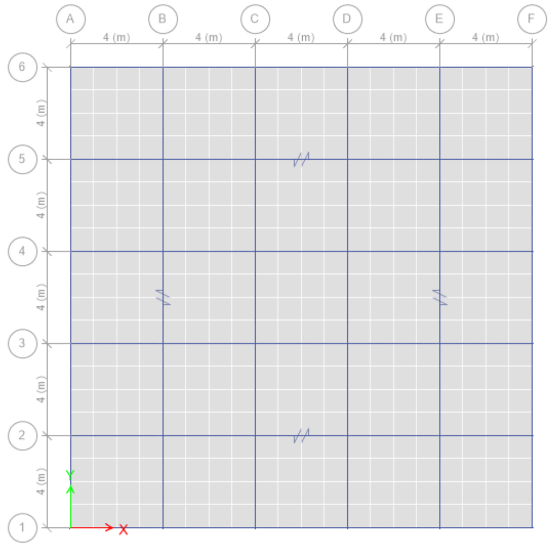

Fig. 3. Plan of proposed structure with locations of BRBFs

Step 1: Design axial force (Pu):
It is said to be demand capacity of BRB which is obtained by indentifying axial force in the mild steel brace member installed in the frame subjected to non-linear dynamic analysis for corresponding time history. It can alternatively be obtained using formula:

$$P_u = \frac{V_u}{\cos\theta} \qquad (1)$$

V_u= Storey shear
Ɵ=Angle of inclination of brace with horizontal
fy= Yield strength of core material

Step 2: Cross sectional area of steel core (Ac):

$$A_C = \frac{P_u}{f_y} \qquad (2)$$

Decide core width (b) and core depth (d). After deciding cross sectional area, compute area of steel provided (Acp) and moment of inertia of section (Ic).

Step 3: Maximum Buckling of the core due to considered axial load
Assume steel core to be axially loaded column with both ends hinged. Calculate crippling load for core by Euler's formula:

$$P_{cr} = \frac{\Pi^2 EI}{l_{eff}^2} \qquad (3)$$

Buckling of the core is then calculated as:

$$\Delta = \frac{M}{P_{cr}} \qquad (4)$$

Where, M is moment at centre caused due to buckling of core and is calculated using flexure formula and Pcr is obtained by Equation (3).

Step 4: Force exerted by buckled core on concrete restraining member is calculated as:

$$W = \frac{48\Delta EI}{l_{eff}^3} \qquad (5)$$

Where Δ is to be obtained from Equation (4)

Step 5: Thickness of concrete member

Thickness of concrete member is then computed by considering a case of thick cylinder subjected to radial pressure exerted due to W calculate in Equation (5).

Step6: Check for core buckling

$$P_{core} = 2\sqrt{\beta EI} \qquad (6)$$

Buckling capacity of core should be greater than axial load it is subjected to (P_u) obtained from Equation (1).

Step7: Check for global flexural buckling

$$P_{global} = \frac{\pi^2 EI_{casing}}{l_{eff}^2} \qquad (7)$$

Global flexural buckling capacity should be greater than axial force it is subjected to (P_u) obtained from Equation (1).

IV. Result and Discussion

4.1 Influences on BRB

4.1.1 Length of core

According to Ziquin et al. [3] the core member length directly influences slenderness of core, obviously affects stiffness of BRB (restraining ratio). Five models of BRB are prepared to understand the influence of length increment on stress functions. In all five models, loading, aspect ratio of core cross sectional area, axial load and support conditions are identical and only variant parameter is length. Stress function results of Equivalent stresses (Von mises), Equivalent strain (von mises) and longitudinal deformation for 5 different models are given in Graphical representation of results in Table 2 is given in Fig. 5.

Table 2: Effect of core length variation

Core length (m)	Equivalent stress (MPa)	Equivalent strain	Longitudinal deformation (mm)
1.5	394.87	0.00199	1.1109
2	419.74	0.00210	1.4359
3	431.25	0.00217	1.9940
4	458.01	0.00233	2.5949
5	481.00	0.00245	3.1955

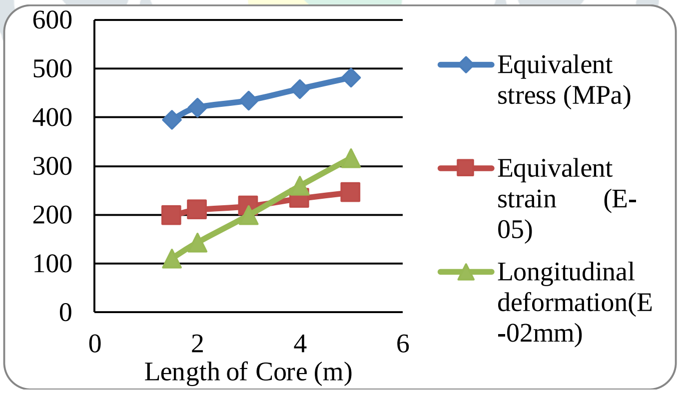

Fig. 5. Influence of length variation on stress functions and longitudinal deflection

Results show that value of equivalent stress has increased significantly from 394 MPa to 481 MPa with increasing length from 1.5m to 5 m respectively. This maximum value of stress is observed at the point of force transfer from wing plate to core of reduced cross-sectional area in all cases. There is remarkable variation in equivalent stain as far as length increment is considered. Equivalent strain varies from 0.00199 to 0.00245. Longitudinal deflection also increases with increase in length significantly. Length of BRB is mainly restricted by geometric and architectural constraints such as floor height, width of bay, forms of bracing to be used etc.

Also, core member length increment remarkably affects stiffness of BRB and thereby has significant impact on core buckling strength and global flexural buckling of BRB as shown in Fig. 6. Adjoining graph expresses the relative reduction in effective stiffness of BRB and global flexural buckling of BRB with respect to yielding length of core. Besides this, longer cores tend to follow multi-wave buckling as compared to shorter one. Thereby increasing the contact force exerted on concrete restraining member and enhancing restraining member thickness demand.

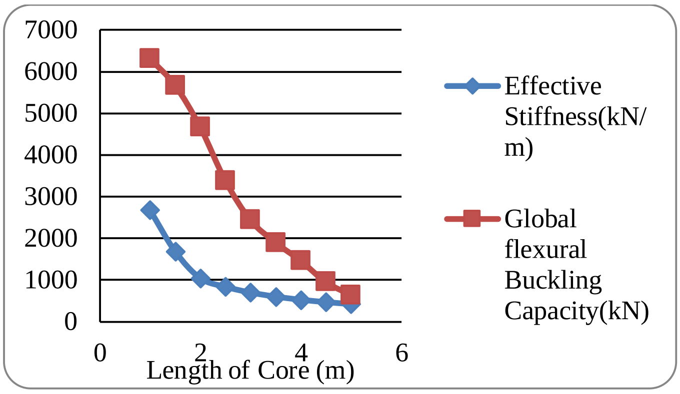

Fig. 6. Influence of core length on Effective stiffness and Global flexural Buckling

4.1.2. Aspect ratio

Being an important design parameter, variation of aspect ratio (width to thickness ratio) significantly affects the BRB performance. Initially the core area required is to be determined from design capacity which is to be followed by finalizing aspect ratio and deciding cross sectional dimensions. Microsoft Excel program is prepared for BRB design procedure based on previously stated design considerations. For various values of aspect ratio, remarkable variation in core buckling waveform and core buckling capacity is observed. Fig. 7 and Fig. 8 include the respective variations in BRB capacity due to change in aspect ratio.

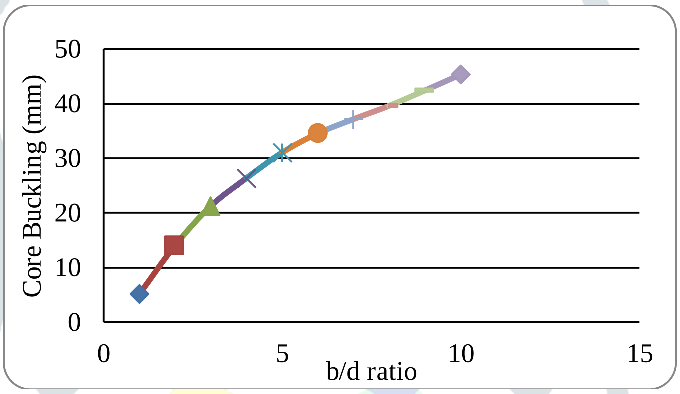

Fig. 7. Core buckling with respect to aspect ratio

4.1.3. Inclination of Brace

Inclination of bracing is usually determined by architectural constrains, viz. bay width and storey height. In spite of this, it can be changed as per requirement providing corresponding eccentricity from beam column junction. Lesser the inclination, more it will contribute to resist lateral loads. In this study, inclination angles at every 50 differences are considered from 250 to 650 and effective stiffness variation pattern with respect to inclination is studied. Related results are shown in Fig. 9.

From Fig. 9 it can be observed that more inclined is the BRB, lesser is its effective stiffness and thereby lesser will be its contribution against earthquake induced lateral loading. Restriction to the lower limit of inclination is provided by bay width and floor height as gusset plate attaching BRB cannot be connected to columns. It is to be attached to either beams or beam-column junction.

4.2. Influence on SMRF installed with BRBs

4.2.1. Time period response

4.2.1.1. Installation of BRB

Fig. 10 shows reduction in time period of vibration of proposed SMRF after application of BRB. It can be observed that time period reduction is approximately 0.48 seconds for first mode of vibration. Buckling of Core with respect to Aspect Ratio vibration and that for the fourth mode is 0.21 seconds. After fourth mode of vibration, variation becomes insignificant.

4.2.1.2. Inclination of Brace

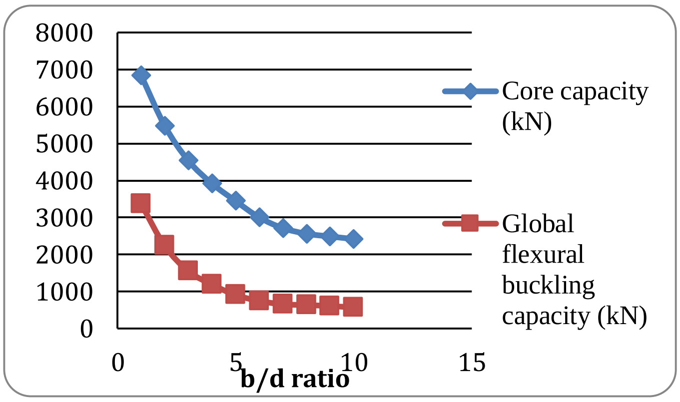

Fig. 8. Core and global flexural capacity with respect to aspect ratio

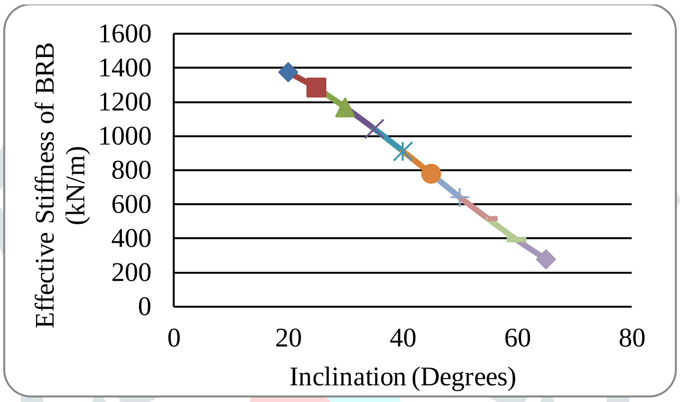

Fig. 9. Effective stiffness of BRB with respect to inclination

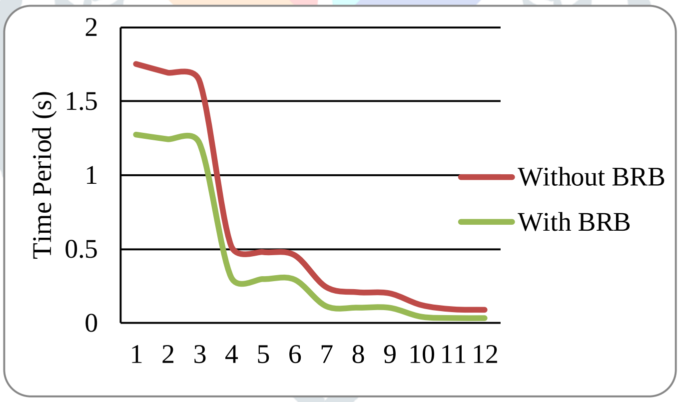

Fig. 10. Time period response on BRB installation

As discussed earlier, flatter installation enhances damping against lateral loads. It is obvious that, higher is the amount of damping, lesser will be the time period. For all previosly stated angles of inclination, response of SMRF was taken into account. Fig. 11 shows time period response of the proposed structure.

4.2.2. Storey Response

Maximum storey displacement is the maximum observed lateral displacement of the top floor at a particular time having the most severe ground acceleration recorded. It is found to be 136.28mm at time instant of 15.6 seconds.Maximum permissible displacement for the structure is 120mm. After application of BRBFs on previously decided locations, displacement of top storey is reduced to 107.5mm which is within permissible limits. Fig. 12 shows reduction in maximum storey displacements.

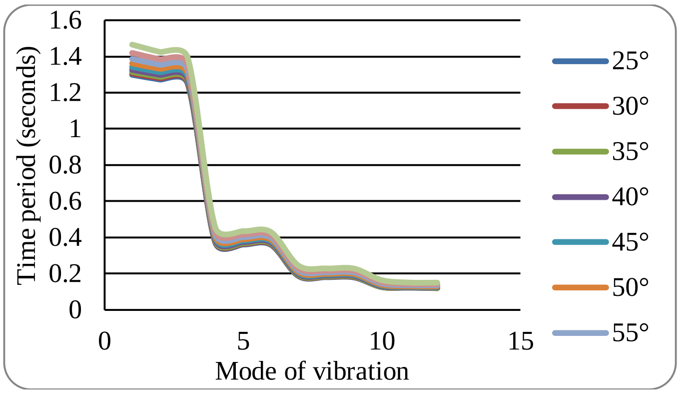

Fig.11. Core and global flexural capacity with respect to aspect ratio

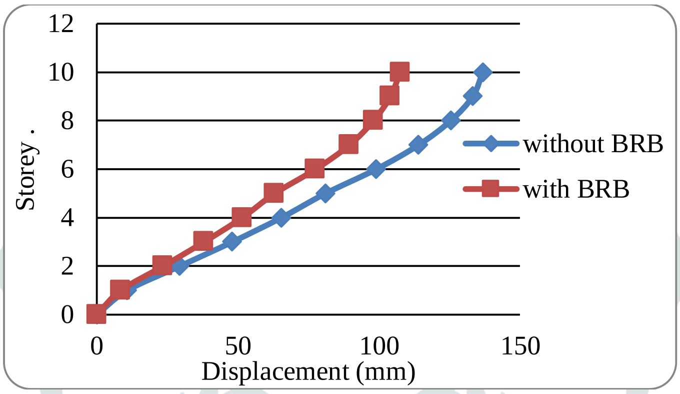

Fig. 12. Maximum storey displacement

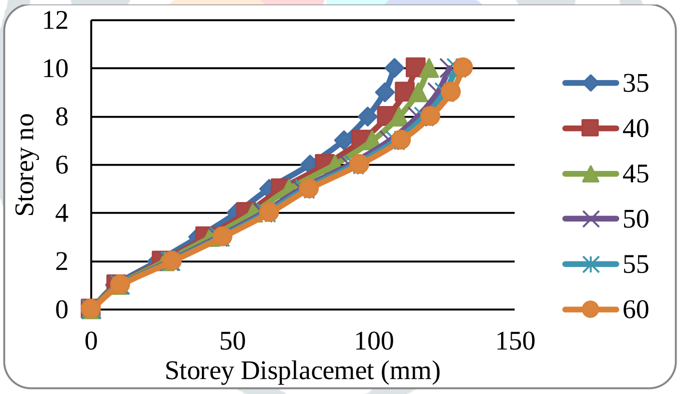

Fig. 13. Maximum storey displacement with various angle of inclinations

Moreover, as discussed earlier, minimum brace inclination results in its maximum contribution as a lateral load resisting system, inclination angles have significant effect on resultant maximum storey displacement. Proposed prototype frame is installed with BRB with various angles of inclination of 35^0, 40^0, 45^0, 50^0, 55^0 and 60^0. Variation pattern of maximum storey displacement in concern with inclination angle is displayed in Fig. 13. Form figure, it is seen that 35^0 inclination allows lateral displacement of 105 mm and that allowed by 60^0 is 131mm which is more than that of allowed by 35^0 inclination but smaller as compared to displacement occurred in the absence of brace, thus, considering BRB contribution is additional damping of the structure.

Along with maximum storey displacements, storey drifts also forms an important criterion that governs seismic performance of the structure. In the present study, storey drift is found to be concentrated at third and sixth storey. Storey drift is the ratio of interstorey drift to total height of the building. After BRB installation, noticeable reduction in maximum storey drifts is observed. Details of maximum storey drifts are shown in Fig. 14 after installation of BRBFs, for all ten stories at the time instant of 15.6 seconds.

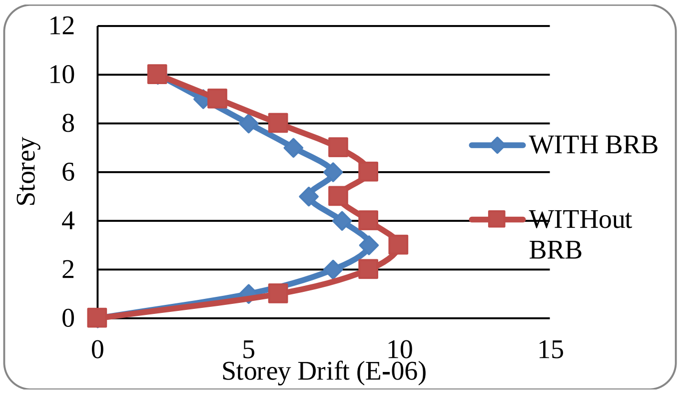

Fig. 14. Maximum storey drift

V. Conclusion

After carrying out analyses described before, following conclusions are obtained:

- If a stress functions criterion is considered, stresses are increased by 22%, strains by 23% and longitudinal deformation by 65% as a result of length increment form 1.5m to 5m.
- Reduction is effective stiffness of core and global flexural buckling capacity is approximately 85% with length hike from 1m to 5m. Thus, length of core is inversely related to load bearing capacity of BRB and it is advised to be kept as minimum as possible overcoming dimensional constraints.
- Aspect ratio is found to be directly related to core buckling and inversely related to that of global flexural buckling capacity of BRB. Maximum BRB capacity is observed at b/d ratio equal to 1. Thus, square cross section is supposed to have more bearing capacity than that of rectangular one.
- Aspect ratio variation is outstanding up to 10. Further increase in aspect ratio doesn't affect the BRB performance significantly as the curve slopes turns to be almost 0.
- Time period of vibration of structure is reduced by 28% for the first mode of vibration. This reduction is found to be more pronounced in first four modes as compared to later one.
- As far as the storey performance of the structure is considered, Maximum storey displacement at top storey and maximum storey drift concentration at third storey is reduced by 28% and 16% respectively.
- Along with length and aspect ratio, inclination of BRB also plays vital role is seismic performance of structure.
- Higher inclination angle reduced BRB contribution in total effective damping of the structure. By increasing BRB inclination from 35^0 to 60^0, reduction in effective stiffness, time period and maximum storey displacement is 73%, 13% and 23% respectively.
- Thus, BRB has proven to be an efficient lateral load resisting component as far as time period and storey responses of the structure, installed with accurately and reasonably designed Buckling Restrained Brace, are considered.

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