BUCKLING RESTRAINED BRACES
FOR VIBRATION CONTROL OF BUILDING STRUCTURE

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ABSTRACT

This paper presents the study of Buckling Restraint Braces (BRB), its analysis, design, modeling and its application in steel building frame. A brief review of work done on BRB is presented and nonlinear time history analysis of 5-story 2D frame is carried using software, SAP 2000 under El Centro earthquake. The response parameters used to evaluate structural performance are natural time period, story displacement, interstory drift, story shear and axial forces. The parameters, length and area of yielding core for modeling the correct behavior BRB are evaluated. Five different types of BRB configuration are studied. It is observed that BRB can be modeled by keeping the area of central core equal to or less than half of end offset area and length of yielding central core equal to 1/3 of total length of brace. Based on the study, new brace configuration is proposed which controls joint displacement over the unbraced and BRB configurations studied.

Key words: Steel frame, buckling restrained braces, roof displacement, storydrift

1. INTRODUCTION

As the population of our country is increasing and land area remains constant, engineers have no option other than going for vertical growth of buildings. As these vertical structures become slender and slender, the effect of earthquake on these structure became ut-most important. These structures are susceptible to collapse or large lateral displacements due to earthquake ground motions and require special attention to limit this displacement. This displacement can be brought into limit by providing the ductility in the structure. This ductile behavior can be achieved by the stable plastic deformation of structural members. To control this lateral displacement, different engineers have used different techniques. A brief review is presented here. Frank Lloyd Wright (1917) used the layer of Talc powder and roller at foundation and received the patent for it. Oka R. (1934) constructed buildings using isolation as roller and sliding system. Kawai proposed the timber log placed in several layers in longitudinal and transverses direction as a base isolation system says Izumi (1988). In 1968, large block of hard rubber were used to isolate three storey building at Skopje, Republic of Macedonia, reported by Jurukovski (1995) [4]. Martel (1929) proposed the concept of flexible first storey for structural isolation of building. Modification to this approach, as a soft first storey was proposed by Fintel and Khan (1969). This concept was shown impractical by Chopra A.K., et al. (1973), since the post yielding stiffness of the columns would have to be impractical if the shear force in the upper storey were to be reduced. Matsushita and Inzuma (1977) proposed a structural system involving a double basement design and special construction over three lower floors involving bearing end device. This study comes under passive control where no external source of energy is required.


According to Soong, Yao at el (1997), put forwarded the theory of active structural control which became the subject of intensive research [17]. Inaud and Kelly (1990) investigated active base isolation with electro hydraulic actuator giving application to four storey building model [7]. Zuk (1968) presented actively controlled structure where external power is required for working of technology. Skinner et al. (1975a, 1975b) led a number of base isolation concept and hysteretic dampers [15, 16]. Kelly (1987) proposed hybrid control strategy consist of base isolation system with active controlled actuator. The work on active structural control includes prestressed tendon to stabilize and control of tall building by cables attached to jacks says Constantinou at el. [1]. Jangid R. S. and Londhe Y. B. (1998) investigated elliptical rolling rods for multistory building to control the displacements [9]. Kelly proposed low cost fiber reinforced seismic isolation system for developed nation in which steel plates are replaced by carbon fiber mesh [10].
Yoshioka H. and Ramalli (2002) proposed smart base isolation system with sponge magneto-rheological (MR) damper for near and far field earthquake [21]. David Mar and Steven Tipping (2002) got patent for story isolation in which the response of gravity frame during earthquake motion is controlled by surrounding reaction frames, with spring and dampers connection in between them [2, 3].

Some different technique to control this displacement is the bracing system in the structure. The bracing system consists of providing the inclined members in the frames of building in addition to the structural members, beam and columns. The conventional braces possess limited ductility capacity under cyclic loading [Tang, 1989] and its hysteretic behavior is unsymmetrical in tension and compression as shown in figure 1. It exhibits strength deterioration when loaded monotonically in compression or cyclically. The design of conventional braces some time may result in the braces selected for some stories stronger than required, while braces in other stories have capacities very close to design targets. The variation in story capacity and some strength losses occurs when some braces buckle prior to others and hence earthquake damage tends to concentrate at few weak stories. Such damage concentration places greater burdens on the limited ductility capacities of conventional braces and their connections.

It has also been noted that lateral buckling of braces may cause substantial damage to adjacent nonstructural elements. Hence a thought was important to avoid the damage by preventing the buckling of conventional braces. During a major earthquake, a large amount of kinetic energy is fed in to a structure. The manner in which this energy is dissipated, determines the level of damage. All building codes recognize that it is not economically feasible to dissipate the seismic energy within the elastic capacity of the materials. The common strategy is to accept the structures yielding, by ensure that yielding occurs at controlled location and ductile manner. The underlying idea is that a successful ductile structure is one in which yielding occurs in designated elements or structural fuses, limiting the build-up of forces in the structure.

In traditional braced frames, the braces are the structural fuses. They yield in compression and tension and absorb energy. However, buckling in compression leads to a sudden loss of stiffness and progressive degrading behavior which limits the amount of energy dissipation. Several attempts have been made to resolve this buckling problem. However, these were unsuccessful until Professor Wada [19, 20] and his team put forth the concept of BRB. The theory of BRB is explained below.

2. THEORY OF BRB

Prompted by the observations and concerns, seismic design requirements for braced frames have changed considerably and the concept of BRB frames has been introduced in which buckling of braces is prevented [19,20]. Different parts of BRB shown in figure 3 are sleeve and core. The core consists of central yielding zone, C (reduced section) and transition zones, B and A (larger area than the yielding zone and similarly restrained) on either side of yielding zone; and connection zones that extend past the sleeve and connect to the frame, typically by means of gusset plates.

The sleeve is the outer part of BRB which covers the core. The basic principle in the construction of BRB is to prevent buckling of a central steel core by encasing it over its length in a steel tube filled with or without concrete or mortar. BRB provides a slip surface between the steel core and the surrounding concrete, so that axial loads are taken only by the steel core. The materials and geometry in this slip layer must be carefully designed and constructed to allow relative movement between the steel element and the concrete due to shearing and Poisson’s effect, while simultaneously inhibiting local buckling of the steel as it yields in compression. In BRB, the basic structural framework is designed to remain elastic during seismic response and all the seismic damage (yielding) occurs within the braces. This class of steel braces dissipates energy through stable tension-compression yield cycles as shown in figure 2. The comparative buckling behavior of conventional brace and BRB is shown in figure 4. The concrete and steel tube encasement provides sufficient flexural strength and stiffness to prevent global buckling of the brace, allowing the core to undergo fully reversed axial yield cycles without loss of stiffness or strength. The concrete and steel tube also helps to resist local buckling. The stable hysteretic behavior of a properly detailed BRB contrasts with the behavior of bracing elements in typical conventional braced frames (CBFs). The BRB has ability to independently control strength, stiffness and yield displacement or ductility by varying the cross-sectional area of the steel core, the yield strength of the steel and the length of the core which is allowed to yield. The invention on BRB started in early 80’s and its testing took place in mid 80’s. It was implemented in Japan in 90’s. Because of its good response, this technology was transferred in US in 1998 whose testing and simulation took place in 1999 and then safely implemented in important projects after 2000 [5]. The development of BRBd is shown in figure 5. The use of BRB at some important project is shown in figure 6.
Figure 1. Hysteretic loop for conventional braces

Figure 2. Hysteretic loop for BRB

Figure 3. (a) Schematic diagram and behavior of BRB, (b) Parts of BRB (after Rafael Sabelli, and Walterio López)

Figure 4. Buckling behavior of (a) conventional brace and (b) BRB [after Read Jones Chrostoffersen]

Figure 5. Development of BRB

Figure 6. (a) Osaka international convention centre, Japan, (b) UC Davis plant and environmental facility, California (after Eric K O, Arup, San Francisco)
2.1. Advantages of BRB

By contrast, buckling-restrained braces (BRBs) do not exhibit any unfavorable behavior characteristics of conventional braces. BRBs have full, balanced hysteretic behavior with compression yielding similar to tension-yielding behavior. They achieve this through the decoupling of the stress resisting and flexural-buckling resisting aspects of compression strength. The steel core resists axial stresses. Because the steel core is restrained from buckling, it develops almost uniform axial strains across the section. The plastic hinges associated with buckling do not form in properly designed and detailed BRBs. The BRBs permit very high compression strength. Because there is no reduction in the available material strength due to instability, the effective length of the core can be considered zero. By confining inelastic behavior to axial yielding of the steel core, the brace can achieve great ductility. The ductility of the steel material is realized over the majority of the brace length.

Thus, the hysteretic performance of these braces is similar to that of the material of the steel core. Braces with core materials that have significant strain hardening also will exhibit strain hardening. Because the strains are not concentrated in a limited region such as a plastic hinge, the braces can dissipate large amounts of energy. Testing has established the braces low-cycle fatigue life; this capacity is well in excess of demands established from nonlinear dynamic analysis. Such analyses also show that using braces with this type of hysteretic behavior leads to systems with very good performance. Drifts are expected to be significantly lower than the specially concentric braced frame (SCBF) due BRBs behavior. First, inelastic demands are distributed over multiple stories due to the ability to provide uniform brace demand-to-capacity ratios. Second, BRBs are not subject to fracture under the demands imposed by the considered earthquakes when they are designed according to current U.S. practice. BRBFs response to seismic loading provides a much higher confidence level in adequate performance than does the behavior of concentrically braced frame (CBF). Analytical studies of the response of BRBF also have been used to estimate the maximum ductility demands on BRBs. BRBs must be designed and detailed to accommodate inelastic deformations without permitting undesirable modes of behavior, such as overall instability of the brace or bearing of the non-yielding zones of the core on the sleeve.

3. DESIGN OF BRBS

Buckling-restrained braced frames (BRBF) are designed using equivalent lateral force method. As in the design procedure for other CBF types, a reduced seismic load is applied to a linear elastic model to determine the frames required strength and stiffness. For common building types, this system tends to be governed by strength. For BRBF with braces proportioned according to this method, the difference between the elastic and inelastic deformation modes is much less dramatic than for CBF. Because of this, an inelastic (nonlinear) analysis typically is not required, although such an analysis can give a much better estimation of brace ductility demands. Typically, frames are modeled using software or by hand, as seismic loads are resisted by axial forces in the frame and bracing members. It should be noted that beam-column connections are fully restrained. Explicit modeling of the gusset plate is not necessary for typical design. However, modeling it as a rigid offset is helpful: The performance of connections requires more research. The brace connections to the gussets can be a fixed or pinned type. Braces with sufficient ductility (both maximum and cumulative) to withstand the demands of seismic loading are required for the analysis to be valid. To ensure this degree of ductility, brace designs are based on successful tests, which exhibit stable hysteretic behavior with only moderate compression over strength while demonstrating the required ductility and dissipating a specified amount of energy. Once BRBs have been designed for adequate strength, other frame members can be designed using capacity design principles. The forces corresponding to the maximum expected that the braces can develop for their expected deformations are used as the required strengths of beams, columns and bracing connections. These maximum expected brace forces can be significantly higher than the brace design force due to over sizing of the brace for stiffness, use of a resistance factor, brace-compression over strength and most significantly, the strain hardening of the brace at large deformations and under repeated cyclic inelastic loading. The design of BRBF is not governed by any building code but recommended provisions are available. A Structural Engineers Association of California (SEAOC) group developed the recommendations. Researchers and manufacturers have developed several types of BRBs commercially available in the United States.

Braces can have a single steel core or multiple cores in single- or multiple-jointed sleeves. Cores can be a single plate, rod, reduced shape or built-up section; core orientation also can be varied. Sleeves can be bare steel, concrete or a combination of the two. Several methods of preventing stress transfer to the sleeve also have been developed. Since use of any BRB is predicated on successful testing, all BRB types are admissible. BRBF can have braces in many configurations. Because there is no strength or stiffness degradation permitted in the braces and because the tension and compression strengths are almost equal, the single-diagonal configuration is permitted without any penalty. K-bracing is not permitted. The chevron (V or inverted V) configurations are popular for BRBF as it maintains some openness for the frame. Because of the balance between brace tension and compression strength,
the beam is required to resist only modest loads; a deflection limit also is imposed to prevent excessive vertical beam displacement. Other configurations of BRBF are possible. BRBs can also be combined with conventional braces as long as designers confine the ductility demands to the BRBs. It can be used in new construction as well as for upgrading the existing buildings with poor ductility where additional stiffness, strength and energy dissipation is needed.

The required cross sectional area of the yielding portion of the brace is then calculated as

$$A_{br} = \frac{F_{br}}{\Phi F_y}$$  \hspace{1cm} (1)

Where, $F_y$ is yield strength of the brace steel material and $\Phi$ is the strength reduction factor, 0.9.

Since the yielding portion of BRB has a substantially smaller cross section as compared to end section, most of the elastic and inelastic deformations take place therein. Considering this, the elastic axial stiffness ($K_{br}$) of BRB is approximated as

$$K_{br} = \frac{EA_{br}}{L_{br}}$$  \hspace{1cm} (2)

The axial strain of the yielding portion is expressed as

$$\varepsilon_{br} = \frac{\delta_{br}}{L_{br}}$$  \hspace{1cm} (3)

Where, $\delta_{br}$ is axial deformation and $L_{br}$ is length of BRB.

Steel with yield stress, 250 N/mm$^2$ and ultimate stress, 400 N/mm$^2$ (i.e. Grade A36 and Gr58) is used for all beams, columns and braces. The stress- strain behavior for the steel material is shown in figure 7 and hysteretic behavior assumed is kinematic. Frame exhibits behavior under lateral loads assuming that the design is governed by lateral stiffness criteria rather than by member strength requirements. In design optimization process, the structure is first analyzed with members taken to have their minimum limiting sizes for both columns and beams. Such original design tends to be too flexible in terms of lateral stiffness requirements. The bare model was designed according to FEMA guidance [6]. Drifts under design forces were calculated, but not used to limit the design. The buildings were designed consistent with seismic use group I and seismic design category D with an importance factor of 1.0 and site class D (firm soil). Beams connecting to braces at their mid-span were designed for the maximum expected unbalance force from the braces. The compression strength was assumed to be 10% larger than the strength in tension.

The columns were designed using the over-strength amplification factor applied to forces rather than computing the maximum forces that could be delivered to the frame system based on the actual capacity of the braces. Braces were designed for the force calculated based on the computed equivalent static base shear. Brace sizes were set to within two percent of the computed required cross-sectional area (based on a nominal yield stress of 250 MPa for the yielding core); strength reduction factor of 0.9 was used. For BRB, stiffness was calculated assuming a yielding length as 33% of the brace length and cross-sectional area as 50% of non-yielding zone which is arrived after results of analysis.

![Figure 7. Stress-strain behavior for steel material (SAP 2000)](image)

4. MATHEMATICAL MODELING

Mathematical modeling plays very important role in representing true behavior of structure in assessing its performance. Here the modeling of bare steel frame, conventional braces and BRB is explained using SAP 2000 [13]. Beams and columns were modeled using element type 2. This element allows axial load bending moment interaction, but with no stiffness or strength degradation. A slab is modeled as a plane strain area element. A beam
to column connections with gusset plates attached were modeled as fixed one. The columns were modeled as having a fixed base with foundation. Braces were modeled as pin-ended members. A conventional brace element is prismatic and hence can be easily modeled. BRB are modeled as non prismatic element. The central yielding portion of BRB has less cross sectional area than the end offset area. So different sections were first defined and then assigned to form the non prismatic section to perform as a BRB. The yielding lengths and proportion of area of end offset for BRB is studied and decided. A separate study is made for the same. The masses source used in the analysis to account for horizontally acting inertia forces was taken to be contributing from load and floor mass. Horizontal and vertical ground excitations were considered with global P-δ effects based on the mass.

Lateral loading used for analysis is the time history of three x, y and z component of El cento 1940 earthquake. The load combinations for Dead Load (DL), Live Load (LL), Earthquake Load (EQ) and/or Wind loads (WL) as per IS 1893- 2000 [8] are: a) 1.7(DL+LL) b) 1.7(DL ± EQ) and c) 1.3(DL+LL±EQ). To find the maximum response parameter, the possible combination of the three components of time history was considered by adding 30% responses from the other two components in the major direction’s response.

5. STUDY EXAMPLES

The five configurations of BRB used in this study are shown in figure 8. The analyzed and designed steel frame without and with braces is shown in figure 9 (a, b) and proposed new configuration based on the study is shown in figure 10. The frame has typical story-height 3.5m, bay width 6 m, floors and roof slab thickness 100mm, Live Load 6 kN/m² and critical damping 2% (steel structure). The columns are continuous for their full height. For practical consideration, sizes of external and internal beam section are assumed constant. Table 1 shows summary of final sections used for analysis and design of this frame.

![Figure 8. Bracing Configuration](image)

<table>
<thead>
<tr>
<th>Model description</th>
<th>Section for</th>
<th>All column section</th>
<th>All beam section</th>
<th>Braces size/s at yield zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare model (no Braces)</td>
<td>Analysis</td>
<td>W18x76</td>
<td>W18x76</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Design</td>
<td>W18x76</td>
<td>W18x76</td>
<td>--</td>
</tr>
<tr>
<td>Conventionally Braced model</td>
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<td>W18x76</td>
<td>W18x76</td>
</tr>
<tr>
<td></td>
<td>Design</td>
<td>W18x76</td>
<td>W12x65</td>
<td>W12x65</td>
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<tr>
<td>BRBd model</td>
<td>Analysis</td>
<td>W18x76</td>
<td>W18x76</td>
<td>W18x76</td>
</tr>
<tr>
<td></td>
<td>Design</td>
<td>W18x35</td>
<td>W18x35</td>
<td>W18x55</td>
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</table>

6. RESULTS AND DISCUSSION

The results in this paper are divided into two parts. First part presents the results of correct modeling of BRB which are based on the control of roof displacement and interstory drift. Second part presents the results of response of unbraced and braced frames with different BRB configurations shown in figure 8. The response of these frames is found in terms of peak roof displacement, interstory drift for the frame and axial force, shear force and bending moment of the members.

During modeling, each BRB is divided into three parts: central yielding portion and two ends as end offset portion. The conventional braces have constant area (A) for yielding and end offsets portions. The BRBs are modeled by varying the end offset area and keeping yielding central area (A) constant. The comparison is made to propose the suitable brace configuration mentioned above for response control of frame. Figure 9 shows representative frames.
and their deformation in the 1st mode for bare frame and cross BRBd frame. Based on the study and response of BRB, the new configuration is proposed as shown in figure 10.

The interstory drifts for bare and BRBd frame is determined and presented in tabular form. As compared to bare frame, conventionally braced frame has less roof displacements in all brace configurations studied. From the literature it is learned that BRB is more effective over the conventional braces, hence an attempt was made to use the BRB for the same frame under study.

To rely upon the results of BRBd frame, it was necessary to model the BRBs correctly. Modeling of BRBs is based on its appropriate length of yielding zone and its cross sectional area. Figure 11 shows the representative frame with story drift against the story levels in case of cross BRBd frame for variable yield length portion of BRB. During modeling, central yielding length of BRB was varied from 33% to 100% of total length by keeping the area of yielding and end offset length constant. Hence this was as good as conventional brace. Figure 11 shows that for the yielding length between 33 to 67% of total length of BRB, story drift is reduced uniformly. The roof displacements in case of BRB frame are less than conventionally braced frame. Roof displacement for BRBd frame modeled in this way is least in all brace configurations assumed in this study.

Once the length of yielding portion was decided as above, further modeling of BRB is done with fixed length of central yielding zone as 1/3rd of total length of BRB and varying the area of end offset and keeping area of yielding portion constant. During this modeling, the yielding area, A, was constant and end offset area was varied from 50 to 600% of yielding cross sectional area. Figure 12 shows the plot of story drift along story level for different area. This figure 12 shows that story drift is reduced and figure 13 shows that drift remains uniform for end offset area more than twice the area of yielding core.

Another parameter observed is the joint rotation drift to assess the tendency to concentrate damage in a floor, and to place significant flexural demands on the columns and beams for adjacent stories for a floor level. Table 2 shows the peak roof displacement, roof rotation and time period for the BRBd frame with constant yielding length, 1/3rd and variable end offset area. The roof displacement of frame braced with BRB with end offset area less than yielding core area is least. Its time period is also more. For the model with BRBs, end offset area more than double of yielding core area, roof displacement, joint rotation and time period is observed to be constant. Similar results are also observed for other BRBd frame modeled in this way.
Figure 13. Effect of area of end offset, as a % of central yield portion on story drift

Table 2. Parameters of frame with cross BRB (constant yielding length, 1/3 and variable end offset area)

<table>
<thead>
<tr>
<th>Roof joint displacement of frame, mm</th>
<th>Roof-rotation of frame, rad/sec</th>
<th>Time period, sec</th>
<th>End offset area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T&lt;sub&gt;1&lt;/sub&gt;</td>
<td>T&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>14.10</td>
<td>0.00032</td>
<td>0.283</td>
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<td>24.55</td>
<td>0.00075</td>
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<td>0.071</td>
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<td>17.60</td>
<td>0.00066</td>
<td>0.239</td>
<td>0.07</td>
</tr>
<tr>
<td>14.80</td>
<td>0.00063</td>
<td>0.234</td>
<td>0.07</td>
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<tr>
<td>14.40</td>
<td>0.00068</td>
<td>0.232</td>
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<td>13.31</td>
<td>0.00062</td>
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<td>0.069</td>
</tr>
<tr>
<td>13.40</td>
<td>0.00061</td>
<td>0.229</td>
<td>0.067</td>
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</table>

Table 3 shows the peak roof displacement, roof joint rotation and time period for the BRBd frame with variable yielding length and constant end offset area, 2A. The roof displacement of cross BRBd frame braced with BRBs yielding length more than 1/3<sup>rd</sup> is least. Its time period is also less than the time period of bare and conventionally braced frame. For the model with BRBs constant end offset area and variable yielding length, the roof displacement, joint rotation and time period is observed to be constant. Similar results are also observed for other BRBd frame modeled.

Hence from the study of figure 11, 12 1nd 13 and table 2 and 3, it is concluded that BRB can be well modeled with yielding length more than or equal to 1/3<sup>rd</sup> length of BRB with cross sectional area, A and end offset area, 2A. Further study is based on the modeling the BRBs in this way.

Table 3 Parameters of frame with cross BRB (constant offset area, 2A and varying yield length)

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Name of the model</th>
<th>Roof displacement, mm</th>
<th>Roof joint rotation, rad/sec</th>
<th>Time period, sec</th>
<th>Yield length</th>
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<tr>
<td>1</td>
<td>No brace model</td>
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<td>2</td>
<td>Cross conventional braced</td>
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<td>3</td>
<td>Cross BRBd model</td>
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<td>0.00066</td>
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<tr>
<td>4</td>
<td>Cross BRBd model</td>
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<td>5</td>
<td>Cross BRBd model</td>
<td>17.1</td>
<td>0.00066</td>
<td>0.239</td>
<td>0.07</td>
</tr>
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</table>

Table 4 and 5 show comparative story displacements and interstory drift for unbraced frame and frame braced with conventional bracing and BRBs used in the study. The roof displacement and story drift for all conventionally braced frames is much less than frame with no brace. In all brace configurations, the story displacements and interstory drift for BRBd frame is least for the frame with no brace and conventionally braced. From these tables, it is observed that inverted bracing system is found to be most effective of all concentric braces.
Table 4 - Story displacement (mm) of frame with different BRB configuration in single story

<table>
<thead>
<tr>
<th>Story Level</th>
<th>Bare Model</th>
<th>V Bracing</th>
<th>Inverted V Bracing</th>
<th>Forward Bracing</th>
<th>Backward Bracing</th>
<th>Cross Bracing</th>
<th>New Brace configuration</th>
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<td>4.61</td>
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<tr>
<td>1</td>
<td>12.28</td>
<td>2.71</td>
<td>1.076</td>
<td>3.03</td>
<td>4.78</td>
<td>1.17</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 5 - Interstory drift (%) of frame with different BRB configuration in single story

<table>
<thead>
<tr>
<th>Story Level</th>
<th>Bare Model</th>
<th>V Bracing</th>
<th>Inverted V Bracing</th>
<th>Forward Bracing</th>
<th>Backward Bracing</th>
<th>Cross Bracing</th>
<th>New Brace configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.996</td>
<td>0.626</td>
<td>0.257</td>
<td>0.702</td>
<td>0.714</td>
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<td>0.492</td>
<td>0.198</td>
<td>0.580</td>
<td>0.604</td>
<td>0.217</td>
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<td>0.131</td>
<td>0.424</td>
<td>0.463</td>
<td>0.149</td>
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<td>0.202</td>
<td>0.077</td>
<td>0.251</td>
<td>0.302</td>
<td>0.085</td>
<td>0.084</td>
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<tr>
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<td>0.077</td>
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<td>0.086</td>
<td>0.136</td>
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Figure 14 to 17 shows the comparative response of unbraced frame and frame braced with different BRBs. Representative comparative response of unbraced frame and frame braced with V and inverted V type braces are plotted and shown in figure 14 and 15. Figure 16 and 17 shows the roof displacement and interstory drift for frame braced with different BRB configurations.

Figure 14. Interstory drift Vs. story level for 5-story 2D frame braced with V-bracing

Figure 15. Interstory drift Vs. story level for 5-story 2D frame braced with inverted V-bracing

Figure 16. Roof displacements vs. story level for 5-story 2D frame braced with for different BRB

Figure 17. Inter-story drift vs. story level for 5-story 2D frame braced with for different BRB

7. CONCLUSION

The seismic response of steel frames braced with buckling restrained braces (BRB) has been studied. The important parameters associated while modeling the BRB are the length of yielding zone and end offset area of BRB. Study in the paper shows that by keeping the cross sectional area of end offset more than twice of yielding zone and yielding length as 1/3rd of total length, the BRB can be well modeled and gives good control over story displacement and story drift. Following are the concluding remarks drawn from the study.
• Length of the central yielding zone of BRB is 67 to 84% of the total length of brace.
• Buckling restrained brace are non prismatic section. The end offset area of BRB can be maximized as a percentage of the area of yielding cross section. This area should be more than 200%.
• Reduction in roof displacement by V type BRB is 68.64%.
• Reduction in roof displacement by inverted V type BRB is 87.12%.
• Reduction in roof displacement by forward diagonal type BRB is 64.84%.
• Reduction in roof displacement by backward diagonal type BRB is 64.23%.
• Reduction in roof displacement by cross diagonals type BRB is 86.04%.
• Reduction in roof displacement by new BRB proposed configuration is 87.38%.

Thus, buckling restrained bracings provides good control for the roof displacement as compared to the bare frame (frame with no braces). The frames with poor or insufficient stiffness can be retrofitted with addition of such bracing to control the roof displacements and resist the lateral loads. The BRBs are also the reliable and practical alternative to enhance the earthquake resistance of existing and new structures. Bracings are capable of providing both the rigidity needed to satisfy structural drift limits, as well as a stable and substantial energy absorption capability. They are also simple to attach in the frame and cost effective and very easy to install in site. The research and implementation of the BRB is an excellent example of global engineering and collaboration between manufacturers, designers and the building owners.

8. ACKNOWLEDGEMENTS
The author is thankful to BCUD, University of Pune for providing the grand under research proposal scheme.

9. REFERENCES