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The Effect of Column Location and Bracing on Progressive Collapse of Steel Structures

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ABSTRACT: During their service lives, the buildings may be exposed with natural or human-made threats. Considering the shock nature of the loads caused by explosions or seismic events, it is likely that columns are eliminated suddenly when being subject to these loads and lose their bearing capacity. Some structural elements are particularly important to reduce collapse progressive mechanism. Bracing elements are thought to be effective in preventing structural collapse. Among modern bracing types, buckling restrained brace (BRB) is a type of bracing commonly used in structures. These kinds of braces have similar behavior in tension and compression. Therefore they have high likelihood of attracting energy through submitting brace in tension and compression and are commonly known as hysteretic dampers. This paper investigates the performance of structures after middle and corner column eliminated and how the presence of braces redirect the load path preventing total collapse of the structure. Pushover analysis is used on a steel structure that is equipped with BRB. The structure is designed based on the sixth and tenth chapters of Iranian National Building Regulations.

Keywords: Buckling restrained brace, Collapse, Pushover Analysis.

1 INTRODUCTION

The safety of structure is always important as a principle for engineers who are responsible for designing civil projects. One of the mechanisms which have received attention in recent decades is the progressive collapse due to an external incident where one or a couple of elements of structure suddenly collapse resulting in the progressive collapse of the structure. Noticing progressive collapse was first created in engineering community because of local failure of Ronan Point 1 building in London in 1968. Events of 11 September, 2001 drew more attention as driving force. Various committees have investigated this issue and revised it and have proposed their standards against progressive collapse. These committees include America Department of Defense (DOD), general service administration of America (GSA) and European regulations. [1]

Therefore, a definition which is proposed for progressive collapse is: when one or some members of structure collapse and as a consequence the damage of other structural elements are caused, one after another until a new mode of structural interaction and load path is created leading to total eventual collapse of the structure [2].

Dividing the designing strategies against progressive collapse have been appeared and include three attitudes for reducing progressive collapse. This division is as follows:

1- Specified local resistance and protective non-structural measures (event control)
2- An alternative route of load
3- Designing rules

First and second attitudes are directly referred while the third one is indirectly referred. In terms of local resistance, key vertical load-bearing elements are specifically designed to be able to resist against predicted dangers such as explosion or firing loads. Designing key elements require developed analytical technique for calculating structure non-linear dynamic behavior. The attitude of alternative load route is used in designing structure so that the tensions can be distributed based on open vertical load-bearing elements. Simplifying is acceptable for designing process and assuring of the existence of alternative route. The range of this method includes linear static analyses, non-linear static analyses till linear or non-linear dynamic analyses. The attitude of alternative load route has been chosen by various standards such as general repairs of the Department of Defense. Both two organizations have published the guidelines which specify the details of calculation methods completely. In third attitude the related rules to node loads are used which are proposed by European code, English standard and the department of defense. The goal of these regulations is assuring appropriate connection between horizontal and upright components so that the structure has the ability to transfer from destroyed column with chain effects. [3]

2 BUCKLING RESTRAINED BRACED

Buckling restrained braced has been used in this study as lateral load-bearing system which has more appropriate performance at the time of applying lateral loads such as earthquake. Therefore many researches have been done for optimizing these braces for achieving an ideal Elasto-plastic behavior. For achieving this goal, compressive buckling of brace was necessary to be prevented by a suitable mechanism and the possibility of steel compressive yielding be provided. The method which was considered included enclosing a ductile steel core among a volume of concrete which is surrounded by a mental membrane. The main basis of this damper performance is preventing the occurrence of steel core buckling in order to the occurrence of compressive yielding in it and as result the possibility of absorbing energy in this member of structure. This case will be possible through covering all over the steel core length in steel pipe filled with concrete or mortar. This system requires providing a sliding surface or discontinuity layer between the metal core and confining concrete. The behavior of frames with Buckling Restrained bracings, in spite of appearance similarity, is very different from frames with common braces. In Buckling Restrained braces system, hysteresis loops have been sustainable ones and cannot be seen during numerous loading cycles, decline in strength and stiffness of system. [4]

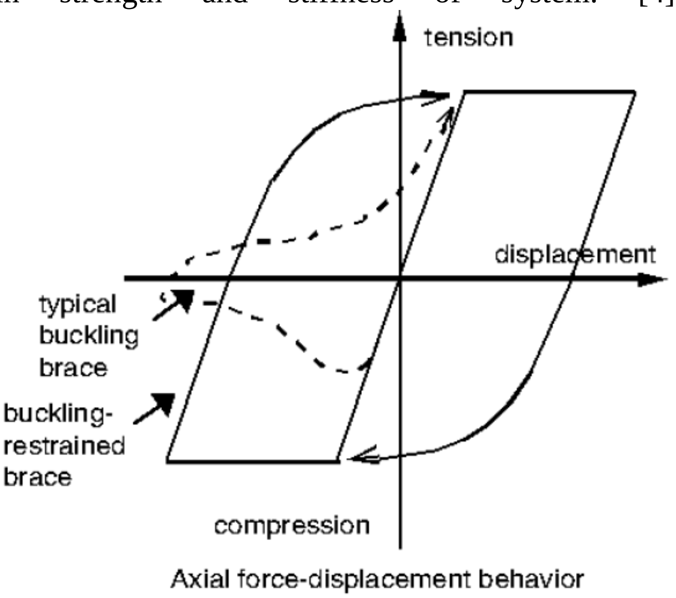

Figure 1. Cycle behavioral comparison of buckling restrained brace and usual brace.

Because the structure is equipped with buckling restrained brace, the cross section of steel core in BRB has been considered equal with the usual ones' and also considering 0.33 ordinary length of braces as the core of yielding length of BRB, core hardness of these members has been considered as 1.5 [9].

Since SAP software is for modeling as macro, so it cannot be expected to show buckling brace. Therefore with this assumption modeling concrete part of BRB is not necessary.

In fact considering and modeling the concrete and creating a cross-section including that with each kind of material, SAP software considers concrete part also as cross-section and forces it and this is against the hypotheses of BRB which shouldn't contribute with concrete in load-bearing. So considering and defining steel core for defining the cross-section of BRB are adequate and correct in SAP [13].

3 MODELING

In this research, braced three-dimensional three-floor building have 3 spans of 5 m in length x and y directions and raster particle beams and the height of each floor as 3.2 meter were analyzed by Pushover in SAP2000 [13] based on instruction FEMA-356 [5]. Building use is residential and the type of soil is III. Considering the sixth and tenth topics of National Building Regulations [9] and [10] and 2800 standard [11] are designed. Dead load of floors 5 kN/m^2 and live load of roof 1.5 kN/m^2 and live load of floors 2 kN/m^2 and the load of lateral walls 2.1 kN/m and also mound load has been considered as 0.74 kN/m.

In the trend of analyzing, common standards of GSA have been used in software environment for choosing the way of special loading for structures. According to mentioned regulation, in accomplishing non-linear static analyses, progressive collapse of specified load applied to structure should be determined through equation (1):

$$G_N = \Omega_N(1.2D + 0.5L \; or \; 0.25\,S)) \qquad (1)$$

Where D loads are dead surface wide and L load live and S load snow and Ω_N is obtained for steel frames. The value of Ω_N in this research has been obtained as 1.1

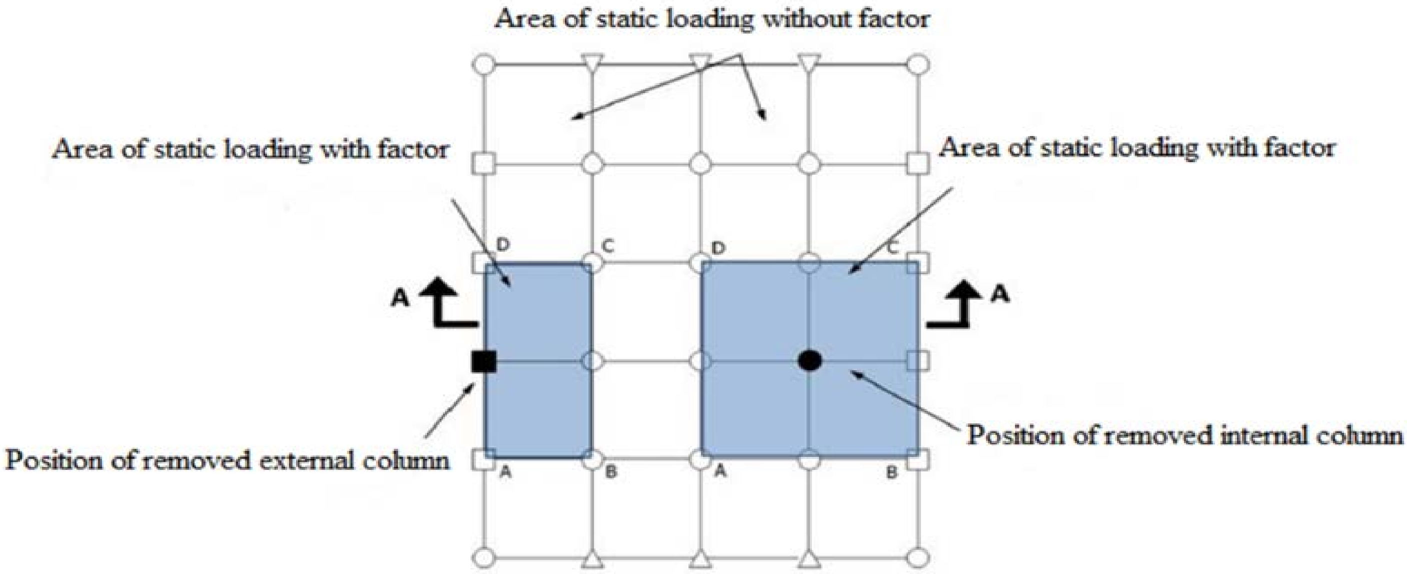

Figure 2-a. Special loading in static analyses in view of plan.

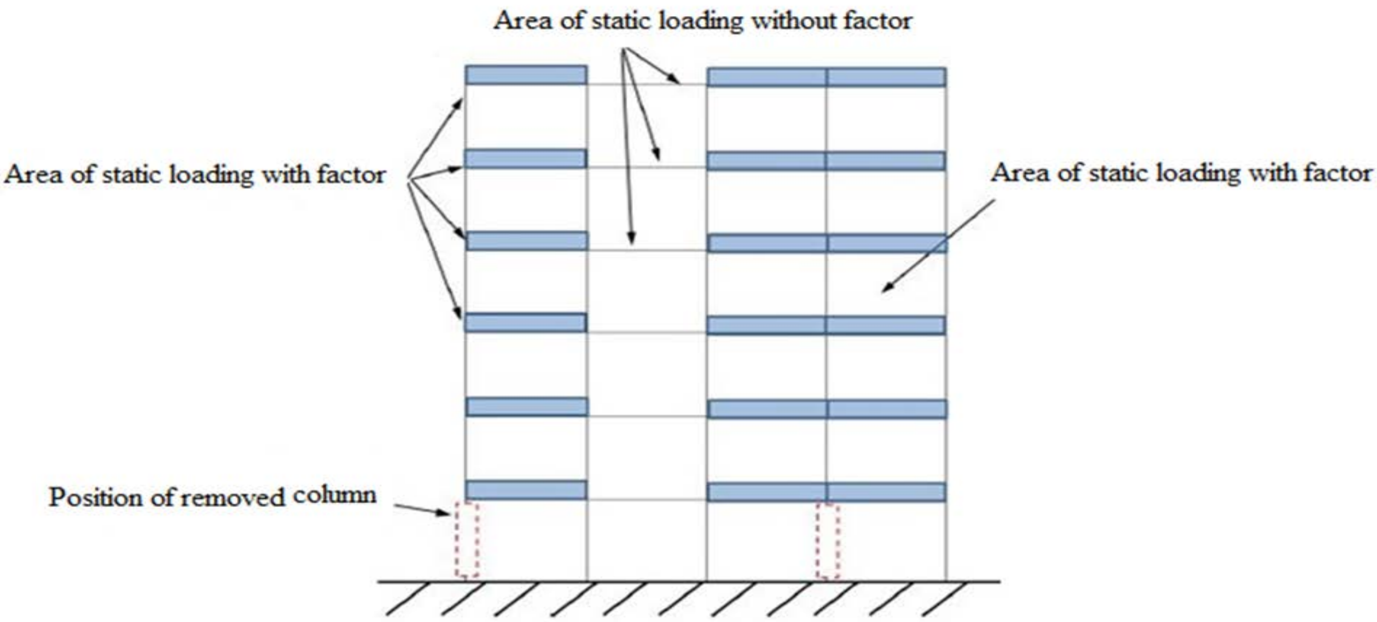

Figure 2-b. Special loading in static analyses in shear view

3.1 *Introducing the joints of plastic*

All plastic joints in model are defined based on the rules of FEMA-356 regulation [5] and force-change curve, which has been shown in figure 3, is used for defining non-linear behavior of members with controlled behavior by deformation in software a deformation. The effects of strain hardening have been considered as reactionary part dip considering a depth equal to 3 percent.

Defined non-linear joints for columns, interactional joint P-M3 at the beginning and ending of the columns' lengths, for beams moment joint M3 in 0.05 and 0.95 beam length and for braces core joint P at the beginning and ending of bracing length have been introduced. [12]

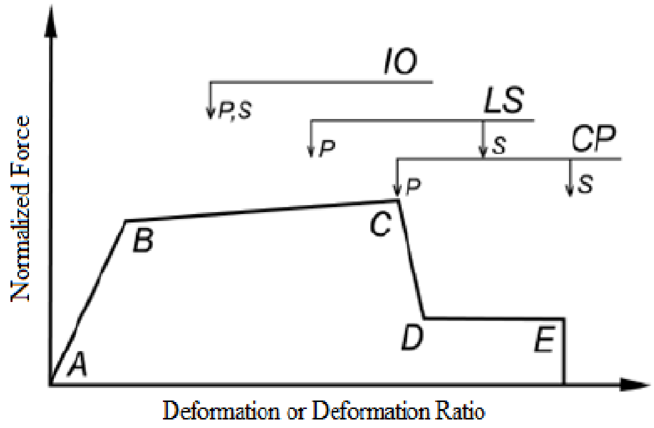

Figure 3. Generalized force-deformation relationship for components

Discrete hinge properties for frame elements are based on FEMA-356 criteria as per Section 5.5.2.2.2 (Figure 3).

Point A is the origin.Point B represents yielding. No deformation occurs in the hinge up to point B, regardless of the deformation value specified for point B. The displacement (rotation or axial elongation as the case may be) will be subtracted from the displacements at points C, D and E. Only plastic deformation beyond point B will be exhibited by the hinge.Point C represents the ultimate capacity of the plastic hinge. At this point hinge strength degradation begins (hinge starts shedding load) until it reaches point D.Point D represents the residual strength of the plastic hinge. Beyond point D, the component responds with substantial substantial strength to point E. Point E represents total failure. At deformation greater than point E, the plastic hinge will drop load to zero.

For BRB bracings, core plastic joint is used according to figure 4, these joints are allocated to the beginning
and ending of bracing. The surface of mentioned performance is based on FEMA-356 and optimizing instruction, life safety level.

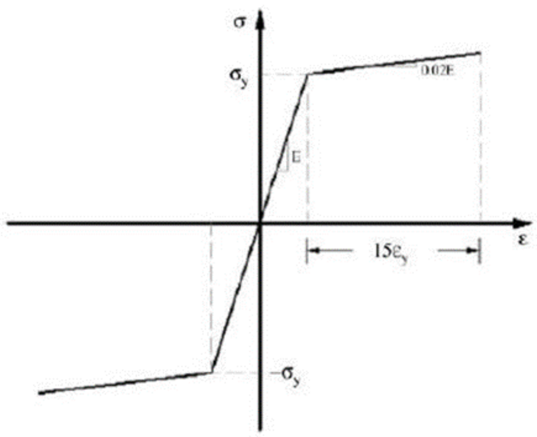

Figure 4. Core behavioral model for BRB bracing

3.2 *Pushover non-linear static analysis*

The expected behavior of structure in analyzing extra load is estimated through comparing resistance and shift in demand based on plan earthquakes with available capacities in mentioned performance levels. Therefore analyzing extra load will have important and key role because without requiring time consuming, expensive and complex analyses of structure final non-linear dynamic behavior in terms of distributing plastic joints, type and the way of forming collapse mechanism, overall and relative displacements of demands, final power of members and so on are estimated very accurately. Moreover through some methods such as capacity spectrum method the rate of structure safety can be measured either in terms of resistance or floor or structure final displacements comparing with permissible values corresponding to the structural and non-structural members. But the important thing is that by the help of this method, a very good comparison of structure behavior, before and after strengthening it can be seen and the rate of accountability and efficiency redesigned on initial model of structure can be estimated. Eliminated columns in plan are in two forms of corner and middle. [11]

3.3 *The graph of structure capacity*

The graphs of structure capacity and in different modes of eliminating column in structure have been shown in below as follows.

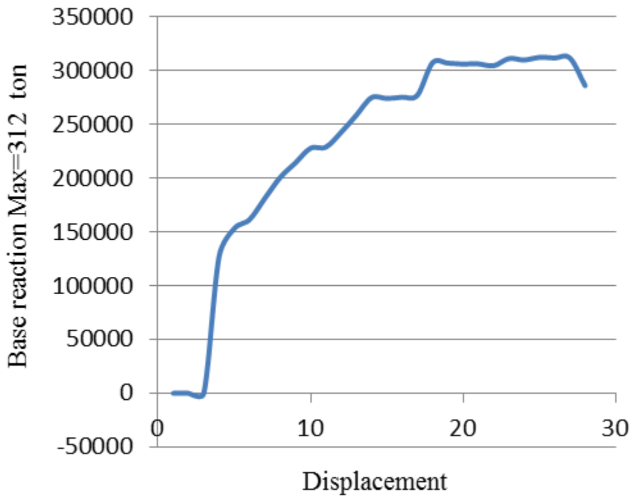

Figure 5. The graph of structure capacity (shear-base) for a mode which column has not been eliminated

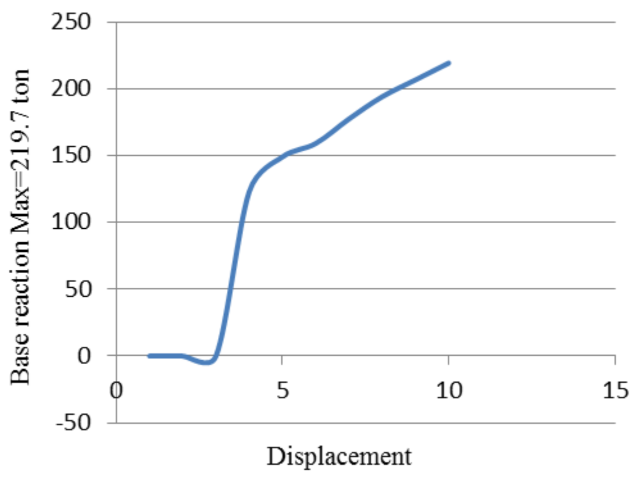

Figure 6. The graph of structure capacity (shear-base) for a mode which corner column has been eliminated

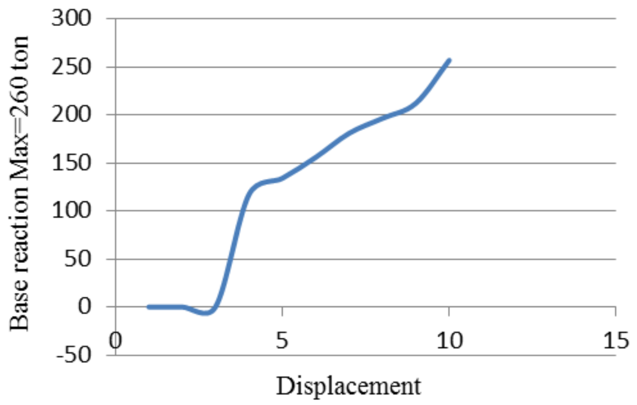

Figure 7. The graph of structure capacity (shear-base) for a mode which middle column has been eliminated.

3.4 *Index of resistance against progressive collapse*

Recent analytical methods for progressive collapse only propose a qualitative evaluation of structural system resistance. Any way for progressive collapse, quantitative results and the remained capacity of transportation of damaged structures are required. The index R is defined as a structure for resisting against progressive collapse and indicates overall performance of damaged structure assuming eliminating damaged loader member.

Index R is a structural and independent from creating initial subjective destruction characteristic and can tell if there is an adequate alternative route for safe transformation of damaged loads.

$$R = V_{damaged}/V_{design} \quad (2)$$

R: The remaining supply resistance

$V_{damaged}$: maximum shear-force of damaged structure as the result of doing the research

V_{design}: structure maximum shear force without collapse

Table 1. Resistance index against progressive collapse

Strength Index	shear base (ton)	
	312	Without eliminating column
0.7	219.7	By eliminating the corner column
0.83	260	By eliminating the middle column

R resistance index which is obtained from the ratio of damaged structure base shear to base shear of undamaged structure shows that destruction location has significant effect on shear resistance of structure. Considering table 1, with collapsing corner and middle column, structure resistance reduces respectively 30 and 17 percent. Therefore with collapsing corner column, structure resistance reduces in transporting damaged loads and has more critical mode in keeping collapse shear resistance of corner column than middle one.

3.5 *Roof lateral displacement*

In this part, roof lateral displacement has shown in three modes of without eliminating column, with eliminating corner column and middle column which has been provided in table 2.

Table 2.Roof lateral displacement in modes of without eliminating column, with eliminating corner column and middle column

Lateral displacement of roof in terms of CM	Mode and position of column
14.11	Without eliminating column
10.71	By eliminating the corner column
3.43	By eliminating the middle column

As it can be seen in table 2, with eliminating corner column and middle column, lateral displacement in structure is more in corner elimination than eliminating middle column which shows corner column has more critical mode.

3.6 *The graph of displacement – load coefficient*

In investigating progressive collapse potential based on pushover non-linear analysis, after eliminating the column, in each step of analyzing structure, the rate of loads corresponding to the vertical shift applied in the location of eliminated column is recorded. Finally it states the ratio of balance load to initial gravity load of structure as load coefficient. In simple terms, this coefficient can be stated as the ratio of load in each moment of pushover graph to total initial load of structure. Among located columns in different positions, the most progressive collapse potential is created by eliminating a column which has the least load coefficient.

As following in figure 8, the graphs of displacement load coefficient in the mode of eliminating corner column and middle column are shown:

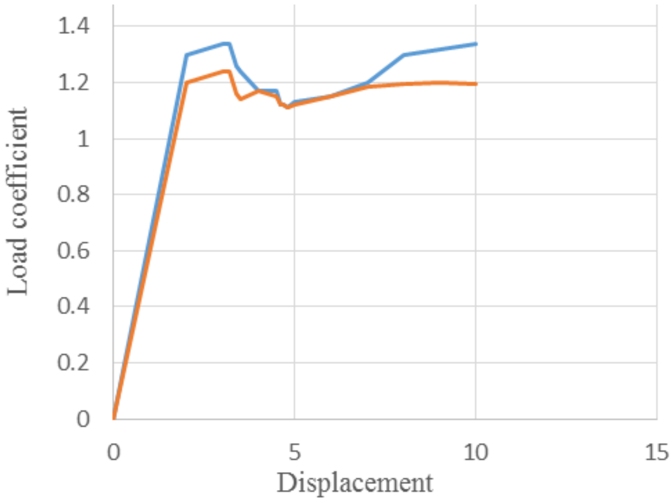

Figure 8. The graph of structure capacity (base-shear) for a model that middle column is eliminated

In figure 8 the graphs of load-displacement coefficient derived from non-linear static analysis after eliminating columns in the position of eliminating corner and middle column have been shown. Increasing the coefficient of load shows the less amount of structure potential against progressive collapse. Considering the graphs, structure with eliminating corner column is more in crisis than the one with middle column collapse because it has less load coefficient.

4 CONCLUSION AND DISCUSSION

According to the obtained results, shear-base reduced 30% with elimination of corner column while with elimination of the middle column, it can be seen that it will increase 13%. Investigating resistance index R shows that with collapsing corner, structure resistance will reduce to a great extent in transferring damaged component shear.

Roof lateral displacement will reduce in both two positions of eliminating the columns (whether corner or middle) but this reduction is more in middle column elimination.

Chain performance after eliminating column from structure is one of the helping mechanisms for rehabilitating structure for achieving alternative static balance. Progressive collapse potential derived from eliminating the column is different in various positions. Through comparing related graphs to displacement-load coefficient, structure potential is more as the result of eliminating corner column in progressive collapse and the results show that the most potential of creating progressive collapse in structure is related to cornet column and the most critical position.

Using BRB increases the shear-force and more bearing of non-elastic deformations and entering plastic area and this leads to increasing the coefficient of reducing structure plasticity that the capacity of structure increases and as result the possibility of eliminating column and progressive collapse will be less and the structure will have better performance.

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