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PERFORMANCE OF STEEL STRUCTURES EQUIPPED WITH BRB AND RBS

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ABSTRACT

Seismic retrofitting and rehabilitation of structures, the most important issues in earthquake engineering.One of the common methods of retrofitting steel structures, using Bracing system for increased stiffness and lateral resistance.

Conventional steel bracing elements show asymmetrical behavior under cyclic loading: high ductility in tension due to the ductile yielding material characteristics and buckling under compression. This stability problem influences the overall cyclic response of the element, reflected by the cyclic degradation. By removing the buckling phenomenon, BRBs offer balanced, extremely ductile and dissipative cyclic behaviour.

Buckling Restrained Braces (BRBs) are a structural component useful when providing bracing for seismic or other loads. BRBs have a large ductility capacity and are designed to yield under loads without buckling. They offer robust cyclic performance and significant cost savings, compared to conventional bracing systems (Deulkar, W. N. et al, 2010).

The new high performance bracing system developed by Golafshani et al that can be installed in the braces as a supplemental part, is capable of removing the permanent drift of stories at the end of excitation and concentrating structural damage in braces. The RBS device which is assembled in a desired location of the brace memberis made of high strength steel. In comparison with conventional brace system (CBS), ribbed bracing system (RBS) can absorbed seismic energy without causing large permanent drift in structure.

In this paper, performance of BRB and RBS in steel structures with modeling in OpenSees software has been investigated under earthquake load. To do this study, the nonlinear dynamic analysis under various earthquake records have been investigated on the 2D steel frames with conventional braces and equipped with BRB and RBS. The results show that these systems have suitable performance compared with conventional braces.

INTRODUCTION

Steel moment-resisting frames are susceptible to large lateral displacements during severeearthquake ground motions, and require special attention to limit damage to non-structuralelements as well as to avoid problems associated with P-Δeffects and brittle or ductilefracture of beam tocolumn connections [FEMA, 2000]. As a consequence, engineers in theUS have increasingly turned to concentricallybraced steel frames as an economical means forresisting earthquake loads..

Individual braces often possess only limited ductility capacity under cyclic loading. Brace hysteretic behavior is unsymmetric in tension and compression, and typicallyexhibitssubstantial strength deterioration when loaded monotonically in compression orcyclically. Because of this complex behavior, actual distributions of internal forces anddeformations often differ substantially from those predicted using conventional designmethods. Design simplifications andpractical considerations often result in the braces selected for some stories being far strongerthan required, while braces in other stories have capacitiesvery close to design targets. Thisvariation in story capacity, together with potential strength losses when some braces buckleprior to others, tend to concentrate earthquake damage a few "weak" stories. Such damageconcentrations place even greater burdens on the limited ductility capacities ofconventionalbraces and their connections. It has also been noted that lateral buckling of braces maycausesubstantial damage to adjacent nonstructural elements.

Prompted by these observations and concerns, seismic design requirements for braced frames have changed considerablyduring the 1990s, and the concept of special concentric bracedframes has been introduced [AISC, 1997; ICBO, 1997]. Considerable research has also beeninitiated improve the performance of concentrically braced frames through the introduction ofnew structural configurations or the use of special braces,including those utilizing composite action, metallic yielding, high performance materials, friction and viscousdamping. During the pastdecade, there have also beenparallel advances in research related to characterizing the seismic hazard at a site, simulatingseismic response, and theories for characterizing seismic performance in probabilistic terms.As such, a review of the overall seismic performance characteristics ofconcentrically bracedframes designed to current standards is timely.

The goal of the overall projectdescribed in this paper is toinvestigate the system levelperformance of concentricallybraced buildings subjected toseismic loads with theintention ofunderstanding thestructural and ground motioncharacteristics that controlbehavior, and to assess and,where necessary, proposeimproved design and analysisprocedures. A series ofnonlinear dynamic analyseshas been carried out examiningthe behavior of concentricallybraced frames havingconventional braces, highperformance hysteretic braces,and visco-elasticdampers.Thispaper highlights resultsobtained for frames utilizingbuckling-restrained and bracesribbed bracing system (RBS).

RIBBED BRACE SYSTEM (RBS)

Golafshani et al. (2006) proposed a new innovative high performance bracing system thatconsists of a simplemechanism based on semi-active control that can be installed in the braces as a supplemental part, Figure 1. In comparison with conventional brace system (CBS), ribbed bracing system (RBS) can absorbed seismic energy without causing large permanent drift in structure. In this system thebuckling of compressive member is prevented and bracing can endure tension force in compressive region. Therefore by using of this system permanent stiffness is provided and structural deformation decreased. Also seismic damage in the equipped structure is concentrated in bracing system and dissipated hysteretic energy in other structural system decrease. Because this mechanism needs just a batterysize power supply, it can be accounted as an efficient semi-active control device. The RBS device which is assembled in a desired location of the brace member, Figure 2, is made of high strength steel and consists of the following parts:

- Ribbed shaft
- Ribbed cylinder
- Switch + release plate
- Shell

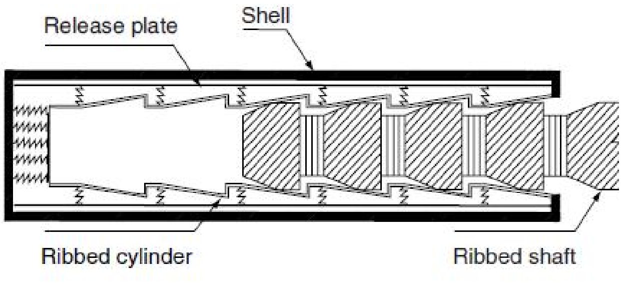


Figure 1: RBS (proposed by Golafshani*et al.* 2006)

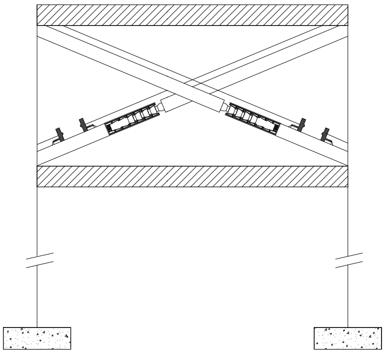


Figure 2:Structure equipped with RBS [2].

There are springs in the inside rim of the shell thatallow the ribbed shaft to squeeze outside toward theshell. When the ribbed shaft is under compressiveaxial force, ribs of shaft squeeze the cylinders ribs andpush the cylinder outside toward the shell and theshaft moves freely inside. On the contrary, undertensile axial force the ribs of shaft and cylinderinteract with each other and the shaft is locked so thesystem can tolerate tensile force, therefore a memberthat only endures tensile forces is developed. Bydeveloping this system, because of locking the ribs ofthe cylinder and shaft in each other, the nonlinearpermanent deformation of the brace is compensatedand the drift of the story does not increase very much(Figure 3).

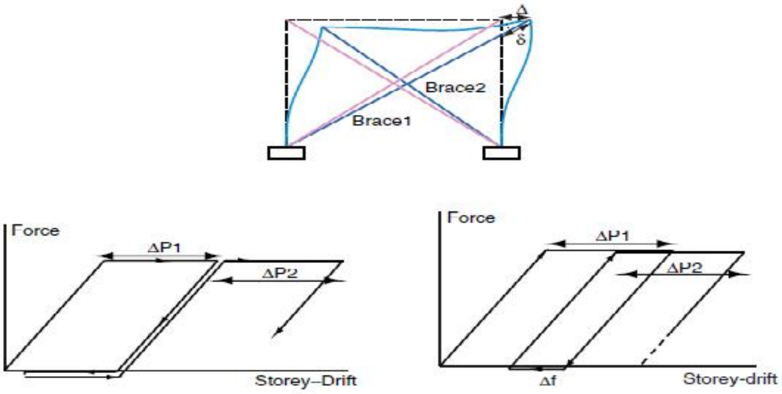


Figure 3:A singlebraceforce-storeydrifthysteric’sloop:
(a) conventional brace; (b) RBS (Golafshani et al. 2006)

In addition to buckling preventing performance of the RBS, it is possible to assign a simple control program to the system to have a more desired seismic behavior. To achieve this goal an operational criterion is considered such as story drift, story damage index or global damage index. By this kind of control the long term functionality of the structure will be improved because of preventing low cycle damage to the frame and bracing elements.

The mechanical system depicted in Figure 4, is the combination of a cable extended along the brace and two steel keys. Initially these two keys are adjusted apart by amount of tolerance, determined by designer and the cable is pre-tensioned. When the brace is shortened more than tolerance, two steel keys contact each other and the electronic switch releases the ribbed shaft by moving the release plate depicted in Figure 2 toward the shell. By adjusting the tolerance to zero, the brace does not endure any force in the compressive displacement region. On the contrary, by lengthening the brace two steel keys are disconnected and the ribbed shaft will be locked, so by interaction of shaft ribs and cylinder the brace endures tensile force. Completely closed RBS is the situation that this eccentricity is set to a large length and therefore the brace can endure tension force in the compressive displacement region (Golafshani et al. 2006) (Figure 5).

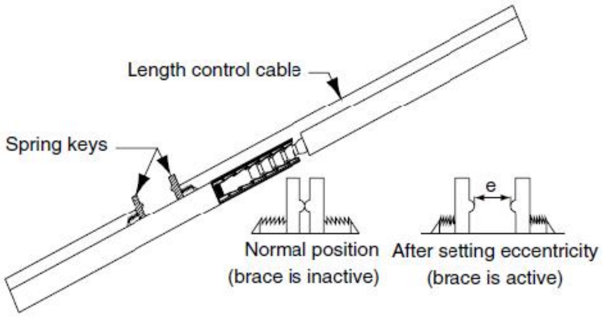


Figure 4: Length-correction control system (Golafshani et al. 2006)

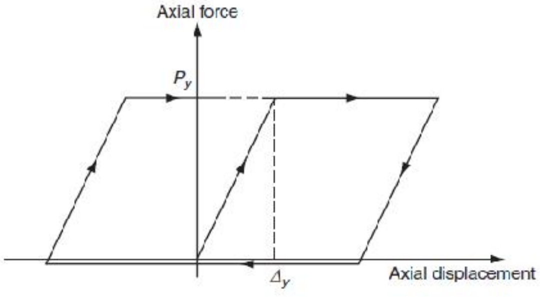


Figure 5: Behavior of CC-RBS

BUCKLING-RESTRAINED BRACES

Since many of the potential performance difficulties with conventional concentrically braced frames rise from the difference between the tensile and compression capacity of the brace, and the degradation of brace capacity under compressive and cyclic loading, considerable research has been devoted to development of braces that exhibit more ideal elasto-plastic behavior. One means of achieving this is through metallic yielding, where buckling in compression is restrained by an external mechanism. A number of approaches to accomplish this have been suggested (see Fig. 6) including enclosing a ductile metal (usually steel) core (rectangular or cruciform plates, circular rods, etc.) in a continuous concrete filled tube, within a continuous steel tube, a tube with intermittent stiffening fins, and so on. The assembly is detailed so that the central yielding core can deform longitudinally independent from the mechanism that restrains lateral and local buckling. Through appropriate selection of the strength of the material, and the areas and lengths of the portions of the core that are expected to remain elastic and to yield, a wide range of brace stiffnesses and strengths can be attained. Since lateral and local buckling behavior modes are restrained, large inelastic capacities are attainable. Theoretically based methods have been developed to design the restraining media. Provisions have been developed in draft form [SEAOC, 2001] for design, specification and testing of buckling restrained braces to help insure braces meet performance expectations.

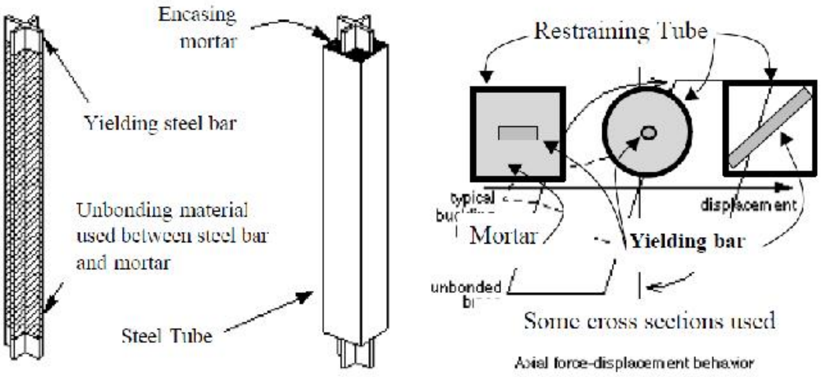


Figure6: Some schematic details used for buckling restrained braces [after Clark, 2000]

The inelastic cyclic behavior of several types of buckling restrained braces have been reported [see, for example, Watanabe, 1989, Iwata, 2000]. These tests typically (see Fig. 7) result in hysteretic loops having nearly ideal bilinear hysteretic shapes, with moderate kinematic and isotropic hardening evident. Interestingly, the difference between the tensile and compressive strength of steel results in greater strength of the buckling restrained braces in compression than in tension (differences up to 10% have been reported). Finite element analysis studies have shown excellent agreement with test results. Low cycle fatigue (failure) characteristics have been shown to depend on a variety of factors, including the restraining mechanism used, material properties, local detailing, workmanship, loading conditions and history, etc. Inelastic deformation (ductility) capacities are generally quite large, with cumulative cyclic inelastic deformations often exceeding 300 times the initial yield deformation of the brace before failure.

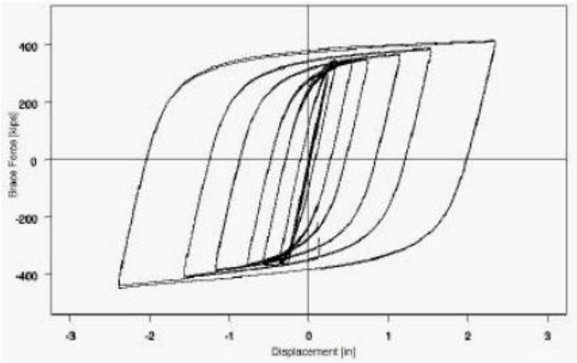


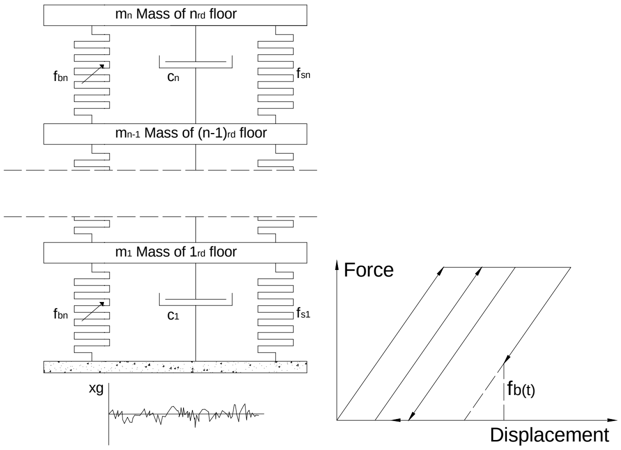
Figure 7: Axial Force-Displacement Plot for BucklingRestrained Brace with Steel Core Unbonded

NONLINEAR DYNAMIC ANALYSIS

For the RBS and BRB equipped structure the horizontal vibration of an n-storey structure is modeled by the first n modes of the natural vibration of system. There are n principal degrees of freedom (DOF) for the floors. The finite element model of this dynamic system is shown in Fig. 8.a. A nonlinear analysis computer code is prepared by [Monzavi2006], which is capable of modeling the conventional braces with the hook element and considering the simple elasto-plastic behaviour for braces and bilinear elasto-plastic for moment frames with ~ Z ۰.۰۵ , also the computer code is capable of modeling the braces equipped with SA-RBS and CC-RBS. The second-order matrix equation of the reduced model by static condensation method may be written as follow:

$$M\ddot{x}(t) + C\dot{x}(t) + F_b(t) + F_s(t) = -Mr_g\ddot{x}_g(t) \tag{1}$$

Where M and C are the mass and proportional Rayleigh damping (¶ Z ۰.۰۵) matrices respectively, and Fs is the moment frame resisting force vector. Fb is the resisting force vector variable according to situation of the ribbed braces during the excitation, Fig 8.b. rg is a location vector shows the extent and distribution of excitations on each DOF.



(a) (b)

Figure 8: (a) Finite element model; (b) brace resisting force

CASE STUDIES

In order to investigate the performance of RBS and BRB system in contrast with CBS, a 3-storey CBF is considered shown in Fig. 9. Because of investigating the effect of different retrofitting systems include RBS, and BRB.The analyses have been carried out for BRB, CBF andRBS. Control limit that used in this study is based on the maximum allowable storiesdrift presented in design building code. Maximum inelastic storey drift based on IBCcode is as follow:

$$\Delta_M < 0.025h \quad T < 0.7 \tag{2}$$

$$\Delta_M \le 0.02h \quad T \ge 0.7 \tag{3}$$

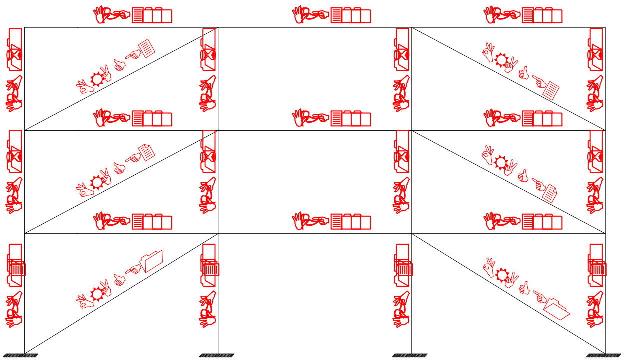


Figure 9: Frame-elevation of case study structures

In order to investigate different retrofitted systems, Northridge record is used and acceleration, velocity and displacement time history for this record is shown in Figure 10 a, b, c.

The outputs are as follows:

-Maximum drift of stories

-Top displacement time history

-Time History of Column Force

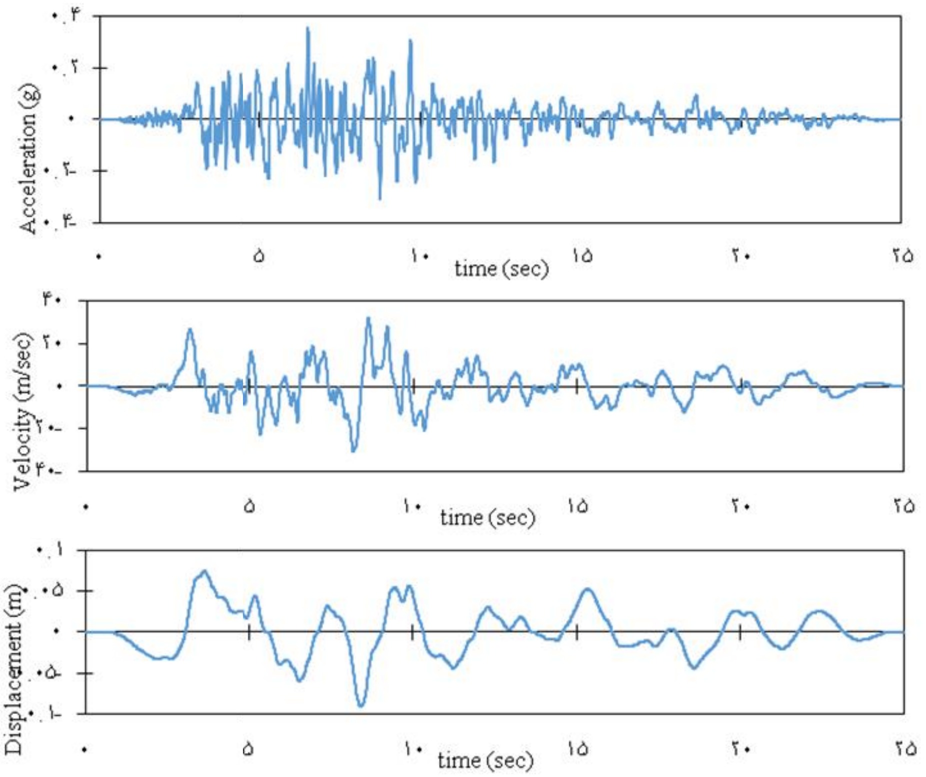


Figure 10:(a) Acceleration, (b) Velocity and (c) Displacement Time History of Northridge

From the analysis of 3-storey structure under Northridgerecord, the roofdisplacement (Fig. 11) shows considerable decreasing approximately 7.54% in the peak displacement for structure equipped with BRBand 8.3% (table1) for RBS retrofit systems against of CBF. It is seen in Fig. 12 and table2 that the maximum storey drifts are decreased in the in contrast with CBF.

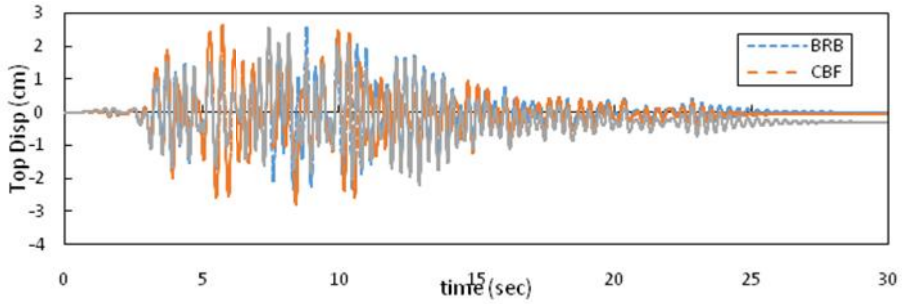


Figure 11:Time History of Top Displacement under earthquake record of Northridge

Table1:Maximum Top Displacement of Structureand their Reduce Percent

Max Top Displacement (cm)		Reduce (%)
CBF	2.77	
BRB	2.56	7.58
RBS	2.54	8.3

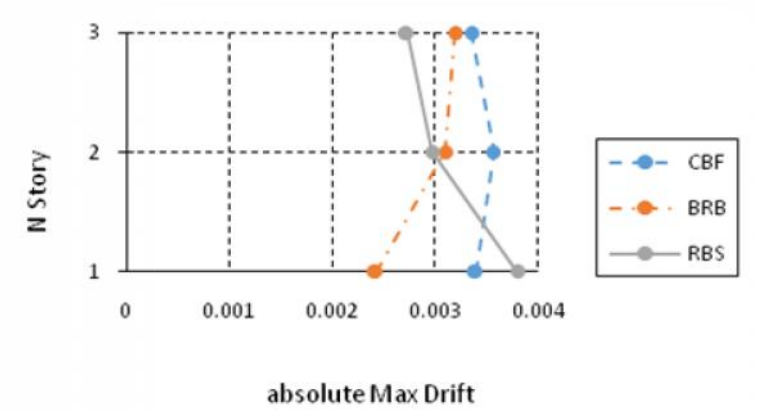


Figure 12:Maximum Drift of Stories under earthquake record of Northridge

Table2:Maximum Drift of Stories

Max Drift			
	CBF	BRB	RBS
Level 1	-0.0034	0.00243	0.0038
Level 2	0.00357	0.0031	0.00298
Level 3	0.00336	0.0032	-0.00273

Fig. 13 shows the time history of Column Force under earthquake record of Northridge in various retrofit systems. It is obvious that RBS equipped frame has most base shear because of continuous stiffness presence during earthquake. Table 3 shows Maximum Column Force of Structure in Level 1 and their Reduce Percent.

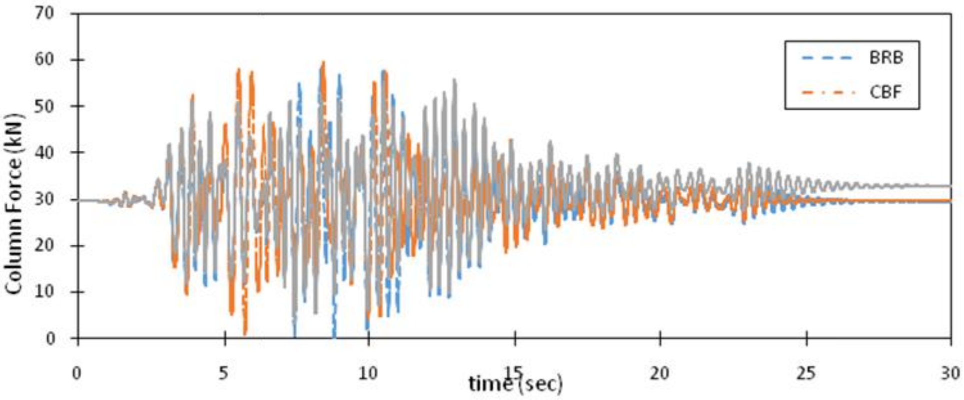


Figure 13:Time History of Column Force under earthquake record of Northridge

Table3:Maximum Column Force of Structure in Level 1 and their Reduce Percent

Max Column Force (kN)		Reduce (%)
CBF	59.46	
BRB	57.78	2.83
RBS	55.868	6.04

CONCLUSIONS

In this paper performance of various systems including of conventional brace system (CBS), ribbed bracing system (RBS) and BucklingRestrainedBrace(BRB), in retrofitting of an existing moment resisting frame (MRF) has been investigated.Using BRB and RBS are cause to reduce of structure response. Reduction in maximum Top Displacement is very important from structural performance point of view. RBS and BRB cause maximum Top Displacement decrease.

Otherwise, structure equipped with BRB and RBS, has drift ratio and column force less than structure with CBS.

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