Performance of Non-Buckling Segmented Brace Members for Mitigating Seismic Responses of Frame Structures

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Abstract

Bracing systems are often used as a means of limiting lateral displacement of frame structures under earthquake ground excitations; however concentric braces tend to buckle under compressive loads, resulting in reduced stiffness and ineffective performance of the brace members. Buckling Restrained Braces (BRBs) have been developed to mitigate the disadvantages of traditional braces, through the use of a concrete filled sleeve that prevents lateral movement of the brace. Though BRBs are effective they are associated with large size, heavy weight, complex connections and the need for complete replacement following seismic activity. This study presents a new non-buckling segmented brace member. This segmented brace member consists of two or more segments that are connected by tensile only or compressive force-controlled joints. Since the joint is fabricated to only take tensile force or controlled compressive force to avoid buckling, its capability of mitigating seismic responses remain effective throughout the entire ground excitation duration. The other advantages of this new design include light weight compared to BRB, easy to be installed, controlled damage locations at the joints so that they can be straightforwardly and economically replaced after earthquake event. The disadvantage is that full energy dissipations can be achieved only when it is in tension and it becomes ineffective under compression. Therefore they will be effective only when cross bracings are used. This paper presents both experimental test and numerical simulation results of using this innovative brace member in mitigating seismic responses of frame structures. Both the advantages and disadvantages of this new brace member will be discussed. This new device may find applications in retrofitting existing structures and designing of new structures to resist earthquake ground motions.

Keywords: Brace, non-buckling, seismic response, cyclic tests, nonlinear response.

1. INTRODUCTION

Bracing systems are used extensively to stabilise a structure subjected to lateral loading. However, one persistent problem with using conventional braces is their tendency to buckle in compression. This is structurally critical when the member is repeatedly stressed under dynamic or cyclic loads such as those found during earthquakes. The repeated buckling and straightening of the member under cyclic loads generates a plastic hinge at the mid-span of the brace, leads to significant reduction in stiffness of the whole structure and load bearing capacity of the brace member in both tension and compression. Figure 1a shows hysteretic loop of a brace member under cyclic loading obtained by Tremblay (2002). As shown under the application of the cyclic loading, both the compressive and tensile strength reduce and displacements increase at the same loading level. The capacity of hysteretic energy dissipation also reduces. These result in the lateral load path of the braced frame severely compromised, forcing structural elements that primarily carry vertical loads to act in an undesirable manner. Similar observations are also made by Lee and Bruneau (2005) and many other researchers.

To improve the efficiency of braces, research into methods to restrict their buckling mode of failure was initiated. The Buckling Restrained Brace (BRB) was first proposed in the 1980s, and has now become popular in the seismic design of structures. The BRB in its current form was first proposed by Watanabe et al. (1988) as a steel core member within a steel tube that functioned as a sleeve, as shown in Figure 1c, with concrete used as infill within the steel sleeve. In the design, either a small gap between the brace member and the steel sleeve or a debonding agent was rubbed on the core's surface to avoid shear stress transition to the restraining system. This resulted in a member that reached yield strength in compression, and was not susceptible to buckling as a form of failure. The steel tube and concrete surrounding the core act as a restraint against lateral movement, so that the core can reach full compressive strength and yield, dissipating energy under compression without buckling. Studies have shown that current BRB designs are effective in restraining the brace from buckling and show optimum energy dissipation in the member. Figure 1b shows the cyclic testing data of a BRB obtained by Tsai et al (2004). Figure 1c illustrates a typical BRB.

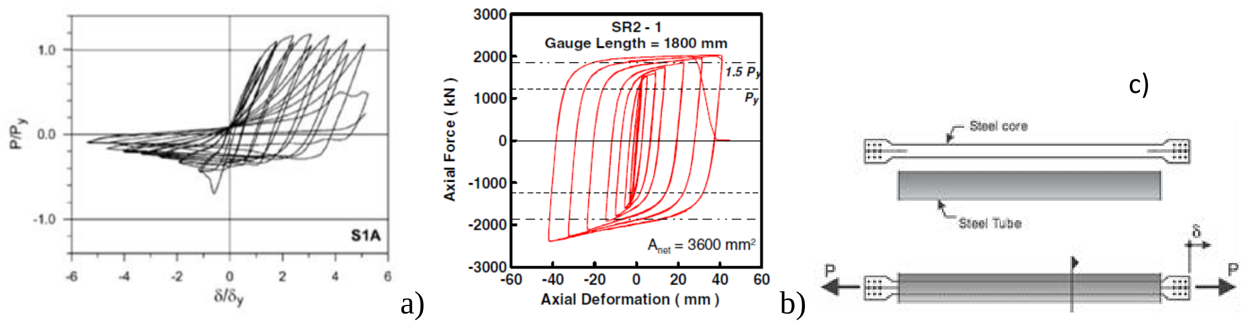


Figure 1. Typical cyclic testing results: a) conventional brace member (Tremblay 2002); b) BRB (Tsai et al. 2004); and c) typical BRB (Tremblay et al. 2006)

Despite their sound performance, there are a number of practical disadvantages to using BRBs, which include the complexity of connections, difficulties in installing BRBs due to the large size and heavy weight, and the need to replace the entire BRB following yielding with large residual displacement after seismic activity. Connections for BRBs are often very detailed and complex, with a large amount of splice plates and bolts required to creating connections. The drawback is that the complexity associated with these connections requires specialized labour for installation and increases difficulty for post-earthquake repairs. In addition to the complexity of connections for BRBs there are drawbacks related to the size of BRBs. The large sheath encasing the BRB, and the concrete infill within this sheath make the installation of BRBs difficult, especially when they are used for retrofitting buildings. As noted by Symans et al. (2008) and Amiri et al (2013), bracing systems such as BRBs offer potential for increasing stiffness through retrofitting, however the large size of BRBs means it can be difficult to fit these BRBs within existing structures. Additionally the use of large amounts of concrete within BRBs makes them very

heavy. This requires specialized equipment to install BRBs within frames, and complicates the overall construction process whilst adding significant design loads to the frame.
The method in which BRBs dissipate energy is another significant drawback. Energy dissipation is achieved through yielding of the core of the BRB. The current design implies that yielding of the steel core of the BRB can occur over almost the entire length of the BRB. Following seismic activity, the plastically deformed BRB has to be replaced, which involves the entire brace being uninstalled and a new brace being reinstalled. As a result of the large size and weight of the BRB, as well as the complexity of connections, the replacement of the entire BRB can be difficult, costly and time consuming. Therefore new designs of non-buckling braces that overcome some or all of the disadvantages of the current BRB designs need be explored.

This paper introduces the concept of a new non-buckling segmented brace member developed to overcome the problems of conventional brace member and BRB. The preliminary experimental work and numerical simulations of the performance of this new segmented brace member have been carried out. The results indicate that the performance of this new segmented brace member is encouraging. This paper presents this new design of non-buckling brace and the experimental and numerical results, and discusses its advantages and drawbacks, as compared with the traditional brace member and BRB.

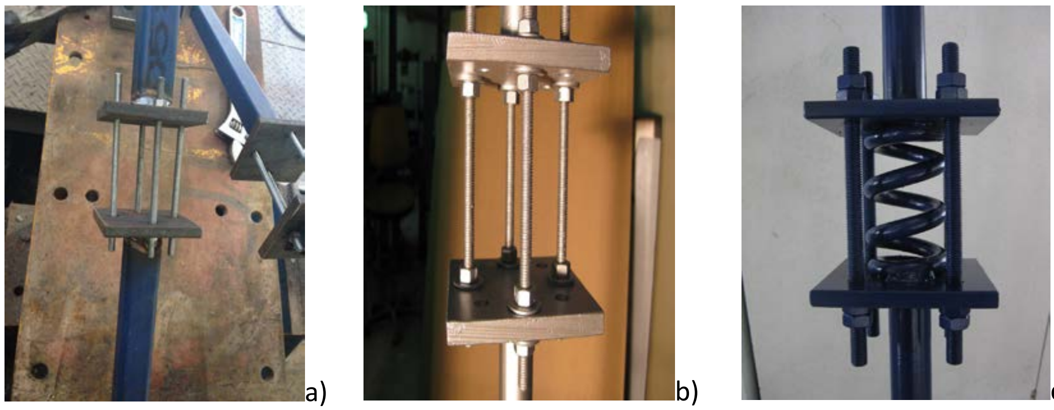
2. SEGMENTED BRACE MEMBER

The segmented brace is an innovative new non-buckling brace designed to provide restraint under tension, but provide no or controlled compressive restraint. This is achieved through the use of segments which transmit tension forces, but under compression allows the brace to slide. Figure 2 shows some typical designs of small scaled segmented non-buckling brace members fabricated and tested in the study. It consists of two CHS sections welded to end plates, which are bolted together. If the bolt arrangement has nuts on the outside of the steel end plates only, as shown in Figure 2a, the bolts prevent tensile movement, resulting in the tensile force being carried through the bolts, whilst in compression the plates can slide closer, providing no restraint and therefore no buckling. If nuts are placed on the both sides of end plates as shown in Figure 2b, the segmented brace can provide both tensile and compressive restraints. However, either global or local buckling, i.e., buckling of the bolts, might still occur. A third design is to place a compression spring in the segment joint as shown in Figure 2c. In that case the compression spring will provide certain compressive resistance and bolts provide tensile resistance. If the stiffness of the compressive spring is properly designed, i.e., its stiffness is smaller than the axial stiffness of CHS and resistance less than the buckling load of the brace member, buckling will be prevented. It should be noted that the spring in Figure 2c is not fixed to the end plates, therefore it cannot take any tensile force.

The scaled specimens of the above three designs as well as a conventional brace were prepared. All specimens were made with the same section of 26.9x2.0 CHS and length 1 m. The conventional brace was made and tested to confirm buckling as its mode of failure, so as to demonstrate the performance of the non-buckling brace designs. The yielding stress of the 26.9x2.0 CHS is 350MPa and cross sectional area is 149 mm^2, which gives a yielding load of the brace member 52.15 kN. In the test, pinned ends were assumed as shown in Figure 3c, therefore the buckling load can be estimated using Euler’s formula

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{1}$$

in which the Young's modulus E and moment of inertia I of the CHS are respectively 200GPa and 1.17x10^4 mm^4. This gives the buckling load 23.1 kN. Therefore the conventional brace member will buckle elastically.



a) b) c)

Figure 2. Typical designs of segmented non-buckling brace member: a) tension resistance only; b) tension and compression resistance; and c) tension and controlled compression resistance

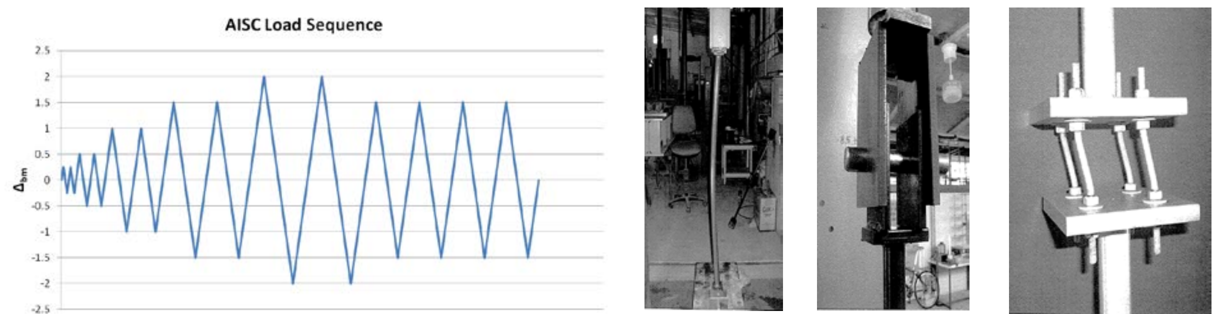
To limit the damage to the segmented brace joint so that it can be easily replaced after an earthquake event, the bolts are selected to yield before the CHS segment. In the current design, four bolts are symmetrically placed and each of them will take the same load. Therefore the yielding load of each bolt should be less than 52.15/4=13.04 kN. Based on this, M10 bolt with cross sectional area 52.3 mm^2 and yield stress 240 MPa is selected. The yield load of each M10 bolt is 12.55 kN. The load required to yield four bolts is therefore 50.2kN, slightly smaller than the yield load of CHS.

If a compressive spring is used to resist compressive load, as shown in Figure 2c, the spring stiffness should be less than the axial stiffness of the segment member to avoid buckling. In this study, a spring with stiffness of 0.625 kN/mm was used, which is substantially smaller than axial stiffness of 1 m long CHS.

The design with nuts on the both sides of the steel plate as shown in Figure 2b was intended to make use of the both tensile and compressive resistance of the bolts. To avoid buckling of the brace, the yielding load of the bolts should be smaller than the buckling load of 23.1 kN calculated above. Four M6 bolts were used in this segmented brace. The yielding load was calculated to be 17.2 kN. However, local buckling, as shown in Figure 3d occurred and the brace did not perform as expected. Therefore this design is not discussed in the present paper.

3. CYCLIC TESTS

Testing of the specimens were carried out on the Instron Universal Testing machine with a maximum loading capacity of 500 kN in the Structures Lab of the University of Western Australia. The quasi-static cyclic tests were displacement controlled. AISC's Seismic Provisions provide specific testing procedures for BRBs (AISC 2010), which must be followed prior to the implementation of the brace. In order to determine whether the segmented brace member is a viable alternative to traditional designs, the proposed segmented brace specimens were subjected to the one dimensional tests specified by AISC. Section K3.4 of the Seismic Provisions defines two deformation values to quantify the load sequence of the uni-axial test. Yield deformation Δ_{by} refers to the 'deformation quantity at first significant yield of the test specimen' and the drift deformation Δ_{bm} refers to the 'deformation in the brace corresponding to the design storey drift' (AISC 2010). Since the analysis was not conducted for a specific structure, Δ_{by} was assumed to be four times of the displacement at the yielding of the conventional brace, approximately equal to 0.5 mm. Therefore Δ_{by} equal to 2 mm was used in the tests, and Δ_{bm} was assumed to equal $4\Delta_{by}$, as specified in the provisions. The complete loading sequence is shown in Figure 3a, where the brace must be gradually loaded until total cumulated deformations exceed 200 times the yield deformation. After achieving the maximum deformation of $2\Delta_{bm}$, the brace is therefore repeatedly loaded through cycles of $1.5\Delta_{bm}$ until the brace accumulates deformations of at least $200\Delta_{by}$. In this project, this was achieved upon four cycles of $1.5\Delta_{bm}$. As can be noticed in Figure 3a, two cycles at each displacement level were applied. The loading rate is kept at a constant rate of 0.01 mm/s in the tests.



a b c d

Figure 3. a) Displacement controlled loading protocol; b) Conventional brace under testing in the universal testing machine; c) Pinned joint; and d) Buckled bolts at the segment joint

Figure 4s shows the test results of the conventional brace. As shown, the conventional brace did not yield but buckled at a compressive load at about 34 kN, larger than the predicted buckling load of 23 kN. This is because the boundary condition is not a perfect pin owing to tight fitting and friction between plates and pin that provide some resistance for free rotation. A slight blemish is also visible at compressive load about 19 kN. This is due to a loose bracket that locks the head into position on the Instron Universal testing machine. Despite these imperfections, the test demonstrated that the conventional brace failed prematurely by buckling, which greatly undermined the ability of the brace member in absorbing seismic energy and resisting further seismic loading.

Figure 4b shows the results of the segmented brace with compressive spring. The result of segmented brace without compressive spring is not shown here because the only difference is that it does not have the compressive resistance. The test results show that yielding occurred at about 53 kN, slightly higher than the predicted yielding load for bolts of 50.2 kN. It is also slightly higher than 52.15 kN, the yielding load for CHS. Careful examination revealed bolts yielded and CHS segment did not, indicating the segmented brace performed as expected. Since the design intends to limit the yielding to the joint so that the damaged bolts can be easily replaced after an event, in real design, some allowance should be provided to ensure bolts to yield before the primary segments of the brace.

In compression, the segmented brace with compressive spring behaved as expected. The compressive spring provided a linear elastic resistance without yielding. Therefore buckling is prevented with this new brace design.

The testing results demonstrate the expected performance of the proposed segmented brace, i.e., provides tensile resistance and energy dissipation after tensile yielding. The drawback of the brace, however, is also obvious that it does not dissipate energy when the brace is under compression. This can be possibly improved by using, e.g., properly designed frictional dampers at the joint to provide compressive resistance and dissipate energy instead of an elastic spring. Since the proposed segmented brace provides tensile resistance only and no or limited compressive resistance, and dissipates energy only after tensile yielding, it must be used in pairs in a frame building to resist earthquake loadings. It should be noted that another advantage is that the segmented member has only minimum residual displacement after unloading because it does not resist compressive force.

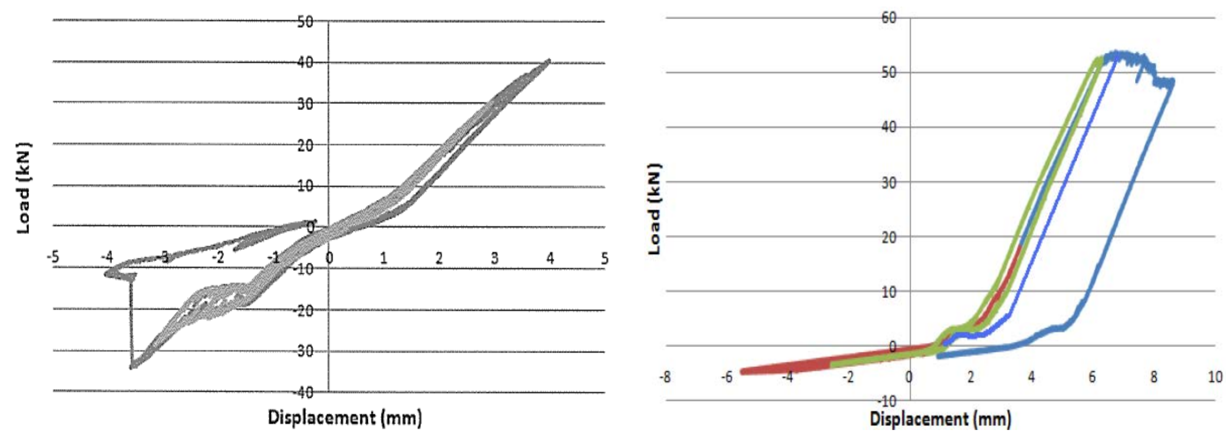


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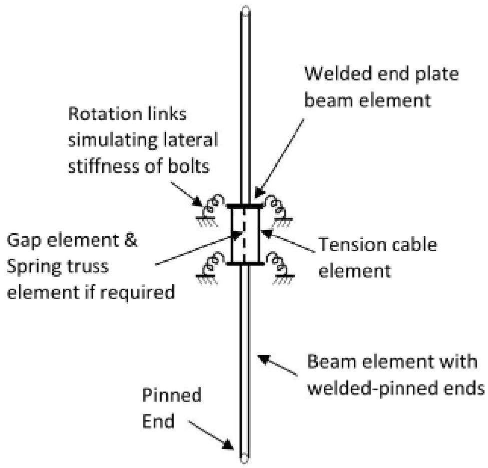
Figure 4. Cyclic testing results: a) Conventional brace; b) Segmented brace with a compressive spring

4. NUMERICAL MODEL

A numerical model is developed to simulate the responses of the segmented brace member in nonlinear dynamic response program DRAIN2D-X (Powell et al 1993). The model is shown in Figure 5a. As shown, the two segments are modelled with beam elements, the bolts are modelled with tension only cable elements, and the joint is modelled with a gap element with or without a spring truss depending on the existence of the compressive spring. To capture the possible bending and rotation at the joint, the welded end plates are also modelled with beam element. The flexural rigidity of each bolt is modelled by a rotational spring, i.e., the bolts can resist tensile force and bending moment, but not compressive force. To calibrate the model, the same dimensions and material properties as the tested specimens described above are used in numerical calculations. A 2% strain hardening after the first yielding and a 0.7% strain hardening after the second yielding are assumed for the tension only cable elements. Same displacement controlled cyclic input as shown in Figure 3a is applied to the segmented brace model. Figure 5b shows the simulated result. Comparing with the testing result shown in Figure 4b, it is clear that the numerical model closely replicates the behaviour of the segmented brace member. Both the spring in compression and the yielding of the bolts in tension match the experimental data. The slight discrepancies along the initial loading line of the test data arise from experimental inaccuracies and material imperfections in the experimental study.



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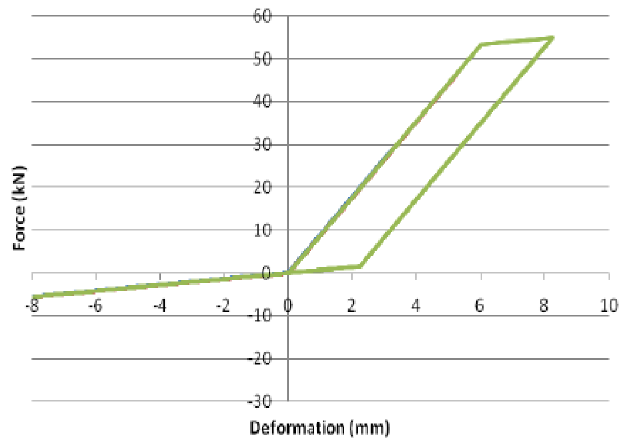

b

Figure 5. a) Numerical model of segmented brace member; b) Simulated cyclic test result

5. APPLICATION OF THE SEGMENTED BRACE MEMBER

To demonstrate the performance of the proposed segmented bracing member, responses of a single-storey moment resisting reinforced concrete frame with conventional brace and segmented brace subjected to simulated earthquake ground motion compatible to the design spectrum for shallow soil conditions are calculated using DRAIN2D-X. The frame member information is given in Table 1. It should be noted that same CHS is used for conventional and segmented brace.

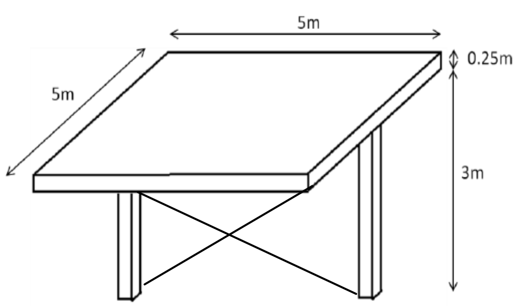

Figure 6. Reinforced concrete moment resistant frame with cross bracing members

Table 1 Example steel frame members and model elements

Column	300x400mm concrete column 2% reinforcement (beam-column element)
Beam	5x5m grid, 250mm thick concrete slab with N16-250 reinforcement (beam-column element)
Brace	168.3x6.4 CHS (beam-column element)
End Plate	200x200x20mm plate (beam-column element)
Rotation Spring	Lateral stiffness of bolts (rotational spring element)
Bolts	250MPa bolts, 10 mm diameter 0.1m length (tension only element)
Gap	(gap element – compression with initial gap)
Spring	Spring stiffness = $8.33*10^5$ Nm (element 1)

Figure 7 shows the simulated ground motion time history compatible to the design spectrum given in Australian Earthquake Loading Code (Standards Australia 2007) for Perth with PGA 0.09g.

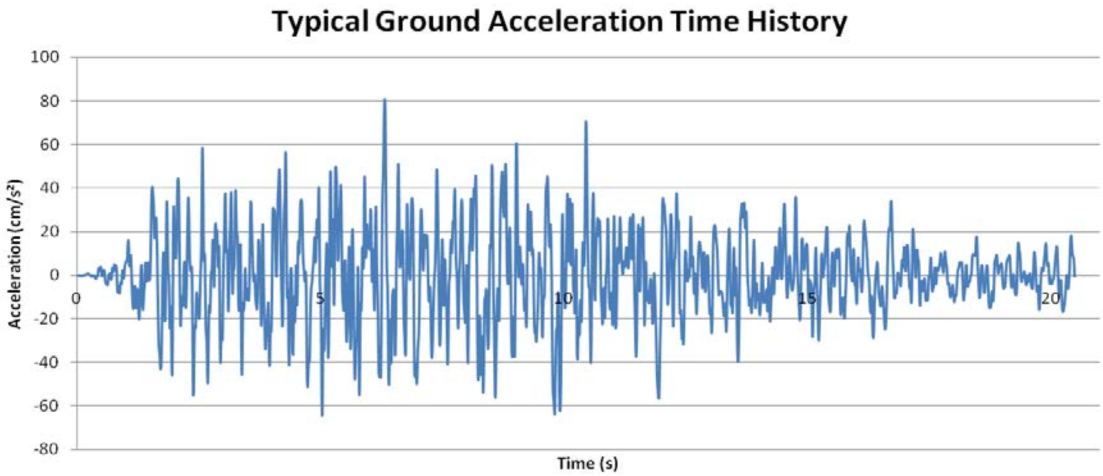

Figure 7. Simulated ground motion time history

Figures 8 and 9 show the displacement response time histories at the floor level obtained with the simulated ground motion and with the ground motion amplified by 8 times, i.e., PGA equal to 0.72g, respectively. In the figure, CBF denotes the frame with conventional bracing members; BRBF denotes non-buckling segmented brace without compressive spring, and BRBS non-buckling segmented brace with a compressive spring; and SMRF the frame without bracing.

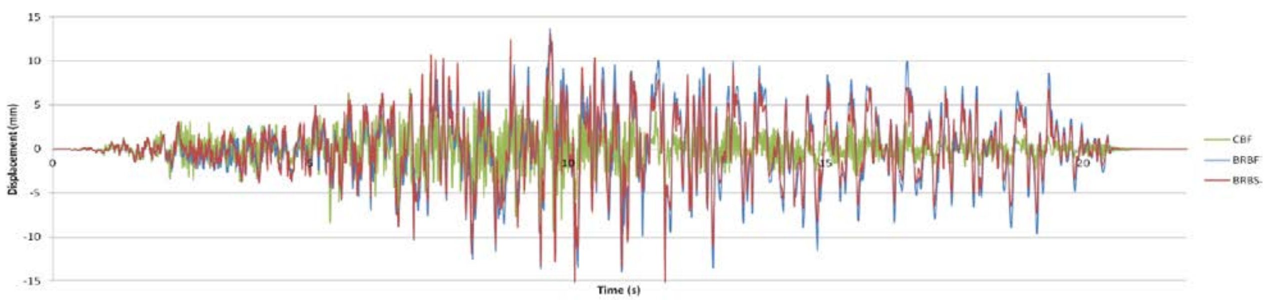

Figure 8. Displacement response of the RC frame with three types of bracing members subjected to the simulated ground motion according to the design spectrum for Perth with PGA=0.09g

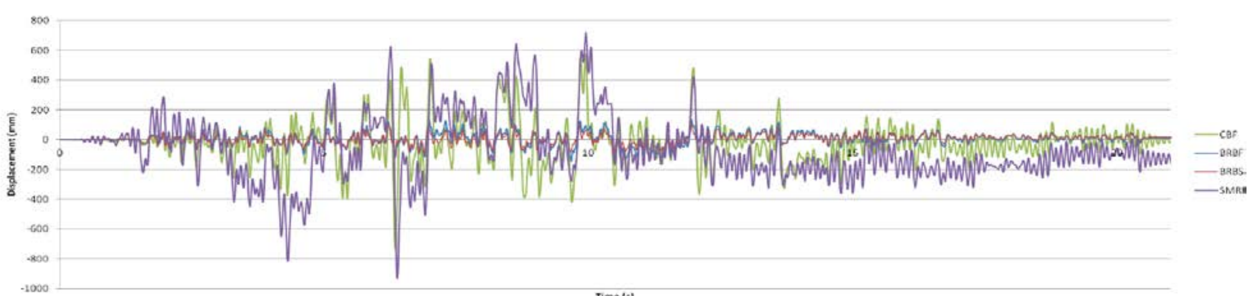

Figure 9. Displacement response of the RC frame with three types of bracing members subjected to the simulate ground motion with PGA 0.72g

As shown, when the response level is relatively small, the responses of the frame with conventional bracing members are the smallest and those with BRBF and BRBS are very similar. This is because the bracing members respond in the elastic range and do not buckle at this small response level. The conventional bracing member provides both tensile and compression resistance, while BRBF provides only tensile resistance and BRBS provides only a relatively small compressive resistance. Therefore, frame with the conventional bracing members performed the best with the smallest dynamic responses subjected to the earthquake ground motion. When the response is large as shown in Figure 9, buckling of the conventional bracing members occur. This makes the conventional bracing member no longer effective, and the responses of the frame with conventional brace are almost comparable to the unbraced frame. The advantage of using non-buckling segmented brace is obvious as they remain effective throughout the entire excitation duration. Although a very large ground excitation is used in the study for demonstrating the performance of the proposed segmented brace, the proposed non-buckling segmented brace does not fail and provides the resistance in the entire excitation duration.

Figure 10 shows the work done, equal to the plastic and elastic energy, by each component of the three types of the braced frames corresponding to the simulated ground motion amplified to different levels, normalized by the total work done by the CBF. As shown, for conventionally braced frame, more work is done in columns than in bracing members, especially when ground motion is large, indicating columns may experience large plastic deformations. Similarly, work done in columns is also larger than bolts and brace in BRBS, however, the percentage slightly decreases with the increase in response level. In BRBF, work done in columns is larger only when the response level is small. Most work is done by bolts when ground excitation is large. This is the ideal performance of the segmented brace because the damaged bolts can be easily replaced. It is also interesting to note that work done in BRBS is always smaller than CBF, whereas the total work done in BRBF is smaller than CBF when the ground excitation is small. It becomes larger when ground vibration is large. Unfortunately the program DRAIN2D-X outputs work done by each element to check energy balance. It does not differentiate plastic (energy absorption) and the recoverable elastic energy. Nonetheless, the above results imply BRBF performed the best in terms of protection of the vertical load-carrying columns as bolts have done the largest percentage of work when the response is large, implying damage will limit mostly to the bolts, which can be easily replaced after the earthquake events.

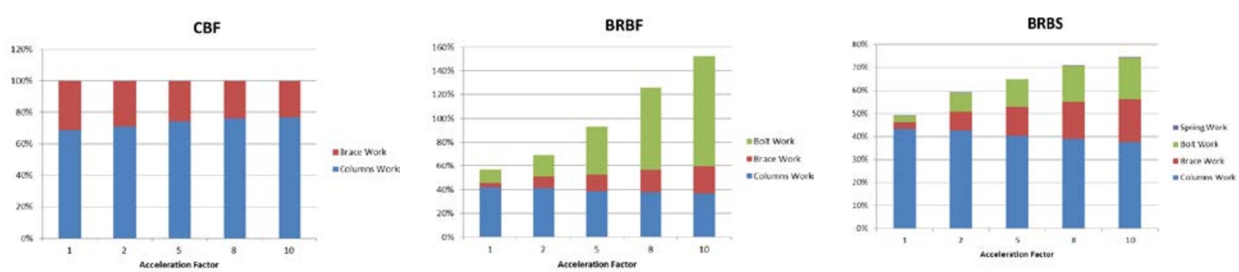

Figure 10. Work done by different components in the frame

6. DISCUSSION

The above experimental and numerical results demonstrated the effectiveness of this new non-buckling brace member designs. Besides non-buckling, it also has advantages of light weight, easy to install, and has only minimum residual deformation after unloading. The primary disadvantage is that it can only resist tensile force therefore they must be used in pairs. Compared to BRB, in which the designed yielding portion can be the entire length of the brace member, which therefore can absorb more seismic energy through plastic deformations. The length of the yielding segment of the proposed brace member can also be increased in the design to increase the seismic energy absorption capacity. This can be achieved by using longer yielding members or using multiple segments with more number of yielding members. Further study of this innovative design will be carried out. This simple design provides an alternative for effective and economic structural retrofitting to resist seismic ground motions.

7. CONCLUSION

This paper presents a new non-buckling segmented brace member that can be used to mitigate earthquake loading effects on frame structures. The preliminary laboratory tests and numerical simulations demonstrated the great performance of this new brace as compared with the conventional bracing members. Compared to the Buckling Restrained Braces (BRB), this new design also has the advantages of light weight, easy installation, controlled damage location and easy replacement. It can be a good bracing member that can be used in frame structures to resist earthquake ground excitations. Further works will be carried out to test the members in structural frames, and investigate the effectiveness of placing dampers in the segment joints, and using multiple segments.

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