Cu-Al-Mn Super-elastic Alloy Bars as Dissipative Brace System in Structural Steel Frame

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SUMMARY:
This paper investigates the applicability of Cu-Al-Mn super-elastic alloy (SEA) bar as a damping brace system in structural steel frame by performing shaking table tests. The problem with conventional steel brace system lies in its inability to restrain residual deformations in structures during and after intense earthquakes. The use of Cu-Al-Mn SEA bars as dissipative device is facilitated by its large recovery strain, low material cost and easier machinability. The experimental program involves an idealized one-third scaled one-bay one-storey steel frame system with crossed dissipative braces provided. For comparison purpose, two types of brace systems are used, steel brace system and Cu-Al-Mn SEA brace system. Conventional steel bracing system under high level of base excitation showed substantial residual drifts resulting in instability of the whole framed structure. On the other hand, SEA bracing with its recentering capability showed no residual deformations even under intense base excitations.

Keywords: Cu-Al-Mn super elastic alloy, structural steel frame, cross-bracing system, shaking table test

1. INTRODUCTION

Several studies on control over behaviour of structures when subjected to large seismic excitations has resulted in development of large numbers of passive seismic protection devices both in existing and new constructions. However, current technologies do come with some limitations such as, problems related to ageing and durability as seen in case of rubber components. Furthermore, retrofitting or replacement of damaged structures that are based on steel yielding is normally difficult and in some situations impractical due to large residual drifts and excessive damages. The present study concentrates on application of high performance material, namely superelastic alloy (SEA) bars as partial replacement to the conventional steel bars as brace system to solve the above listed problems with recentering capability to negate any residual deformation and possibility of effective immediate occupancy of inhibitants. A typical schematic representation of this mechanism when subjected to reverse cyclic loading post plastic yielding of braces can be seen in Fig. 1. Majority of previous researches (Dolce et al. 2000, McCormick et al. 2007) have concentrated on use of NiTi alloy SEA wires or bars whose application is largely limited due to high cost and low machinability. Hence, the authors propose application of newly developed Cu-Al-Mn SEA bars developed by Sutou et al. (2005) and Araki et al. (2010, 2012) whose production cost is significantly lower to NiTi SEA bars with highly superior machinability. Effectiveness on possible application of these Cu-based SEA bars has previously been studied on masonry constructions and concrete beam structures (Shrestha et al. 2011, 2012). This paper presents its effectiveness as brace system in steel framed structure.

2. TEST SETUP AND BRACE SYSTEM

Single bay one storey steel frame system is placed on a 1mx0.6m shaking table as shown in Fig. 2 with front view showing the shaking direction (X-direction) and the side view showing the lateral direction (Y-direction) of shaking. Four unequal angle sections 125mm x 75mm x 7mm are placed

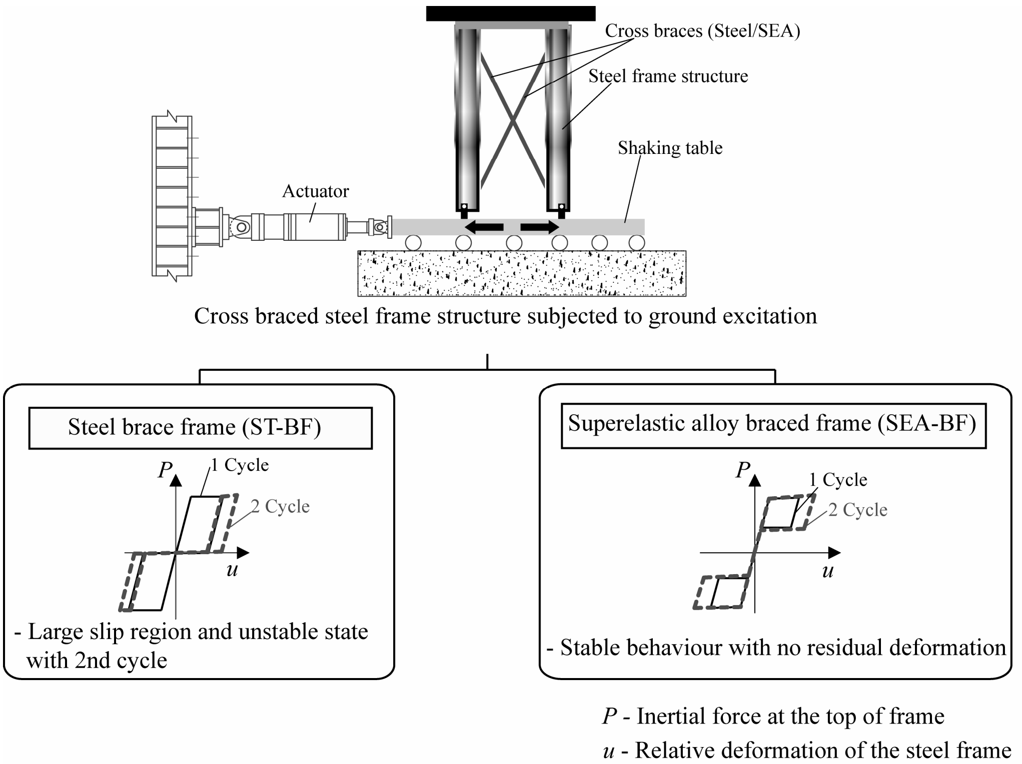


Figure 1. Expected behaviour of steel frame structure based on hysteresis of brace type used

above two base plates through special groove connections welded to the base plates with longer legs in X-direction. After insertion of pin, snap rings are used to connect the angle section leg (longer) to the steel groove. At the top, the angle sections are connected to each other through steel plates on longer legs in X-direction and angle sections (75mmx75mmx6mm) on shorter legs in Y-direction. Main bracing system is connected through the base plate (at the bottom) and angle section (at the top). Two main braces, Brace-1 and Brace-2 are connected in X-direction. Two lateral braces (32mmx6mm) are also connected in Y-direction to keep the frame stable. Steel plate (1200mmx450mmx80mm) of mass 350kg is attached to the top of frame. Care is taken so that the frame does not rotate during the excitation. Here all the steel members used are of SS400 type.

The main bracing system and its components are shown in Fig. 3. The system, at the top, has SEA or steel bar (SNR400B-4mm diameter) connected through the coupler to the threaded steel bar (10mm diameter, 120mm in length). The bottom portion has 12mm diameter steel bar (860mm in length). Both these top and bottom parts are connected to a special attachment member as shown in Fig. 3. The connection is made such that each brace would work only in tension. For this, the top part of attachment member is kept free in compression and the bottom part is fixed with lock-nuts on both sides. The specimens are differentiated as ST-BF and SEA-BF depending on the type of bars used at the top portion of the bracing system. The SEA or steel bars used in the bracing system is of length 150mm. Here the SEA or steel bar has the central portion (110mm in length) with reduced diameter of 4mm and sides (20mm in length) were threaded at diameter of 8mm as shown in Fig. 3 (bottom). The SEA bars used in SEA-BF specimen were pre-trained up to strain level of 5%. Stress-strain curve during pre-training of each SEA bar used is shown in Figs. 4 (a) and (b). Fig. 4(c) shows the stress-strain characteristics of steel bar used.

Preliminary small-amplitude sine wave tests were done to determine the dynamic properties of each specimen. The 1st mode natural frequency of vibration calculated for ST-BF specimen was 8.1 Hz and for SEA-BF was 7.87 Hz. Damping ratio (*h*) was determined using the original free-vibration trace fitted with a straight-line in the logarithmic plot (Lam et al. 2003) and the values for *h* calculated were 3.1% and 4.9% for ST-BF and SEA-BF specimens respectively.

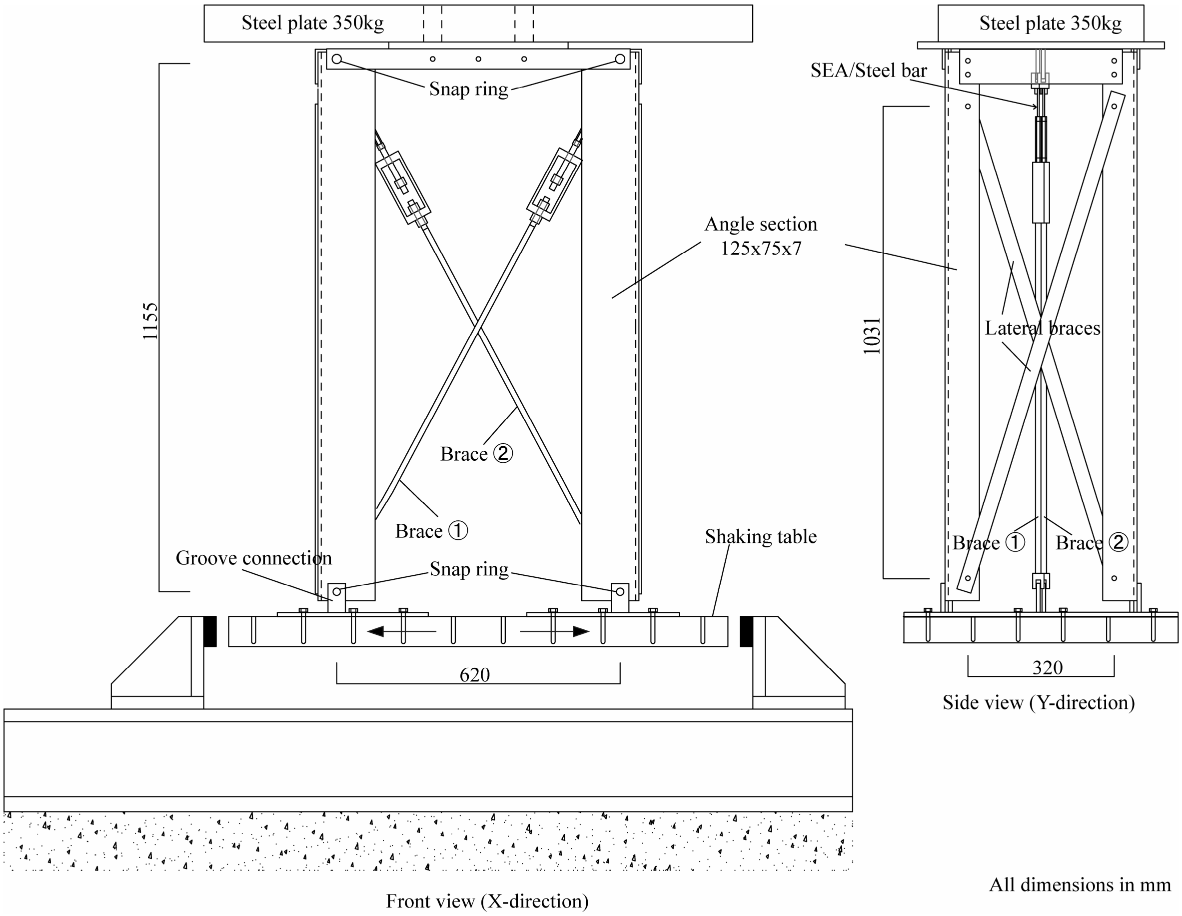


Figure 2. Test set-up with steel frame structure on shaking table

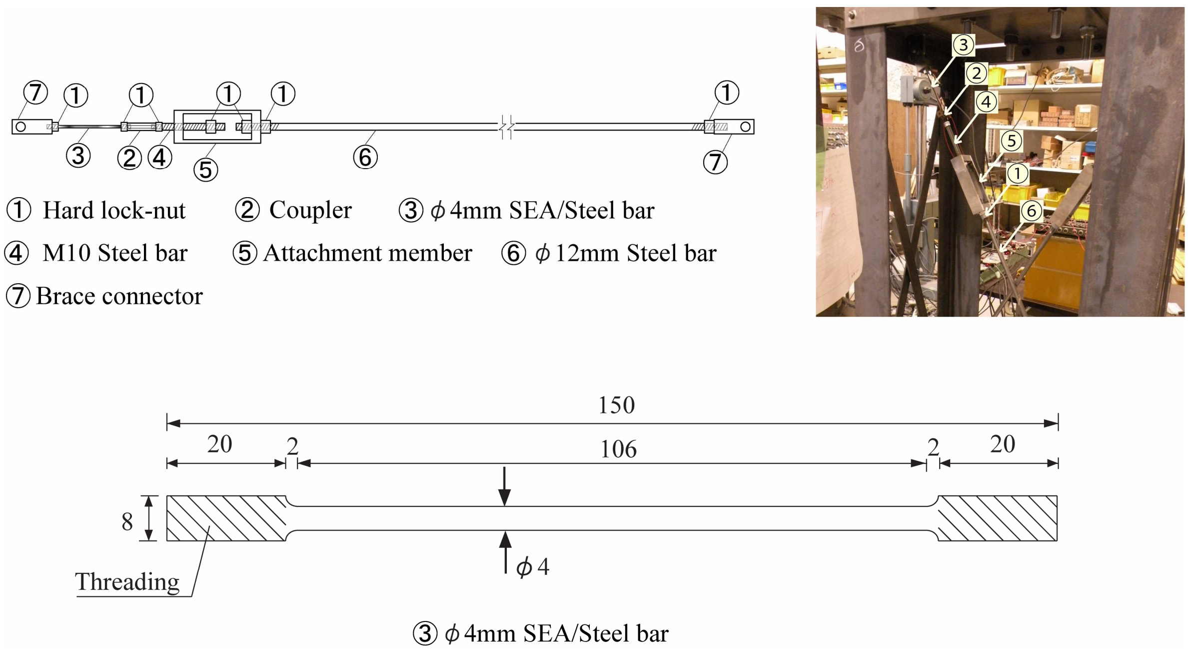


Figure 3. Brace system

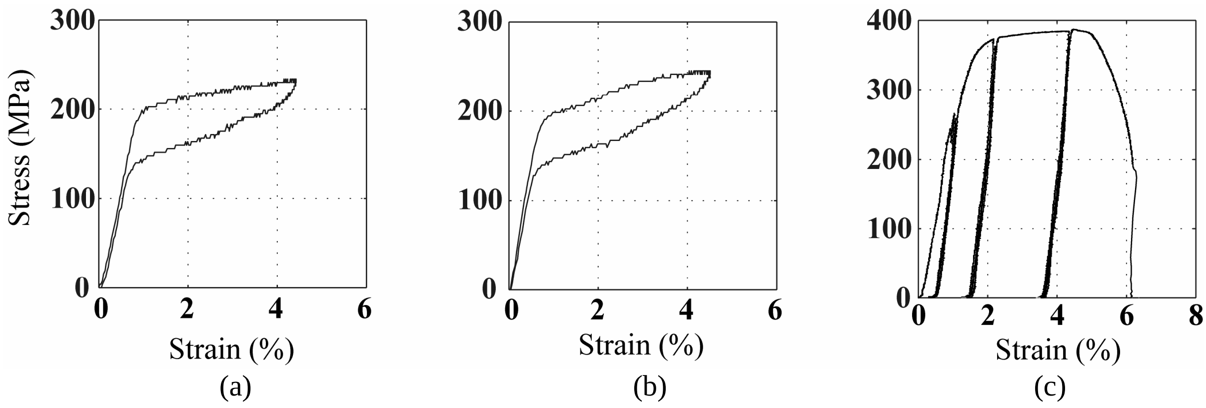


Figure 4. Results of preliminary cyclic loading tests for SEA and Steel bars

3. LOADING PROGRAM AND INSTRUMENTATION

10 cycle sinusoidal waves of frequency 1.5Hz as shown in Fig. 5(a) are given through the shaking table with amplitude of vibration 5mm (RUN1), 10mm (RUN2), 15mm (RUN3), 20mm (RUN4), 25mm-First run (RUN5), 25mm-Second run (RUN6).

Accelerometers (A1, A2) are attached to the shaking table and the top of the steel plate as shown in Fig. 5(b). Laser displacement transducers are used to get the displacement records during the experiment. Cross-marks in Fig. 5 show the locations of displacement records.

4. RESULTS AND DISCUSSIONS

Visual observations for both ST-BR and SEA-BR specimens showed no significant difference in response until RUN 4. However, with the commencement of RUN5, ST-BF specimen showed significant residual deformation due to yielding of steel bars. At RUN6, ST-BF specimen showed visually unstable behaviour with large residual drifts and ultimately resulted in the fracture of steel bars in the brace system (Brace-2) as shown in Fig. 6(a).SEA-BF specimen showed comparatively superior behaviour with no residual deformation visible and no fracture of SEA bars used at the end of RUN6 as shown in Fig. 6(b). A more detailed discussion on the response of each specimen is given below.

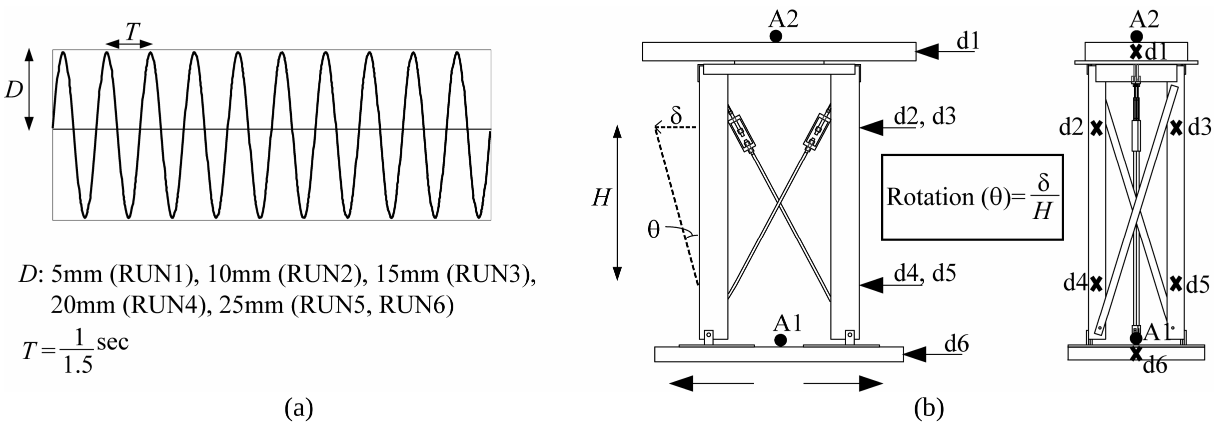
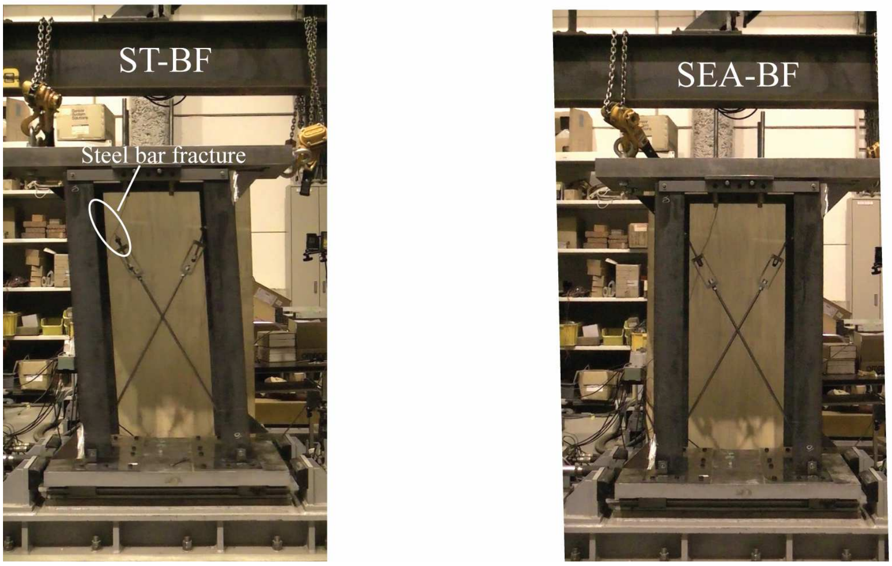


Figure 5. (a) Sinusoidal loading program, (b) Locations for displacement transducers and accelerometers



(a) (b)

Figure 6. Deformed shapes at the end of RUN6: (a) ST-BF specimen, (b) SEA-BF specimen

Fig. 7 shows the acceleration rotation hysteresis plot for ST-BF specimen. RUN5 and RUN6 with peak ground acceleration (PGA) of 0.54*g*, where *g* is the gravity acceleration, shows the pinching behaviour with presence of residual deformation at the end of each loading cycle. Fig. 8 for SEA-BF specimen shows largely stable behaviour with no pinching and the super-elastic property of SEA bars ensures recentering with no residual deformation of the specimen.

Figs. 9 and 8 show rotation angle histories for ST-BF and SEA-BF specimens. For ST-BF specimen, at the end of RUN5, residual deformation of 1.55mm (rotation angle = 0.0026 rad) was observed as shown in Fig. 9(a). Prior residual deformation and RUN6 (Fig. 9(b)) resulted in the subsequent large deformation of the ST-BF and fracture of one of the steel braces. SEA-BF specimen showed no residual deformation as seen in its time history in Fig. 10. At the end of each loading cycle, the recentering capability of the SEA bracings resulted in comparatively stable and superior behaviour.

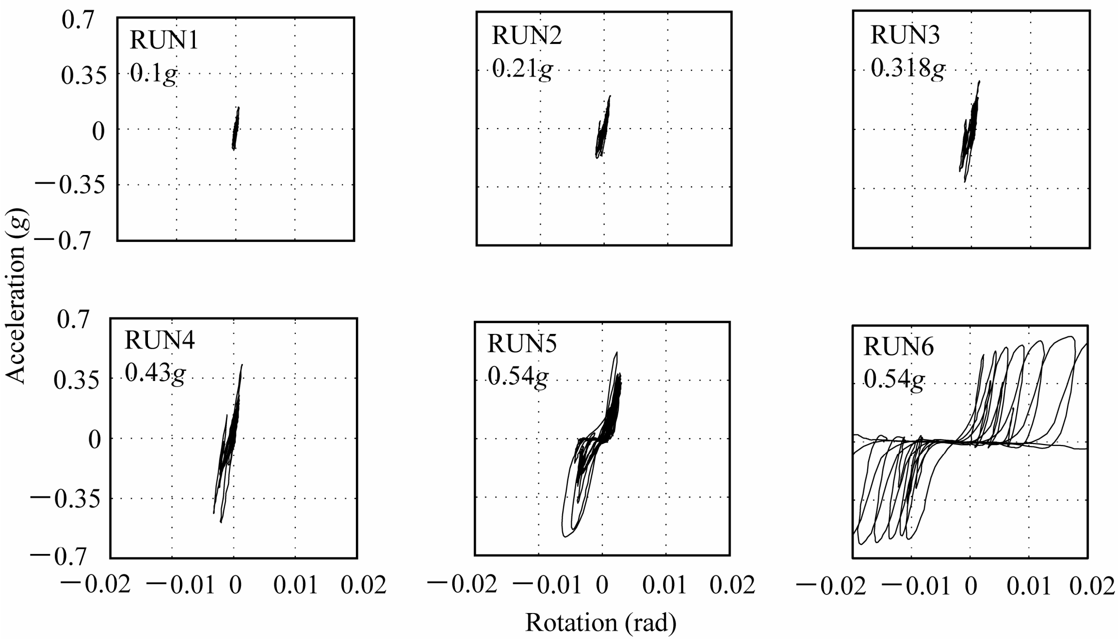


Figure 7. Acceleration-rotation plots for ST-BF specimen

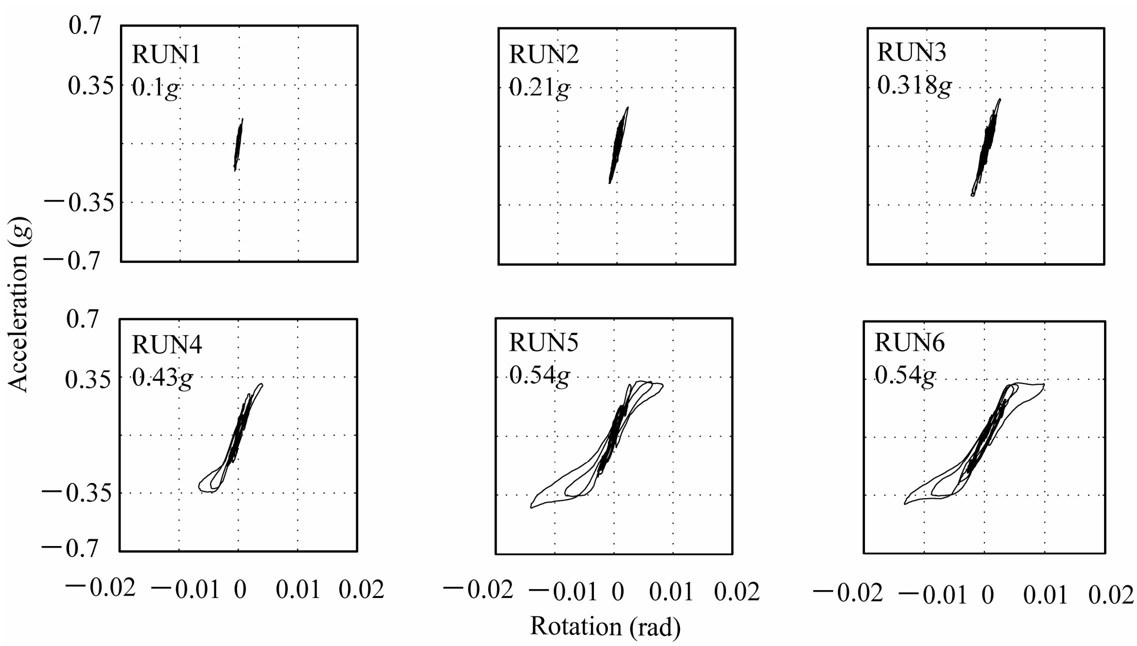


Figure 8. Acceleration-rotation plots for SEA-BF specimen

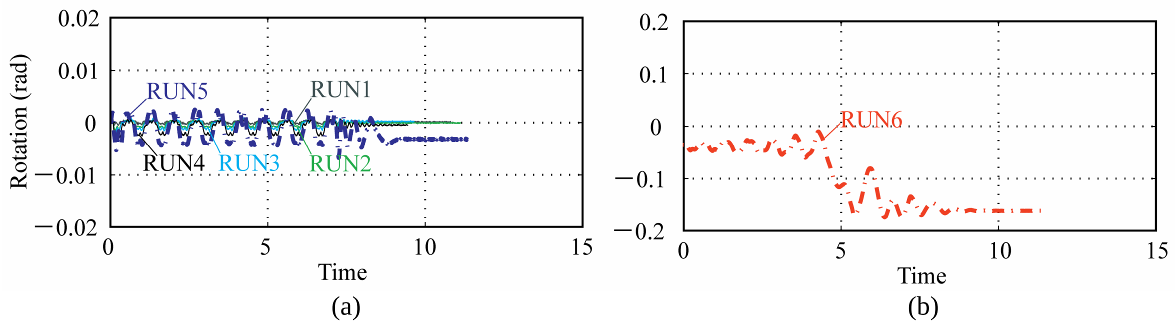


Figure 9. Rotation time history for ST-BF specimen: (a) Upto RUN5, (b) RUN6

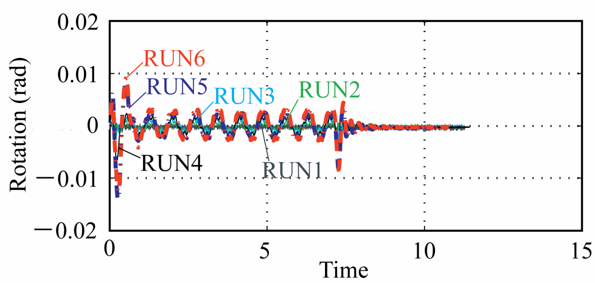


Figure 10. Rotation time history for SEA-BF specimen

5. CONCLUSION

An experimental work was done to investigate the effectiveness of Cu-Al-Mn SEA bar as brace system in steel frame structure with dynamic tests done on one-third scaled single storey single bay steel frame model. Comparisons were made between conventional steel brace system and SEA brace system in terms of their response at different levels of ground excitations. Test showed clearly that conventional steel brace frame structure showed comparatively unstable behaviour with large residual deformation post yielding of steel bars. The large residual deformations and excessive plastic elongation of steel bars subsequently results in fracture of steel brace system during the tests at PGA level of 0.54*g*. SEA brace frame, in comparison, showed far superior response with strong recentering capability shown by the SEA bars used. The superelastic properties of SEA brace system ensured no residual deformation at the end of each loading cycle and clearly showed its effectiveness over conventional steel brace systems.

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