16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 4198

Registration Code: S-I1463228903

EXPERIMENTAL EVALUATION OF ALUMINUM CORE BUCKLING RESTRAINED KNEE BRACED TRUSS MOMENT FRAME UNDER CYCLIC LOADS

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Abstract

Buckling Restrained Braces (BRBs) offer robust cyclic performance and significant cost savings, compared to conventional bracing systems. These braces are becoming increasingly popular alternative to conventional bracing system in high seismic regions due to their ability to yield both in tension and compression. Buckling Restrained Knee Braced-Truss Moment Frames (BRKB-TMFs) are relatively new structural systems which utilize the advantages of both BRBs and TMFs. Experimental study was performed on scaled subassembly of a four-story four-bay BRKB-TMF frame. BRKB-TMF frame was designed using Performance Based Plastic Design (PBPD) method with pre-selected target drift and yield mechanism as key performance indicators. PBPD method ensures controlled distribution of inelastic activity throughout the structure by predefining Designated Yielding Members (DYMs) during the initial design process. These DYMs are designed to dissipate seismic input energy and all other frame members are designed to remain elastic under earthquake excitations. The use of annealed aluminum as a suitable BRB core material was explored. Quasi static cyclic tests were performed on a 1:3 reduced scale model of the BRKB-TMF sub-assemblage according to the provisions of FEMA 461 (2007). The application of BRB with annealed aluminum core significantly enhanced the energy dissipation capacity of the TMF. The BRB performed very satisfactorily and acted like a fuse for the frame by bearing all inelastic deformations. The study frame could successfully meet the 3% target drift imposed by MCE hazard level. The test assembly could even sustain two cycles of 3.75% lateral drift without any considerable damage to primary truss members.

Keywords: Aluminum Core; Buckling Restrained Brace; Truss Moment Frame; Performance Based Plastic Design

1. Introduction

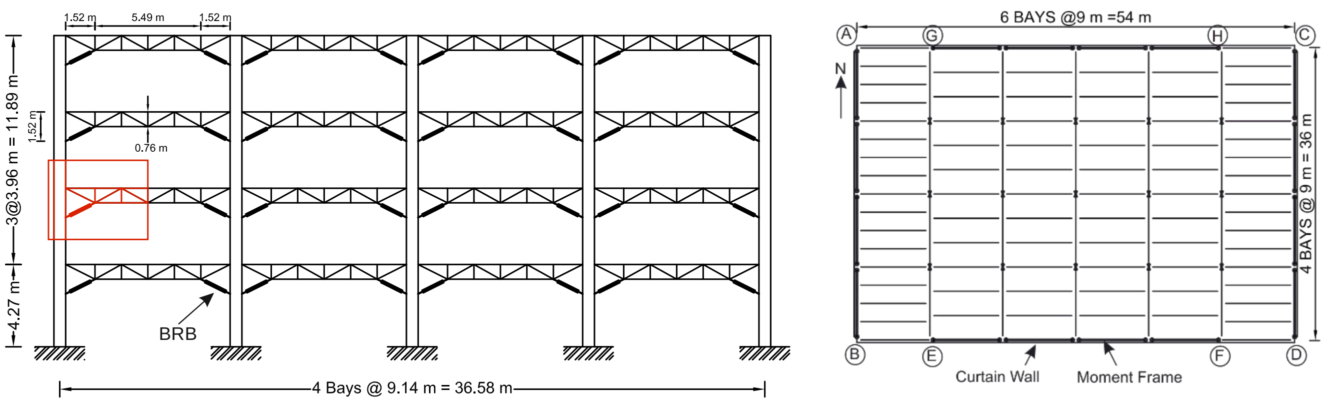
Open web truss moment frames are very commonly used in steel buildings for resisting gravity loads as well as lateral seismic loads. These framing systems have many advantages over moment resisting frames that use solid web beams, the most important one being economy and light weight, especially for long span lengths. However, earlier studies by Goel and Itani [1] on sub-assemblage of an open web truss moment frame designed according to UBC 1988 [2] revealed its poor behavior due to buckling and fracture of truss web members under cycling loading. The research efforts to improvise the performance of truss moment frames (TMFs) lead to the investigation of alternatively designed systems called special truss moment frames (STMFs), where the inelastic deformations due to seismic events were restricted in a specially designed portion of trusses, called special segment while the rest of the frame was designed to behave elastically [3]. Experimental and analytical studies on STMFs with X-diagonal segment [4] and Vierendeel segment [3] revealed excellent inelastic response of special trusses in moment frames when subjected to severe seismic loading. The confinement of inelastic deformations in the specially designed truss segments made the post-earthquake retrofit of the structure quite easy.

Though the damage due to seismic loads was concentrated within a special segment in STMFs, an intention to keep the damage away from truss girders motivated researchers to investigate new innovative framing systems with enhanced performance in terms of safety and economy. Singh and Rai [5] conducted experimental and analytical studies on a scaled Buckling Restrained Knee Braced Truss Moment Frame (BRKB-TMF) to assess the ability of BRB in improving the seismic performance of truss moment frames. The frame was designed by following the provisions of Performance Based Plastic Design (PBPD) [6] such that the inelastic deformations under seismic events are concentrated in BRBs and all the truss members behave elastically. An innovative method to design light weight BRBs using annealed alloys of aluminum was proposed and tests were conducted on the BRBs to verify their ability to sustain expected cyclic axial forces and deformations. BRBs were found to be very effective in controlling the seismic response of the TMF and excellent damping characteristics were observed in BRKB-TMF due to presence of BRBs. Wongpakdee et al. [7] carried out an analytical study to evaluate the performance of BRKB-TMF. The structure was designed using the provisions of PBPD and was subjected to non-linear static (pushover) and dynamic analysis. The system showed excellent response up to target drift with all the inelastic deformations confined to the BRBs.

BRKB-TMFs are relatively new structural systems and the performance of the truss members in BRKB-TMFs at high structural drift values is not very well studied. The interaction of the surrounding frame members, gusset plates and the BRB itself is comparatively unknown. Past studies by Singh and Rai [5], on BRKB-TMFs have shown that with the introduction of BRBs the energy dissipation capacity of the system is greatly enhanced without considerably decrease in the stiffness of the structure. The present study is an extension of research in this area. Aim of this study is to simulate realistic boundary conditions on sub-assembly of a BRKB-TMF designed using PBPD and to verify different aspects of the concept design, such as overall inelastic behavior, development of the selected yield mechanism, and the interaction between the truss and the BRB. This paper describes the results of the experimental studies performed to evaluate the performance of BRKB-TMF sub-assemblage.

2. Experimental Program

A typical four bay four story building analytically studied by Wongpakdee et al. [7] is considered as prototype frame in this study. The chosen structure was originally designed by Goel and Chao [6] as a moment resisting frame. The building has two moment frames in each direction (AB, CD in N-S direction and EF, GH in E-W direction). The building is 54 m long (6 bays @ 9 m) in the E-W direction and 36 m (4 bays @ 9 m) long in the N-S direction. The plan and elevation view of the building are shown in Fig. 1. The prototype building belongs to seismic group 1 and soil type D [8]. The ground motion parameters used to calculate design seismic forces are $S_1 = 0.6\,g$ and $S_s = 1.5\,g$, where S_s is the mapped MCE spectral response acceleration parameter at short periods (0.2 s) and S_1 is the mapped MCE spectral response acceleration parameter at a period of 1 s. The estimated fundamental time period of the structure is 0.94 s. The archetype structure is designed for two seismic hazard levels: the maximum considered earthquake (MCE) with 2% probability of exceedance in 50 years, and the design basis earthquake (DBE) defined to be 2/3 of MCE intensity. The design spectral acceleration is 0.96 *g* for the maximum considered earthquake (MCE) level and 0.64 *g* for 2/3 MCE level. The target drifts is selected to be 3% for MCE level and 2% for the 2/3 MCE level. Yield drift ratio is assumed to be 0.75%. Member forces are calculated using PBPD methodology. The 2% target drift at 2/3 MCE level was found to be governing for the calculation of design base shear [7]. Table 1 summarizes the design sections proposed by Wongpakdee et al., [7] for the BRKB-TMF under study.



(a) Elevation view [7] (b) Plan view [6]

Fig. 1 – Elevation view and plan view of the prototype building

Table 1 - Summary of member sizes [7]

Level	Truss Chord	Truss Diagonal	Exterior Column	Interior Column	BRB Capacity (kN)
Floor 2	2MC200×31.8	2MC150×22.5	W610×262	W610×341	920
Floor 3	2MC180×28.4	2C180×22	W610×262	W610×341	850
Floor 4	2MC150×24.3	2MC150×17.9	W610×174	W610×285	700
Roof	2MC100×20.5	2C150×15.6	W610×174	W610×285	460

2.1 Specimen Details

A 1:3 scaled model of the third floor exterior beam column sub-assembly, highlighted in Fig. 1, was used as the test specimen in this study. Similitude laws were used to scale the prototype test sub-assemblage to a 1:3 reduced scale model. The truss members and the column were designed to remain elastic for maximum BRB force adjusted for its overstrength. The overstrength factors for tensile, ω, and compressive forces, $\beta\omega$, were taken equal to 1.5 and 1.75, respectively [7]. Fig. 2 shows the schematic drawing of the model sub-assemblage.

Tension and compression members were designed as axial members for the scaled forces by using the provisions of IS 800 [9]. Unequal legged double angle sections were used to design the truss members and the wider leg was used to connect them with gusset plates. Stiffening plates were provided in top chord members in order to provide sufficient cross-sectional area so that the members could resist the design tensile and compressive forces. This was done to avoid the usage of too wide legged angle sections which were found to disrupt geometry of the truss beam. The vertical members are zero force members under pinned boundary conditions, however they can attract significant axial forces due to fixity of the welded connection between the top chord and the column. Hence, the forces in vertical members were calculated after designing TC1 by following the ‘truss design concept’ as outlined in Wongpakdee et al. [7]. The column was designed as a beam-column by using the provisions of IS 800 [9]. After accounting for the small change in the dimensions of model sub-assemblage for the ease of experimental setup and scaling down the member forces by following similitude laws, the required yield strength of the BRB in scaled sub-assemblage was calculated equal to 83 kN [10].

Member Label	Design Section
Top Chord (TC1, TC2, TC3)	2L 45mmX30mmX4mm*
Bottom Chord (BC1, BC2)	2L 45mm×30mm×4mm
Diagonal 1 (D1)	2L 30mm×20mm×4mm
Diagonal 2,3 (D2, D3)	2L 45mm×30mm×4mm
Vertical 1 (V1)	2L 30mm×20mm×4mm
Vertical 2,3 (V2, V3)	L 30mm×20mm×4mm
Column	ISMB 175 @19.3 kg/m (b_f = 90 mm, d =175 mm)

*with 2@ 5 mm thick mild steel stiffener plates for TC1 and TC2

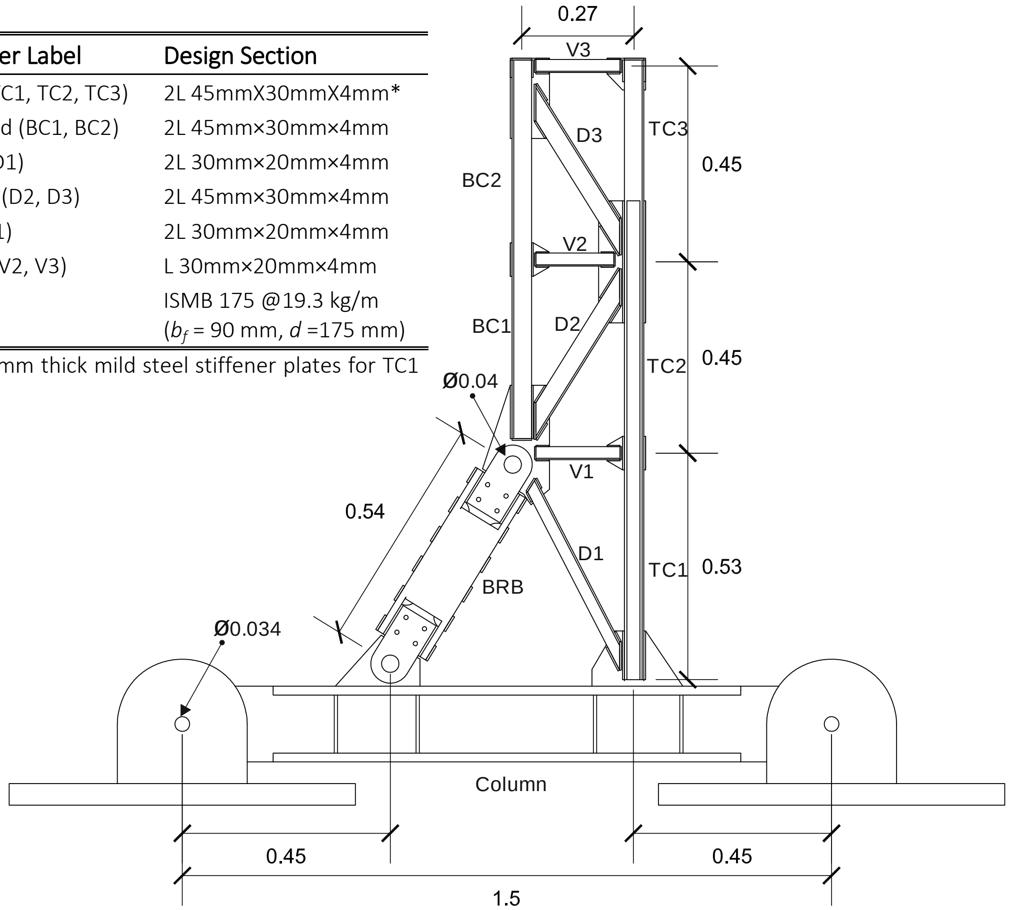
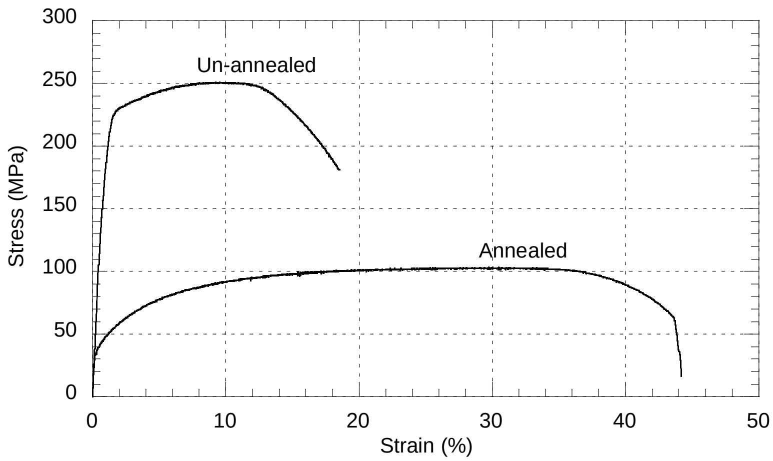


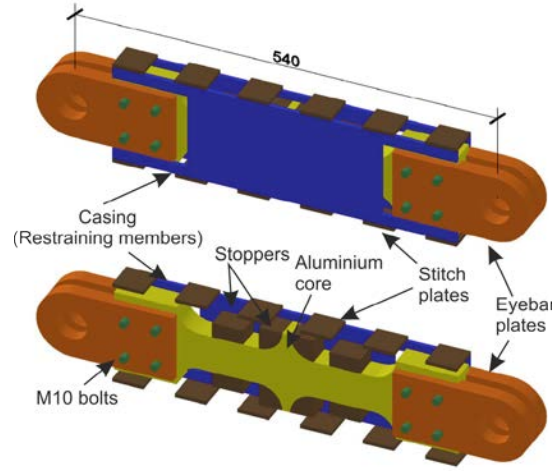
Fig. 2 – Schematic diagram of the designed model sub-assemblage (All dimensions are in meters)

In the present study the use of annealed aluminum as a suitable BRB core material as proposed by Singh and Rai [5] was further explored. The aluminum alloy 6061-T4 with alloying elements magnesium and silicon was used to fabricate the BRB core. The aluminum core of the BRB was annealed to soften the material, increase its ductility, relieve the internal stresses and achieve higher strain hardening. Low yield strength is a desirable property to make BRB core because it allows the use of thicker core which reduces the possibility of local and global buckling of BRB. Material properties of aluminum used in the fabrication of BRB core were determined from tensile testing of annealed and un-annealed aluminum coupons. Stress strain plots obtained from the coupon tests are compared in Fig. 3a. The overstrength factor for un-annealed and annealed aluminum was observed to be a 1.27 and 2.7, respectively. The higher overstrength factor is beneficial because it enhances the energy dissipation capacity of BRKB-TMFs without considerable decrease in stiffness of the structure.

The Fig. 3b shows the details of the aluminum core BRB used in the present study. The core consisted of the yielding middle segment of width 50 mm and non-yielding ends of width 110 mm. The two segments were connected to each other by elastic transition zone of radius 30 mm. The non-yielding segment was connected to the eye bar plate through M10 bolts of 10.9 grade. The casings were designed according to the overall buckling prevention criterion proposed by Usami et al. [11] to prevent the buckling about major axis and were not designed to carry any direct compressive loads. 130 mm×5mm steel plates were found to meet design requirements for aluminum BRB restraining members. Stoppers were provided along the length of the core in order to prevent its buckling about minor axis. A hump of height 30 mm was provided in the middle of the core to prevent the relative movement between the core and casings in the longitudinal as well as transverse direction. The annealed aluminum core was sandwiched between the stoppers and the restraining plates were connected with each other by welding stitch plates over them. Moreover, grease was used as debonding material to reduce the friction between aluminum core and steel casing in order to facilitate free translation of the aluminum core inside the casing.



(a)



(b)

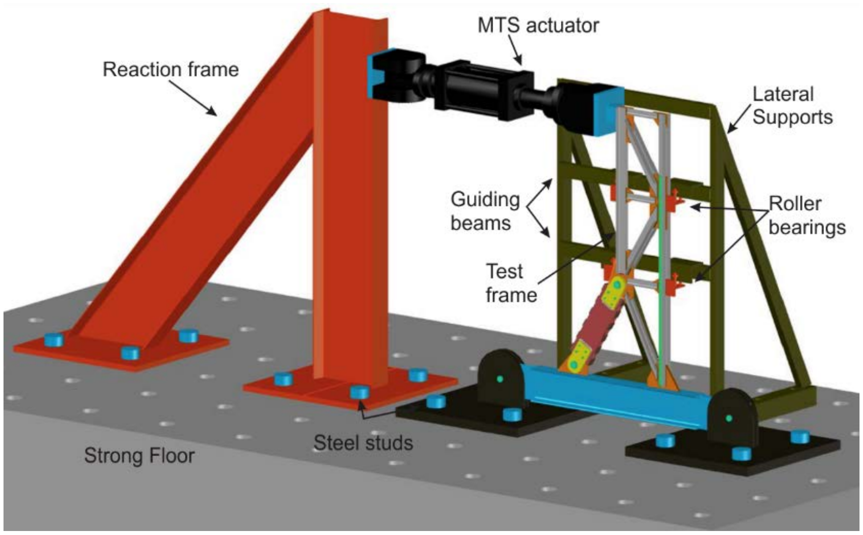
Fig. 3 – (a) Annealed and un-annealed aluminum coupon test results, (b) Details of aluminum core BRB

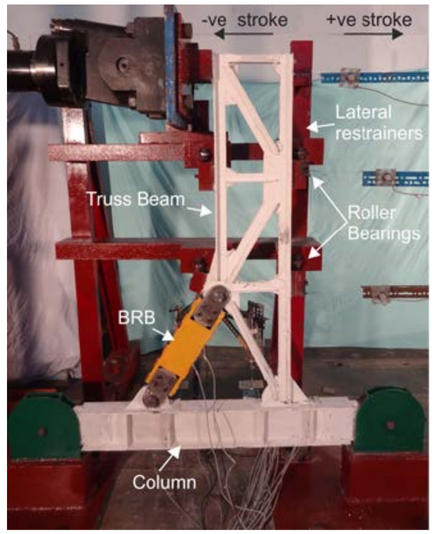
3. Cyclic Tests on BRKB-TMF

The set-up used for the cycling testing the BRKB-TMF sub-assemblage is shown in Fig. 4. The test specimen was mounted on the strong floor of the structural engineering lab at IIT Kanpur in order to test it under lateral loading. Servo-hydraulic MTS actuator of capacity 250 kN and stroke 125 mm was used to apply cyclic lateral load. The out of plane movement of the sub-assemblage was restrained by using lateral supports on one side of the test frame. The frame was firmly held to the strong floor of the laboratory by means of anchorage bolts so that any possible vertical movement or sliding of the frame under lateral load could be prevented. Replication of realistic boundary conditions on the test specimen is an important aspect of sub-assemblage testing. In this study, the desired boundary conditions were enforced by simulating pinned connections at BRB and column ends as shown in Fig. 4.

Appropriate number of sensors were used to measure the response of various components of the frame under lateral loading, as shown in Fig. 5. Quarter-bridge electrical resistance strain gauges of 350 Ω resistances were installed on the truss members at various locations. One strain gauge was installed on each angle of the built-up section so that the composite action of these sections could be confirmed. Strain gauges labelled 1-14 were installed approximately on the neutral axis at mid-length of the sections in order to monitor the axial strains in different truss members. Relative to other locations in frame, high bending strains were expected near the beam column connection, hence strain gauges labeled 15-22 were installed near the connection region in order to study the effect of bending strains on member strength deterioration. Wire potentiometers of stroke length ±270 mm were used to measure the displacement of truss beam along its height. Two LVDTs (Linear variable differential transformers) of ±50 mm stroke were provided near the beam column connections to obtain the deformation profile of the column. One LVDT of ±50 mm stroke was installed along the BRB in order to monitor core deformations.

Cyclic tests were performed on BRKB-TMF according to the provisions of FEMA 461 [12] , to access its seismic capacity and to verify the design methodology used in the present study. The Fig. 6 shows the loading protocol used for cyclic testing. The loading protocol was formulated such that 8 drift levels were executed before reaching the yield deformation. The loading amplitude was gradually increased till the failure of the test specimen was observed. Each displacement cycle was repeated for two times at a frequency of 0.02 Hz.





(a) (b)

Fig. 4 – BRKN-TMF sub assemblage testing for lateral cyclic loads (a) Schematic of the test-setup and (b) photograph of the test specimen

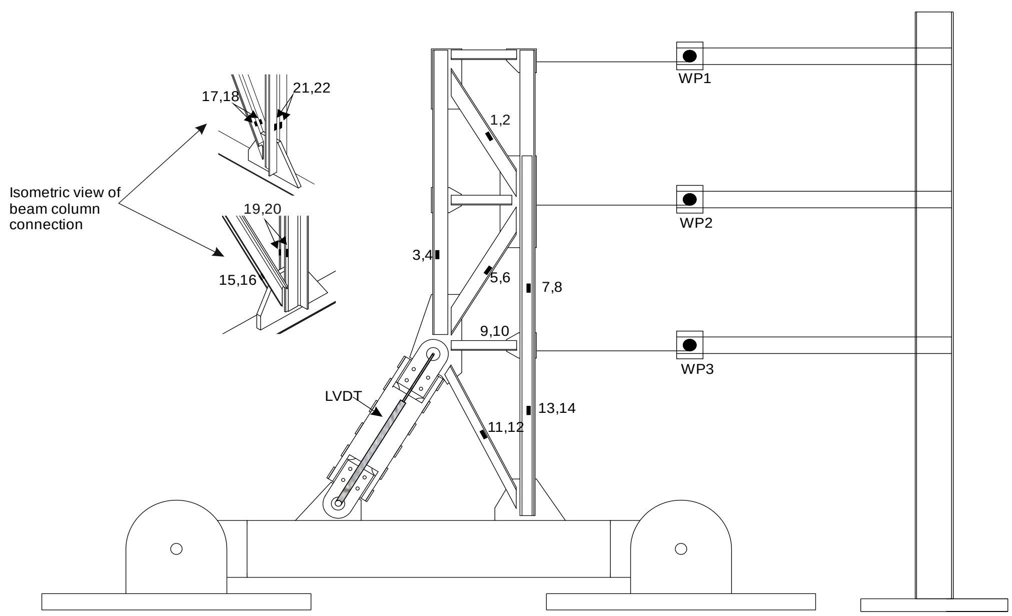
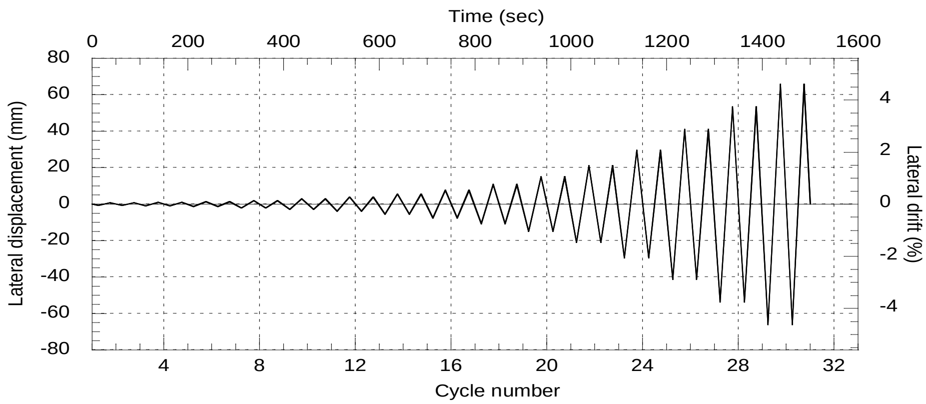


Fig. 5 – Instrumentation details

4. Results of Experimental Testing

4.1 Physical Observations during Testing of BRKB-TMF Sub Assemblage

Minor slippage in the BRB pinhole connection was observed in drift level 11 (1.47% drift) and it persisted in the following cycles. Minor flaking of whitewash was observed at the ends of D1 and TC1 near their connection with column gusset plate during drift level 13 (2.88% drift). Flaking of whitewash in the D1 further increased in the following drift level 14 (3.75% drift). The Fig. 7 illustrates the progression of flaking of whitewash at the connection of members D1 and TC1 with column gusset plate at the end of drift level 13 and 14.



Drift level	Amplitude (mm)	Drift (%)
1	0.73	0.05
2	1.02	0.07
3	1.42	0.10
4	1.99	0.14
5	2.79	0.20
6	3.91	0.27
7	5.47	0.38
8	7.66	0.54
9	10.73	0.75
10	15.02	1.05
11	21.02	1.47
12	29.43	2.06
13	41.20	2.88
14	53.56	3.75
15	65.92	4.61

Fig. 6 – FEMA 461 loading protocol for cyclic testing of BRKB-TMF sub-assemblage

(a) (b) (c)

Fig. 7 – Connection of T1, D1 with column gusset plate: (a) Before starting the test, (b) At end of DL 13, and (c) At end of DL 14

Asymmetric deformations in BRB core length were spotted in the drift level 12 (2.06% drift). The inelastic deformations started concentrating towards the beam end of the BRB and the concentration of inelastic activity kept on increasing in subsequent drift levels. At the end of drift level 14, significantly large asymmetric deformations were observed in the BRB core which led to almost closure of the gap between BRB core and beam gusset plate. As a result of this the gusset plate at the beam end of the BRB came in contact with the restraining members in the next cycle of 4.61% lateral drift, which led to transfer of direct compressive loads from the gusset plate to the BRB restraining members. This was followed by buckling of the restraining members and the aluminum BRB core. The Fig. 8 illustrates the failure of BRB under compressive loading.

(a) (b) (c) (d)

Fig. 8 – BRB failure after drift level 15: (a) Front view of BRB, (b) Side view of BRB, (c) Front view of core, and (d) Side view of core

4.2 Global Response

The Fig. 9 shows the hysteretic behavior of the BRKB-TMF under cyclic loading. The actuator load normalized with the actuator load corresponding to design base shear (51 kN) has been plotted on the second y axis. The peak load of 73.5 kN reached during the second negative excursion at 3.75% drift. Maximum load of 60.8 kN was observed during the first positive excursion at 3.75% drift. The observation of higher lateral load during negative excursions can be attributed to higher load carrying capacity of BRB due to confinement of core under compression. Small slippage was observed under load reversal in the hysteretic response. This slippage can be ascribed to bearing deformations at the BRB pin connection.

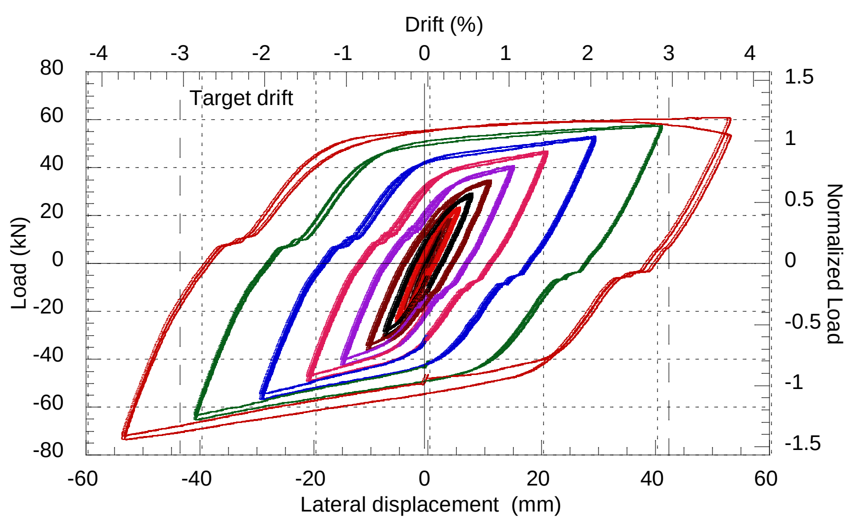


Fig. 9 – Hysteretic response of the BRKB-TMF under cyclic testing

At 2% drift, the frame attracted lateral load of 52.7 kN and -54.3 kN under +ve and –ve actuator stroke, respectively. These loads are very close to the design load of 51 kN for 2% drift at 2/3 MCE level. Load drop was observed during the second positive excursion at 3.75% drift. This can be because of the yielding of diagonal element, D1 as observed by flaking of whitewash in Fig. 7. The frame could sustain lateral load equal to 1.4 times the design load of 51 kN. The specimen successfully completed two cycles at 3.75% drift without significant load deterioration and damage to truss members, therefore, the acceptance criterion of 3% lateral drift for this specimen was satisfied.

Backbone curve of the sub-assemblage, also referred to as envelop plot is presented in Fig. 10. Maximum lateral displacement during each drift level was plotted with the corresponding actuator load to obtain the envelop curve. The backbone curve showed a smooth trend until 2.88% drift after which a strength drop was observed. It can be seen from the backbone plot that the frame yielded at around 0.27% drift. The backbone curve was almost regular and stable with most of the area under the curve in the plastic region. Good post yield behavior of BRKB-TMF was observed as expected.

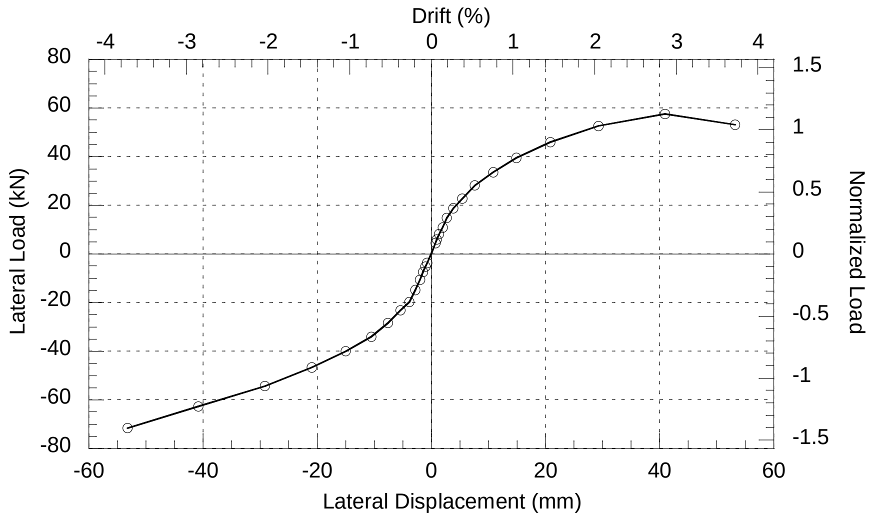


Fig. 10 – Backbone curve of BRKB-TMF sub-assemblage

The Fig. 11 shows the hysteretic response of BRB under cyclic testing of BRKB-TMF. Data obtained from the LVDT installed along the BRB was used to calculate the BRB deformation during cyclic testing. The BRB force was calculated by writing the moment equilibrium about the beam column connection and the moments due to beam-column fixity were assumed to be negligible in calculation of BRB forces. As expected the BRB exhibited very stable response and could sustain a maximum load of 204 kN under compression and 168 kN under tension. It yielded at core strain of 0.13% and could take maximum of 6% strain in both tension and compression.

The total energy dissipated by the BRKB-TMF and the BRB contribution in energy dissipation were calculated from the area under their hysteretic curves in different loading cycles. The Fig. 12a shows the energy per cycle dissipated by the frame and the BRB at different drift levels and the Fig. 12b shows the percentage contribution of BRB in dissipating total energy. The total energy dissipated and the BRB contribution reached a maximum value of 8.3 kN-m and 7.3 kN-m, respectively in DL-14 (3.75% drift). It can be seen from Fig. 12b that percentage contribution of BRB in dissipating energy remained almost constant through all drift levels. On an average the BRB dissipated 90% of the total energy in all drift levels. Hence, it can be concluded that the application of BRB significantly increased the energy dissipation capacity of the frame.

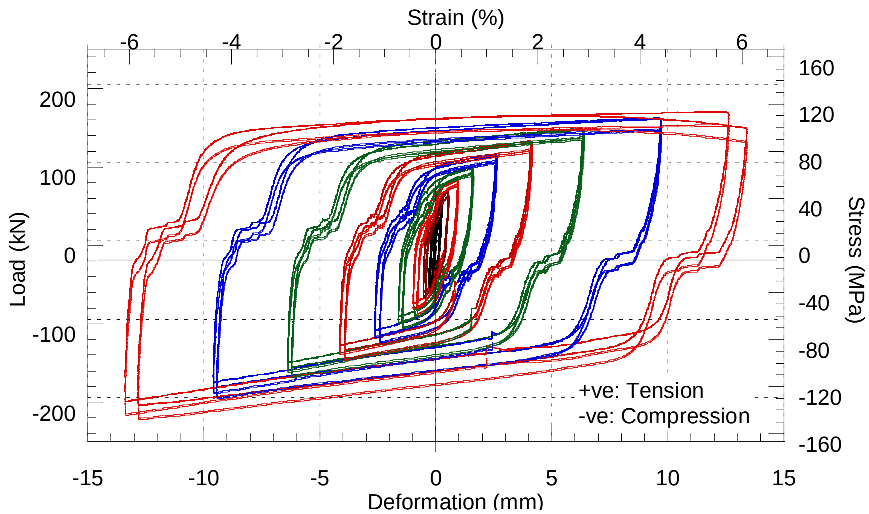


Fig. 11 – Hysteretic response of BRB under cyclic testing of BRKB-TMF

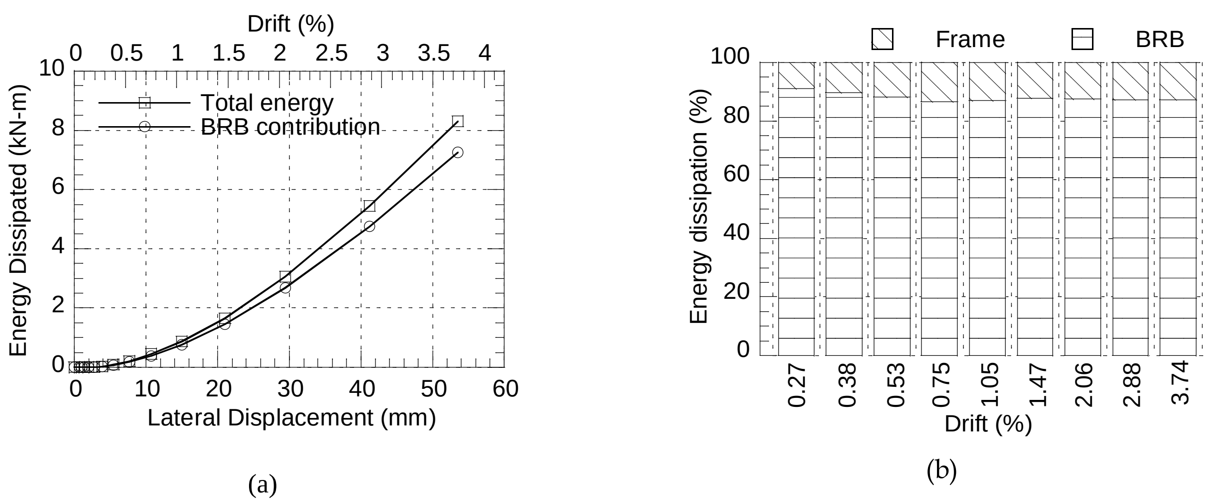


Fig. 12 – Comparison of total hysteretic energy dissipated by frame and contribution of BRB

4.3 Local Response

The Fig. 13 shows the maximum axial strains experienced by frame members under different loading cycles. Both percentage strains and strains normalized by the yield strain (0.002 m/m) have been reported in the graph. Maximum strain of 0.13% was observed at the center of diagonal element D1. From the strain profiles it can be inferred that all members remained elastic under axial loads. The Fig. 14 shows the variation of strain across different drift levels at critical locations near beam column joint. In Fig. 14, D1-T is the toe of D1 near its connection with column gusset plate, D1-C is the bottom of the connecting leg of D1 near its connection with column. Similarly, TC1-C and TC1-T are the corresponding locations in TC1. Strain in the strain gauge installed at bottom of the connecting leg in D1 reached a value of 0.23% in DL 11 (1.47% drift), signifying initiation of yielding at the bottom of D1. Top chord, TC1 was also found to yield in DL 11 as the strain gauge installed on its toe reported a maximum value of 0.23%. Compressive strain as high as 1.13% was monitored at the bottom of connecting leg of diagonal element D1 in DL 14. High strain values in these locations were also demonstrated by flaking of whitewash in these regions during drift levels 13 and 14.

Though strain as high as 1.12% was observed in diagonal element D1, it did not have much detrimental effect on overall hysteretic response of the frame, as can be seen from Fig. 9, and the frame could successfully sustain 3.75% lateral drift. However, the yielding observed at these critical locations should be checked by carrying out further studies and arriving at suitable demand amplification factors to design members at these critical locations.

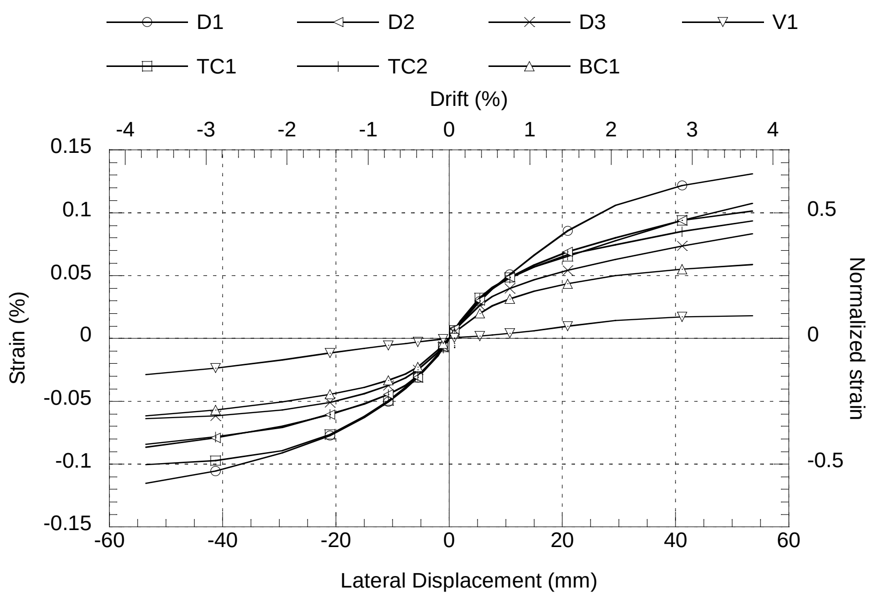


Fig. 13 – Maximum strains observed at middle of truss members

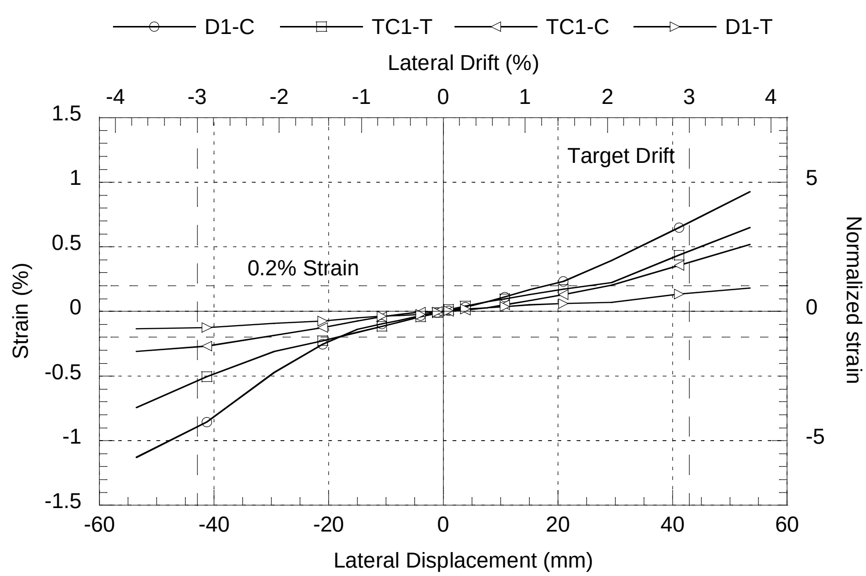


Fig. 14 – Maximum strain in D1 and TC1 near beam column connection

5. Conclusions

This study was concerned with the experimental evaluation of the sub-assemblage of a buckling restrained knee braced truss moment frame (BRKB-TMF) designed using the provisions of Performance Based Plastic Design (PBPD). The application of BRB with annealed aluminum core significantly enhanced the energy dissipation capacity of the TMF. On an average the BRB dissipated 90% of the total seismic energy in all drift levels. The

BRB performed very satisfactorily and acted like a fuse for the frame. Its performance in terms of its load carrying capacity and behavior of restraining members complied suitably with the design procedure. The restraining mechanism of BRB was very effective in preventing the buckling of core as well as increasing its energy dissipation capacity. The test confirms that the overall design method is satisfactory; however, the detailing issues regarding the provision of minimum clearance at the connection around the BRB are essential so that its deformation can be accommodated without the casing coming in contact with other elements. All truss members behaved elastically within the domain of target drift. However, some inelastic activity was observed in the truss members near the beam column connection during the drift levels of 2.9% and 3.75% drift, but it did not have any detrimental effect on load carrying capacity of the frame. These inelastic deformations can be attributed to the origin of secondary moments in truss members due to fixity at the beam column joint. In order to ensure elastic behavior of the members at these critical locations, it is recommended to design these members by accounting for the secondary moments at high drift levels.

6. Acknowledgements

The authors gratefully acknowledge the financial support from the Ministry of Human Resource Development and Poonam and Prabhu Goel Foundation at IIT Kanpur for research and outreach activities in Earthquake Engineering. The authors sincerely appreciate the support received from the staff of Structural Engineering Laboratory at Indian Institute of Technology Kanpur.

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