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Experimental study on steel beam-to-column joint strengthened by buckling-restrained knee brace using steel bar core

Togtokhbuyan Munkhunur [1], Hiroshi Tagawa [2], Xingchen.Chen[3]

[1] *Ph.D. student, Graduate School of Engineering, Hiroshima University, Japan, unur@must.edu.mn*
[2] *Professor, Graduate School of Engineering, Hiroshima University, Japan, htagawa@hiroshima-u.ac.jp*
[3] *Assistant professor, Graduate School of Engineering, Hiroshima University, Japan, xchen@hiroshima-u.ac.jp*

Abstract

This paper presents the behaviour and increase of plastic deformation capacity of rigid beam-to-column connections based on the innovative application of buckling-restrained knee braces (BRKBs). A slender knee brace configuration, which consists of a steel bar core with the tube buckling-restrainer, is proposed here. The benefit of adopting the steel bar core is that it enables to downsize of the knee brace connection between the knee brace and beam-flange, which can reduce the degradation of the plastic deformation capacity of the beam-flange. Advantages of the tube buckling-restrainers include relatively simple members for ease of construction, and weightless as compared to other mortar filled buckling-restrainers. Displacement-controlled cyclic loading tests were conducted to examine the plastic performance of the rigid beam-to-column connections with the proposed BRKB. The structural performances, such as hysteretic behaviour, strength degradation, and strain distribution at the beam flanges, were measured and discussed in detail. The results showed that load-bearing capacity, deformation capacity of the rigid connection beam-to-column connection with slender knee brace structure was significantly improved by proposed BRKB. The results also showed that plastic hinge occurrence was spread out in either inside or outside of the knee brace portion at the beam. Based on the research carried out thus far, it was found that the steel core bar BRKB can be one of the viable options to increase the plastic deformation capacity of the rigid moment beam-to-column connection.

Keywords: Steel beam-to-column joints; buckling-restrained knee brace; experimental study; steel damper

1. Introduction

In order to improve the seismic performance of the conventional structural steel framing systems, numerous types of braced frame systems such as concentrically braced system, eccentrically braced system, and knee braced (KB) system have been extensively investigated to date. Among these systems, studies and applications of the KB have been becoming more common and accessible for the strengthening of the steel frame systems. An advantage of the KB system is that it provides less passage obstruction in the bay of structures as compared with the conventional bracing system.

Thus, several studies have addressed the ductile behavior of the knee braced moment frame system under seismic loading. In this system, inelastic activities are confined to the designed elements such as KB. On the other hand, if the KBs have sufficient strength, the plastic hinges forming in the beams are relocated away from the column, which can avoid the damage at the beam-to-column connection area. In other words, KB yields under external loads followed by plastic hinging at the ends of beam segments outside the knee portions. Leelataviwat and Suksan [1] carried out an experimental study into the seismic behaviour of knee braced moment frame (KBMF) to investigate the ability of the system to dissipate earthquake energy. From the test results, it was concluded that cyclic tests of relatively large-scale specimens indicate that KBMF behaves in a ductile manner with a stable hysteretic characteristic. In that study, seismic energy is dissipated by yielding and buckling of the KB and flexural yielding of the beams outside the knee regions. However, knee bracing systems are relatively vulnerable to cyclic loadings, such as earthquake ground motions depends on its shape and configurations. Thus, buckling-restrained knee braces (BRKB) have been becoming investigated as an energy-dissipating element increasingly.

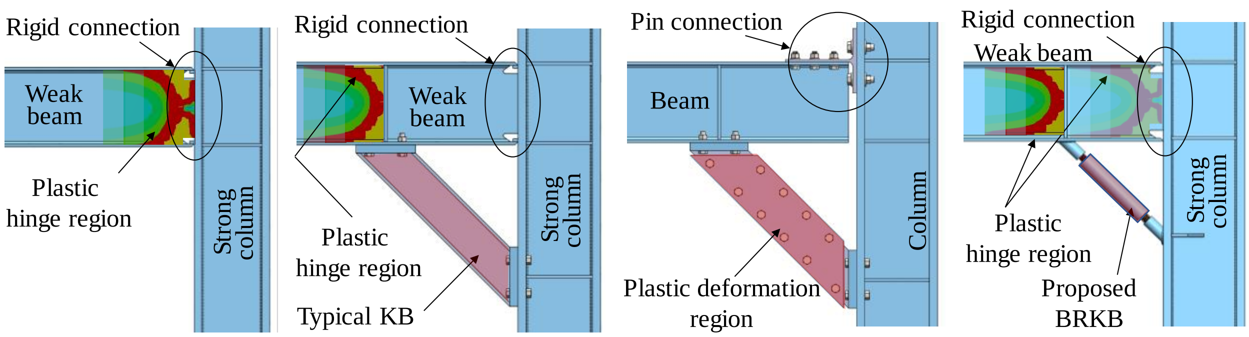
In general, the BRKB elements comprise buckling-retainers and core elements. A steel angle, tube, and flat steel plate have been used for the core elements, while U-shaped halves, double steel plates, and tubes are used for buckling-restrainer in the BRKB components. A major current focus in that is how to find a proper configuration of the BRKBs and to examine its capacity of the energy dissipating using a simple shear beam-to-column connection (pin connection) herein. Tagawa and Kaneko [2], for example, proposed BRKBs using core plates with U-shaped holes sandwiched by two buckling-restraining plates. That study adopted the pin connection for the beam-to-column joint to magnify the damper deformation and increase energy dissipation efficiency. The study also has confirmed that the shape and configuration are the most important for the plastic deformation capacity of the proposed BRKB system. Takamatsu and Tamai [3] have carried out an experiment of a non-compression knee brace for the T-shaped fixed beam-to-column connection. In that study, where steel bars were used for the main brace members. Their study investigated that the steel bar is excellent energy absorption dampers and is applicable to the rehabilitation of moment resisting framed structures, although a compression knee brace with a steel bar for the rigid beam-to-column connection has not considered well so far.

In this study, an experimental study of the BRKB having a steel bar core was carried out to investigate the ability of the proposed system to dissipate cyclic loading energy. The proposed BRKB was installed in a T-shaped rigid beam-to-column connection and tested under cyclic loading. In advance, several variants of finite element analyses (FEA) of the rigid beam-to-column connection with the proposed BRKB having steel bar cores were performed to examine a plastic deformation behaviour of the proposed system. Based on the results of FEA, the experiment specimen was chosen to assess the cyclic performance of the proposed BRKB system. The test program and details of the test specimen are then provided, and results from a cyclic test of the specimens are discussed.

2. Proposed buckling-restrained knee brace system

2.1 Fundamental concept

The welded connections are known as an ordinary rigid moment connection (RMC) in steel structural engineering. For the typical RMC connection, a plastic hinge at the weak beam-end is formed, as shown in Fig.1(a). Because the previous earthquakes induced damage to the welded beam-to-column connections in many steel frames, the BRKB and typical knee bracing (TKB) have been used for the strengthening of the connection to eliminate damage at the beam-end. As shown in Fig.1(b), TKB is the most established method for the knee brace strengthening to the beam-to-column connection. When the TKBs have sufficient strength, the plastic hinge is relocated away from the face of the column, as shown in Fig.1(b). However, BRKBs have been increasingly investigated to dissipate seismic energy for the pin connection system, as shown in Fig.1(c). For this system, the beam is designed to be fully elastic under the largest forces induced by KB. Hence, it can be seen that TKB is utilized for the rigid connection system, while BRKB is used for the pin connection mainly. However, the concepts are also applicable to be opposite for either pin or rigid connection systems. Further, this study investigates the application of slender BRKB for increasing the plastic deformation capacity of the rigid beam-to-column connection, as shown in Fig.1(d). For this system, the plastic hinge can be formed either inside or outside of the knee brace portions at the beam-end. In practice, fully assembled or set of complex proposed BRKB can be welded to the rigid beam-to-column connection by a fabricator under controlled environments.

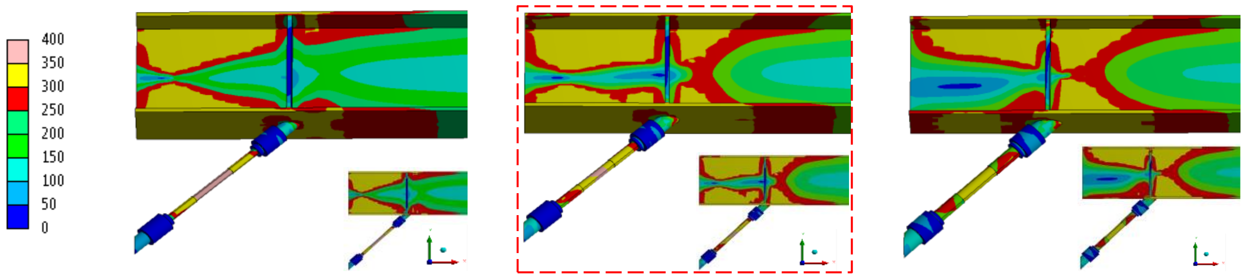


(a) Ordinary rigid moment connection (RMC) (b) RMC with typical knee bracing (c) Pin connection with BRKB (d) RMC with proposed BRKB.

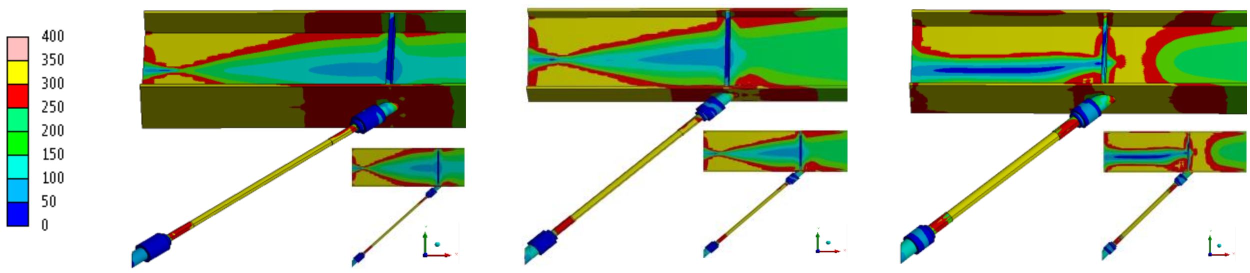
Fig. 1– Expected plastic behaviour in various types of beam-to-column connections

2.2 Preliminary investigation

Munkhunur, Tagawa, and Chen [4] carried out non-linear finite element analysis so that an appropriate variant could be selected to perform an experimental test.



(a) M16W300 (b) M22W300 (c) M30W300



(d) M16W500 (e) M22W500 (f) M30W500

Fig. 2 – Equivalent-Von Mises stress distribution at the final stage of analysis (MPa) [4]

The rigid beam-to-column connections with the proposed BRKB having steel bar cores of diverse lengths and diameters were analyzed considering upward loads at the beam-tip. The key concepts for controlling the moment distribution of plastic hinge regions were observed, and equivalent-Von Mises stress distributions at the final stage of analysis are illustrated, as shown in Fig.2. The core bar diameters of M16, M22, M30, and brace locations were employed as analysis parameters. Here, the brace locations were selected as 300 mm and 500 mm for each diameter of the core bars. From the analysis results, stress distribution in the M22W300 case was significantly different among others, as shown in Fig.2(b). In other words, the plastic deformation occurrence was extensive at either inside or outside of the knee brace portion at the beam end. The observation reveals that the proper lengths and diameters of core bars for the further experimental study of the proposed system are M22W300. Finally, a comprehensive experiment, as described in the next section, was carried out to investigate plastic deformation distribution at the beam-end and BRKB region based on the selection of analyses results.

3. Cyclic loading tests

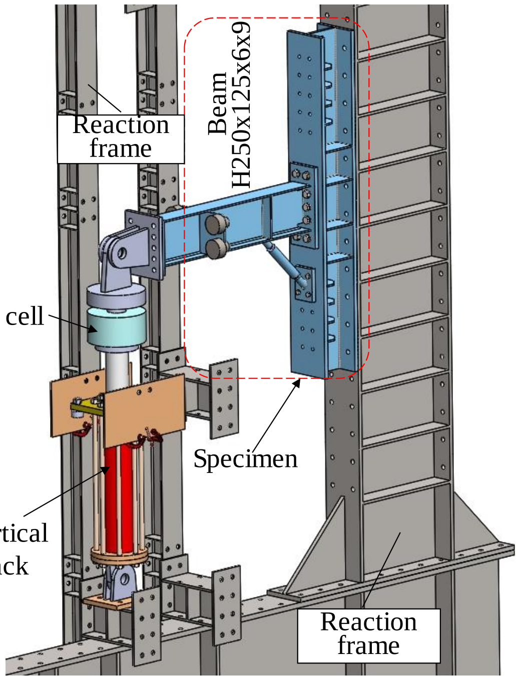
3.1 Test specimen

In this study, a T-shaped partial frame specimen was fabricated and tested, as shown in Fig.3(a). Strong-column/weak-beam philosophy is valid to promote plastic hinges in the beams rather than in the columns. The section of H-250×125× 6× 9 (H-depth×flange-width×web-thickness×flange-thickness) and the section of H-250×250×19×25 were used for beam and column (which is built-up), respectively. Geometries of the specimen are illustrated in Fig.3(b). The beam end-plate and column members were considered as fully elastic elements. The plastic hinges were expected to occur in the beam.

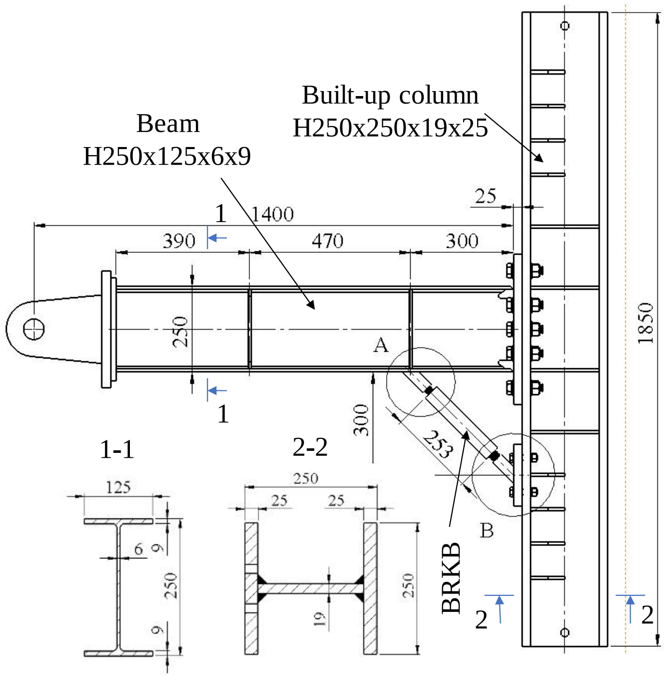
As for BRKB, Fig.3(c) presents an illustration of the general concepts and geometry of the proposed BRKB. The main loading resistant member is the steel core bar, which is placed inside a round steel tube (buckling-restrainer) and is connected by the left and right screw connector to the column and beam flanges, respectively, where the right screw connector is welded to the beam in the steel fabrication industry in advance. Whereas, for ease of construction, the left screw connector is prepared by fabricator individually and is erected with the other members in the experimental laboratory. To illustrate more clearly the general components of the BRKB, every single member is depicted in Fig.3(d). Furthermore, a proper strength of spring is also inserted between the left screw connector and round steel tube so that it can support and hold the round steel tube to maintain the lower contraction allowance zone during the cyclic loading test, as shown in Fig.3(d). Table 1 presents all of the material properties of the full-scale specimen.

Table 1 – Material properties

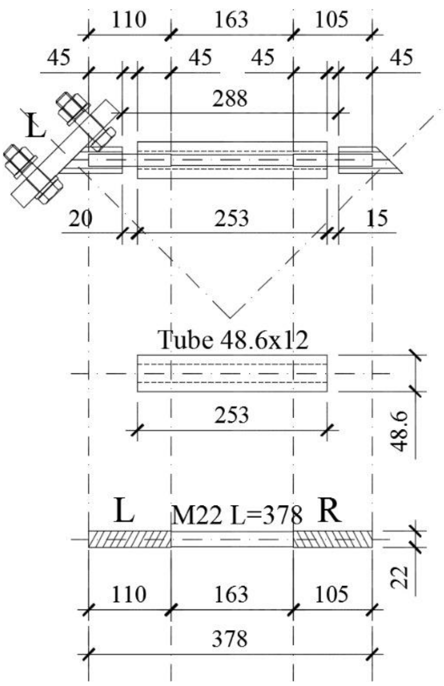
T-Shaped full-scale specimen				
Steel grade	name	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)	Elongation (%)
SN400B	Beam	313	458	27
SN400B	Column	303	452	30
ABR400	M22 bar	307	461	32
STKM 13A	Round tube	287	464	58
SN400B	End plate	351	483	28



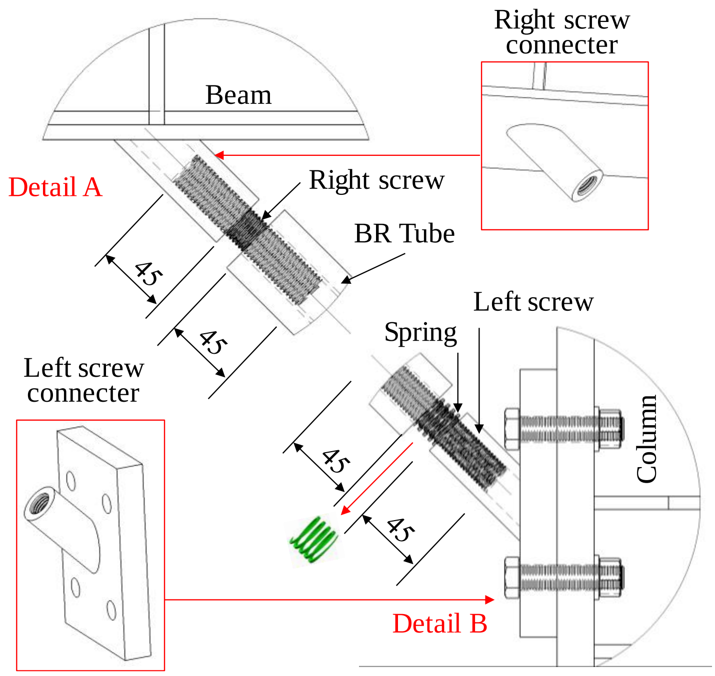
(a) General apparatus



(b) The geometry of the full-scale specimen with the proposed BRKB (units: mm)

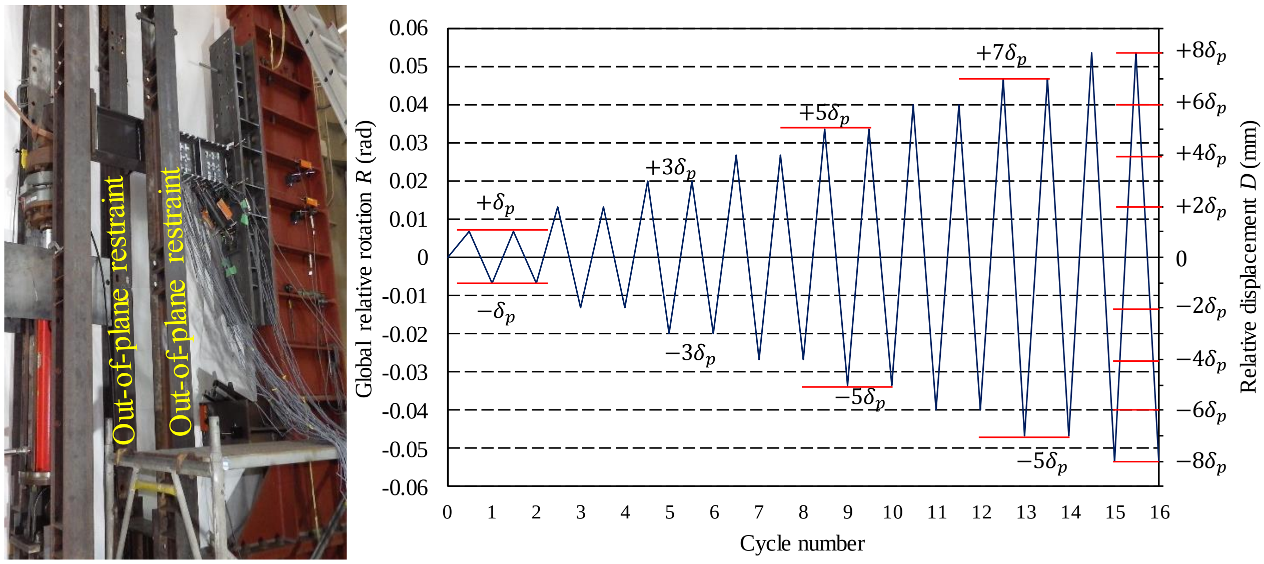


(c) The geometry of BRKB (units: mm)

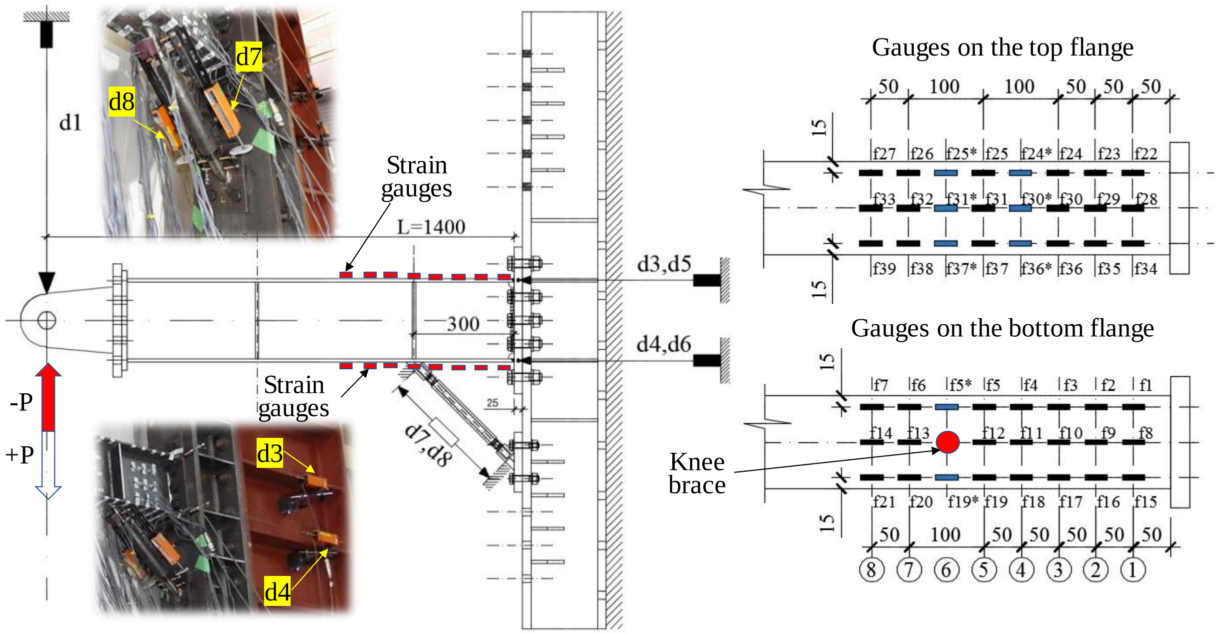


(d) An insertion of core bar screw

Fig. 3 – Apparatus and geometry of the full-scale test specimen



(a) Photograph of the test set up (b) Cyclic loading protocol



(c) Displacement sensor positions (d) Strain gauge positions

Fig. 4 – Test set-up and measurement plan

3.2 Test set-up

The test was performed at the Building Structure Laboratory of Hiroshima University. The specimen was set up to the reaction frame, as shown in Fig.4(a). The column of the specimen fixed completely to the reaction frame. The vertical load was applied using a hydraulic actuator (which could provide a maximum force of 1000 kN and a maximum stroke of ±500mm) at the beam-tip, where downward is assigned as the positive direction. A pair of the vertical bracing device (out-of-plane restraint) was used to avoid out-of-plane instability of the specimens during the whole testing process.

3.3 Test data measurements

Measurements of the test data were summarized as follows: (1) vertical load and corresponding vertical displacement of the beam-tip of the specimen; (2) rotation of the beam end-plate; (3) strains of the beam top and bottom flanges; and deformation of the BRKB.

The displacement sensor of the DP-1000D was used to obtain the vertical displacement of the beam tip. Meanwhile, in order to measure the displacement of the beam end-plate rotation, the displacement sensors of SDP-50 were utilized, as shown in Fig.4(c). The strains of the beam top and bottom flanges were measured by a series of strain gauges, as shown in Fig.4(d). Finally, two displacement sensors of the SDP-50 were also attached to measure the deformation of the BRKB, as shown in Fig.4(c).

3.4 Loading history

The loading protocol is presented in Fig. 4(b). Displacement-controlled cyclic loading was adopted, and it was increased gradually until the beam exhibited strength deterioration. Two cycles of loading were performed for each displacement level of δ_p, $2\delta_p$, $3\delta_p$,… and $8\delta_p$. Here, δ_p corresponds to the state when the full-section plasticity was developed in the beam despite an effect of BRKB.

3.5 Test results

3.5.1 Load and global relative rotation relationship

In Fig.5, the relationship between the lateral load P and a global relative rotation R is depicted. Here, $R = d_1/L - \theta_c$: where θ_c denotes the beam end-plate rotation angle measured by displacement sensors of d_3 to d_6. It can be found from Fig.5 that the hysteretic loop in each cycle of loading exhibits a suitable shape for the proposed system. Overall, it is also observed that the R(rad)=−0.6% in the elastic range of cyclic load-carrying capacity (LCC) were slightly larger than positive rotation. Furthermore, the LCC of the system gradually increases up to positive R(rad)=4.5% and negative R(rad)=−3.9% regarding with the downward and upward loading, respectively. It is seen that after above mentioned global relative rotations, strength deterioration was observed under further cyclic loading. However, the difference of an absolute value of the load at both directions of the global relative rotation with each step of cyclic loading was significantly small, as observed in Fig.6.

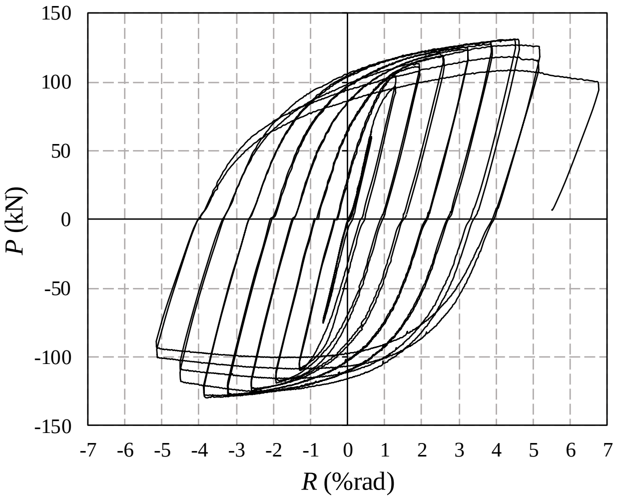


Fig. 5 – Relationship between the load and global relative rotation

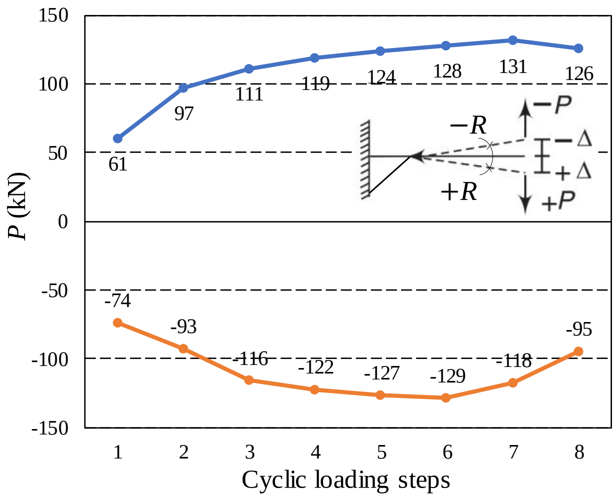
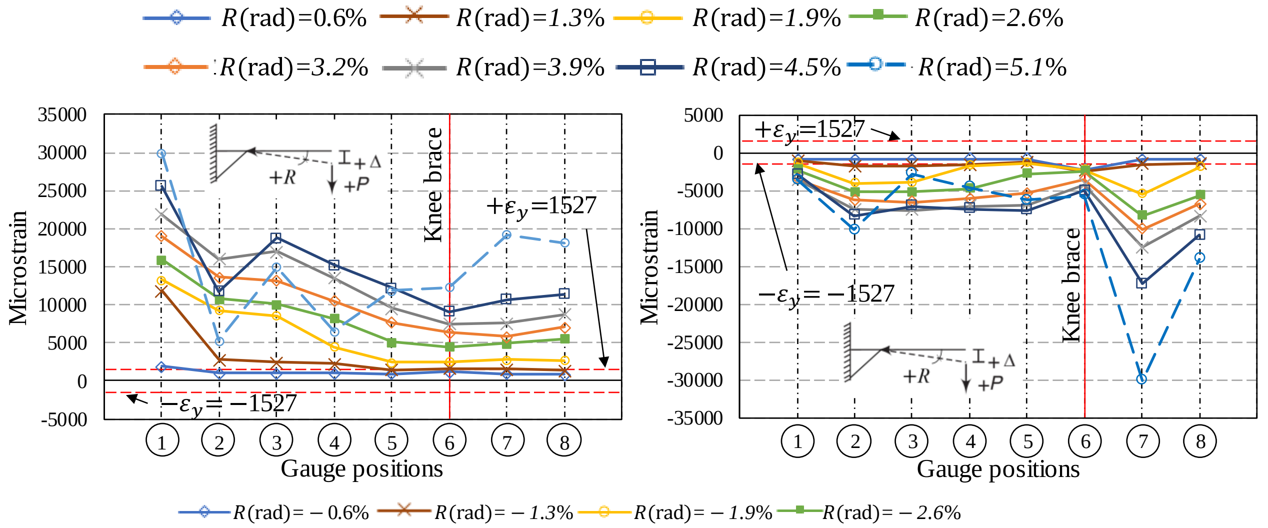


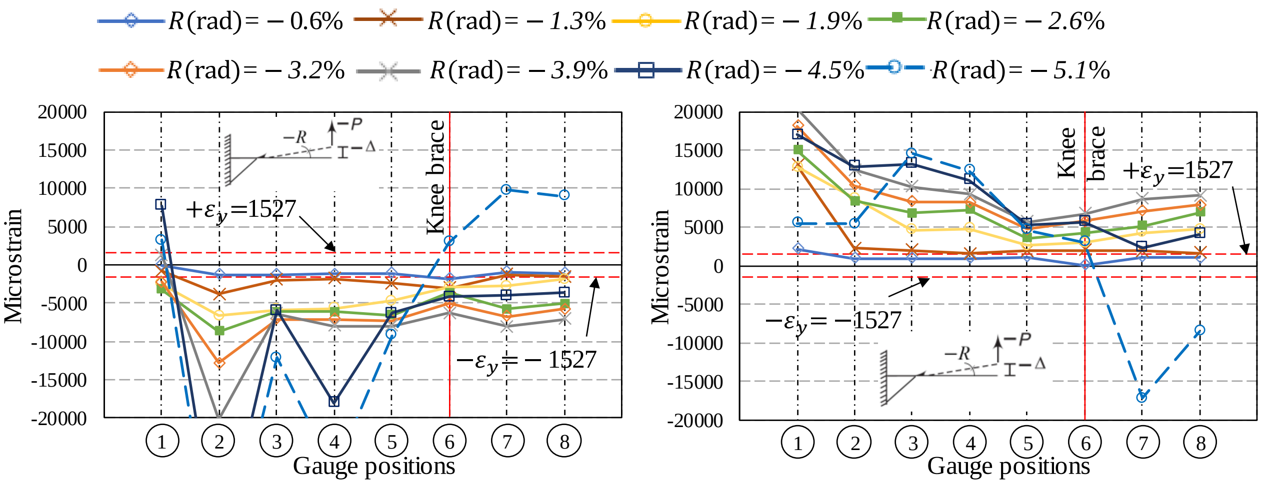
Fig. 6 – Relationship between the load and cycle steps of loading

3.5.2 Variation of strain distribution

Fig.7 presents strain distributions on the beam flanges at each loading level from *R*(rad)=±0.6% to *R*(rad)=±5.1%. In that figure, the strain distributions were observed both inside and outside of the knee brace portion at the beam flanges. For the case of the positive rotation of the beam under external loading, the top flange of the beam is subjected to the tension force, whereas the bottom flange of the beam corresponds to the compression. As seen from Fig.7(a), yielding occurred earlier at the beam end close to the column. Meanwhile, strain distributions were slightly decreasing from beam end to beam tip for the designated location up to beam rotation of the *R*(rad)=+3.9%. Fig.7(b) portrays relatively interesting behavior of the strain distribution at each of the loading level. In the gauge locations of the number of 6 to 8, the strain distributions were dominated.



(a) Top flange for the tension (b) Bottom flange for the compression



(c) Top flange for the compression (d) Bottom flange for the tension

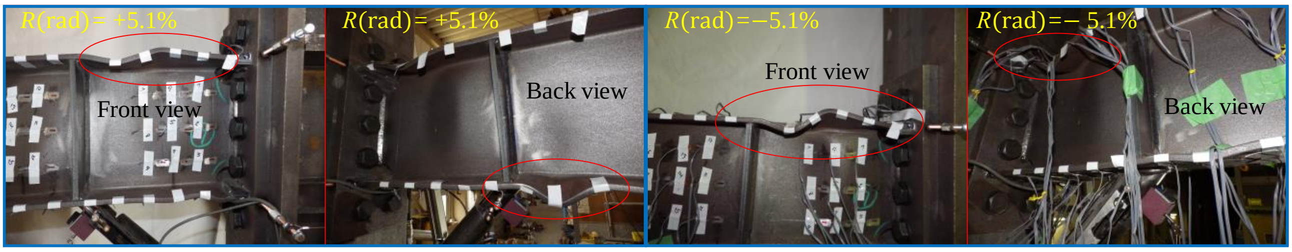
Fig. 7 – Strain distribution of the beam top and bottom flanges

It can be seen from Fig.7(c) that one significant drop appears at the gauge location number of 2 up to the *R*(rad)= −3.9% loading levels. The peak values of strain were observed at the inside of the knee brace portion at the beam. However, in general, the stress distributions were spread from the location of gauge number 3 to 8 at each loading levels, excluding two loading levels, which are *R*(rad)= −4.5% and *R*(rad)= −5.1%. At the bottom flange for the tension, similar behaviors with the positive rotation of loading at the top flange tension were exhibited. However, under the influence of the knee bracing, the strain values were significantly different at both tension sides, as shown in Fig.7(d).

3.5.3 Deformation at the final stage of loading

When the global relative rotation reached *R*(rad)= −4.5%, the small buckling behavior was observed at the front side of bottom flange close to the beam-end, where no enlargement was seen when the rotation reached to *R*(rad)=+5.1%, as shown in the first photo of Fig.8(a). Although, new local buckling was developed outside of the knee brace portion at the bottom flange in the increase of R simultaneously, as shown in the second photo of Fig.8(a).

The local buckling corresponding to the negative global relative rotation occurred in the top flange at the beam-end dominantly, as shown in Fig.8(b). The reason for that occurrence was that the knee brace yielded in the early stages of the cyclic loading, followed by local buckling at the beam-end close to the column flange. A comprehensive discussion of BRKB deformation has not been included in this paper.



(a) Local buckling of the flanges (*R*(rad)=+5.1%) (b) Local buckling of the flanges (*R*(rad)=−5.1%)

Fig. 8 – Deformation of the beam flanges for the rotation of *R*= ±5.1% (rad)

4. Conclusions

This paper has presented the test results of the T-shaped rigid beam-to-column connection with the proposed BRKB system. From the test data, the following conclusions can be drawn:

(1) Adopting slender BRKB in the rigid beam-to-column joint, a sequence of plastic hinge occurrence was induced. This characteristic behavior is distinctive for the proposed system and is not seen in other ordinary knee braced systems (which were discussed in the Section.2.1). Especially, the beam-to-column joint with the steel core bar BRKB exhibits the high performance of the load-bearing capacity under cyclic loading.

(2) The strength and stiffness degradations were slowed down in the proposed system. The small size of the knee brace connection between the knee brace and beam-flange can reduce the degradation of the plastic deformation capacity of the beam-flanges.

Acknowledgment

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