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Experimental investigation on monotonic performance of steel curved knee braces for weld-free beam-to-column connections

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ABSTRACT

Steel knee braces are used in weld-free beam-to-column connections to improve the performance of steel moment resisting frames. This paper proposes a special kind of steel knee brace for weld-free beam-to-column connections, herein referred to as steel curved knee brace, which is characterized by a curved axis. With a curved component axis, initial stiffness and yield strength of the brace can be designed independently to a certain extent, then different seismic performance objectives of the structure may be achieved. Simplified model is developed for the steel curved knee brace, and a series of experimental tests were performed on steel curved knee braces to evaluate their monotonic behavior. The effectiveness of steel curved knee braces for decoupling stiffness and strength was validated by the test results. It was also found from test result comparisons that steel curved knee braces develop higher tensile strength than compressive strength and possess better ductility under tension, these differences become more obvious as the curvature decreases.

1. INTRODUCTION

A scheme to minimize the welds in beam-to-column connections is the utilization of the structural system owing mechanical joints equipped with steel knee braces, named weld-free system (Inoue 2006). The present paper proposes a special kind of steel knee brace, called steel curved knee brace (SCKB), for weld-free system. SCKBs are characterized by its intentional curvature of axis as illustrated in Fig. 1. Numerical analyses and experimental studies have been carried out by researchers on braces with initial eccentricity, and it has been verified that yield strength and elastic stiffness of these braces can be designed independently to a certain extent (Palermo 2015; Skalomenos 2016). By adopting SCKBs, the independent design of initial stiffness and

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yield strength of weld-free system may be achieved. However, the mechanical properties of SCKBs are still not clear. Besides, research has seldom been conducted on braces possessing different intentional eccentricity, and a SCKB generally possesses a lower nominal slenderness, i.e. the ratio of distance between brace ends to radius of gyration. Consequently, there is a need to study the behavior of SCKBs.

The present study reports experimental work on six SCKB specimens, which were designed to hold different initial stiffness but similar yield strength. The efficiency of the independent design of SCKBs are verified. The monotonic performance of SCKBs are evaluated.

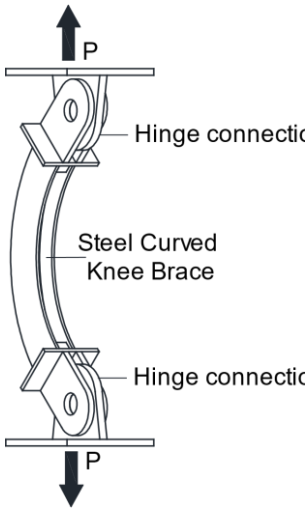


Fig. 1 Steel curved knee brace

2. SIMPLIFIED MODEL

A SCKB consists of a curved part possessing H-section and four ear plates at two ends for pin connections, and is designed to resists force acting along the axis connecting the centers of two pins as shown in Fig. 1. The axis of the curved part is circular arc, and its curvature is around the weak axis of the H-section. The curved part and the ear plates are connected by two end plates. For the convenience of the determination of initial stiffness and yield strength, ear plates can be simplified as prolongation of the curved part and holds the same H-section. This simplification is reasonable as the ear plates are thicker than the flanges of the curved part, and the bending deformation is concentrated in the curved part when loaded, which plays a significant role in the deformation of the SCKB. Besides, because the distance from the center of the pin to the near end of the curved part is much shorter than the length of the curved part, the straight parts at the two ends are further simplified to have the same radius of curvature as the curved part. Thus, the simplified geometry of a SCKB can be completely determined by its cross-section, equivalent curvature θ and equivalent length L (Fig. 2).

The equivalent curvature θ can be expressed using:

$$\theta = \theta_c + 2\theta_s = \theta_c + 2\arctan\frac{L_e}{R} \tag{1}$$

In which θ_c is the curvature of the curved part, θ_s is the equivalent curvature of the straight part, L_e is the distance from the center of the pin to the near end of the curved part, and R is the radius of curvature of the curved part. The relationship among the length L_c, radius of curvature R, and curvature θ_c of the curved part can be defined by the following expression:

$$L_c = 2R\sin\frac{\theta_c}{2} \tag{2}$$

The equivalent length, L, can be computed using the following equation:

$$L = L_c + 2L_s = 2R\sin\frac{\theta_c}{2} + 2L_e\cos\frac{\theta_c}{2} \tag{3}$$

In which L_s represents the length of the straight part of a SCKB.

Besides, as indicated in Fig.2, an initial eccentricity, Δ_0, caused by the initial curve can be obtained using:

$$\Delta_0 = \Delta_c + \Delta_s = \frac{L_c\left(1-\cos\frac{\theta_c}{2}\right)}{2\sin\frac{\theta_c}{2}} + L_e\sin\frac{\theta_c}{2} \tag{4}$$

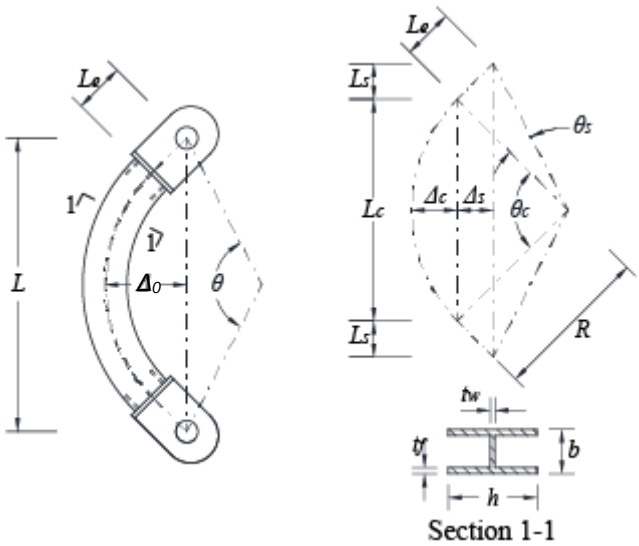


Fig. 2 Geometry of a SCKB

Based on the simplified geometry, the initial stiffness can be computed by applying the principle of virtual works:

$$K_{ic} = \frac{E}{\dfrac{L^3}{4I\sin^3\dfrac{\theta}{2}}\left(\dfrac{\sin\theta}{4}+\dfrac{\theta}{4}-\sin\theta+\dfrac{\theta}{2}\cos^2\dfrac{\theta}{2}\right)+\dfrac{L}{A\sin\dfrac{\theta}{2}}\left(\dfrac{\sin\theta}{4}+\dfrac{\theta}{4}\right)} \tag{5}$$

where I is the moment of inertia of the cross-section, E is the young's modulus. Shear deformation is not considered.

Based on the bearing capacity of cross-section under axial force and bending moment, the yield strength of a SCKB is preliminarily estimated by the following formula, where geometrical nonlinearity is not considered:

$$P_y = \frac{\gamma W A f_y}{\gamma W + A\Delta_0} \tag{6}$$

In which γ is the plastic adaption coefficient of the cross-section, i.e. $\gamma = M_u/M_y$, where M_u and M_y are the ultimate and elastic limit flexural capacity respectively. W is the sectional modulus and A is the area of the cross-section. As web plate is set at mid height of the cross-section, its influence on γ *is neglected, i.e.* γ is estimated as 1.5.

3. EXPERIMENTAL INVESTIGATION

3.1 Specimen preparation

As shown in Fig. 3, three configurations of SCKBs are determined, which possess different initial stiffness but similar yield strength computed using Eq. (5) and Eq. (6), assuming that young's modulus is 2.06×10^5MPa and yield strength f_y is 345MPa. For each configuration, two specimens were constructed for monotonic compression and tension respectively. The detailed geometric parameters of the specimens are listed in Table 1.

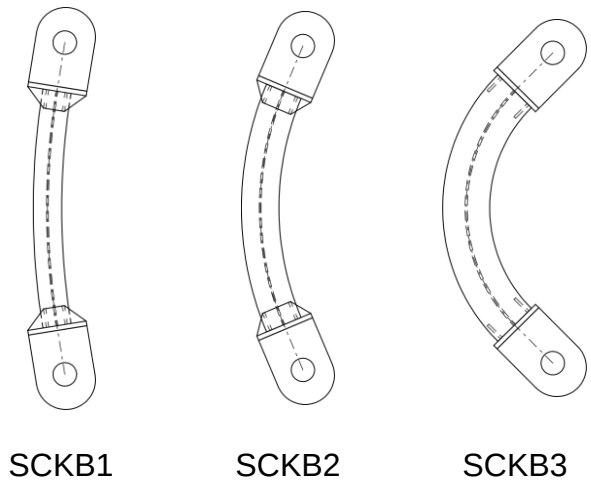


Fig. 3 Specimens

Table 1 Geometric features of specimens

Specimen label	L_c (mm)	L_s (mm)	Δ_c (mm)	Δ_s (mm)	θ_c (°)	θ_s (°)	h (mm)	b (mm)	t_f (mm)	t_w (mm)
SCKB1-C SCKB1-T	1000	207	40	73	18	3.76	120	100	10	8
SCKB2-C SCKB2-T	1000	194	101	183	45	9.13	160	100	12	10
SCKB3-C SCKB3-T	1000	163	206	368	90	18.02	200	100	14	10

All specimens were fabricated using Chinese Q345 steel. The computed yield strength and initial stiffness of all specimens are listed in Table 2. All the SCKBs tested were loaded along the axis connecting the centers of the two pins, as shown in Fig. 4.

Tabel 2 Estimated mechanical properties of specimens

Specimen label	Initial stiffness (kN/mm)	Yield strength (kN)
SCKB1-C, SCKB1-T	109.32	243
SCKB2-C, SCKB2-T	60.12	267
SCKB3-C, SCKB3-T	37.10	261

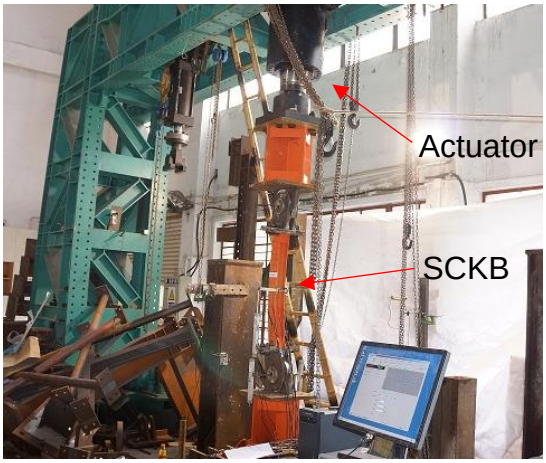
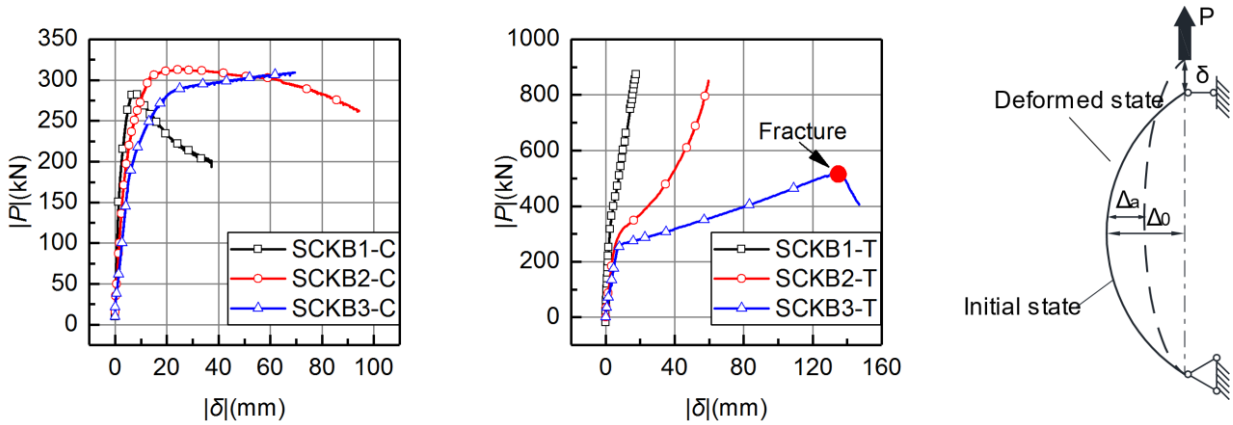


Fig. 4 Layout of SCKBs test

3.2 Test Results

The relationships of absolute values of load P and relative displacement δ between the centers of the two pins are illustrated in Fig. 5. The strength of SCKB1-C and SCKB2-C decreased after reaching their ultimate strength, while SCKB3-C hardened constantly through the loading process. Local buckling or fracture was not observed on SCKB1-C. The flanges at mid height of SCKB2-C buckled when $|\delta|$ grew up to 53mm (Fig. 6). For specimens under tension, sharply decrease in tangential stiffness was observed after tensile strength exceeded the computed yield strength, therefore the computed value can estimate the yield point of SCKBs. The ultimate tensile strength is higher than the ultimate compressive strength, thus the latter is

chosen to represent the ultimate strength of SCKBs. The tensile strength of SCKB3-T dropped suddenly when the ultimate tensile strength was attained because of local buckling at compressed flange edge and fracture at flange edge under tension (Fig. 7). The ultimate compressive strength P_u was compared with the computed yield strength N_c in Table 3, which indicates that N_c is about 85% of N_u.



(a) Under compression (b) Under tension (c) Deformation of a SCKB

Fig. 5 Load (|P|) versus relative displacement between center of pins (|δ|) curves

Fig. 6 Local buckling of SCKB2-C

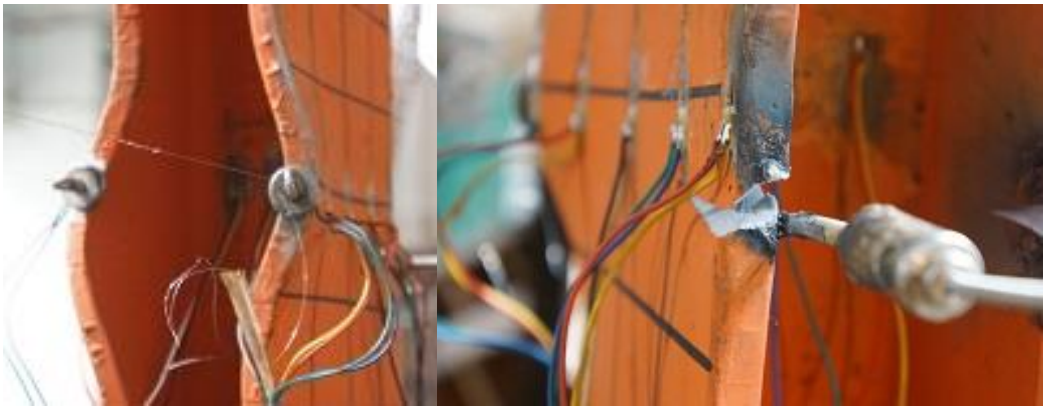


Fig.7 Local buckling and fracture on SCKB3-T

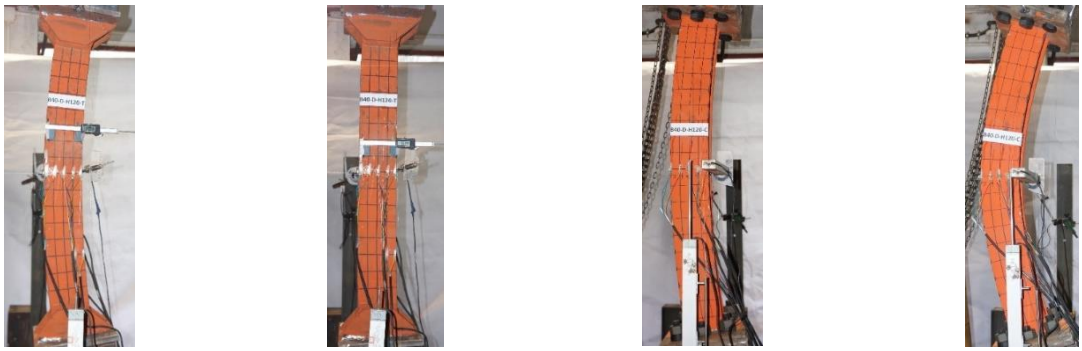
Table 3 Comparison of N_u and N_c

Specimen label	N_u(kN)	N_c(kN)	N_c/N_u
SCKB1-C	283.9	243	0.854
SCKB2-C	313.6	267	0.853
SCKB3-C	309.1	261	0.845

The initial stiffness measured in tests, K_{it}, is compared with that computed according to the simplified model, K_{ic}, as listed in Table 4. The simplified model gives an appropriate evaluation of the initial stiffness of SCKBs. A higher initial stiffness under tension compared to that under compression was obtained, because the eccentricity tends to decline and increase under tension and compression respectively, as shown in Fig. 8, which is also responsible for the higher ultimate tensile strength than the ultimate compressive strength. This phenomenon is much prominent for SCKBs with a relatively small curvature, as the variation of eccentricity becomes more obvious. Generally, based on similar yield strength and ultimate compressive strength, different initial stiffness was obtained.

Table 4 Comparison of K_{it} and K_{ic}

Specimen label	K_{it}(kN/mm)	K_{ic}(kN/mm)	K_{it}/K_{ic}
SCKB1-C	96.27	109.32	0.88
SCKB1-T	130.22		1.19
SCKB2-C	47.56	60.12	0.79
SCKB2-T	68.15		1.13
SCKB3-C	30.33	37.10	0.82
SCKB3-T	34.76		0.97



(a) SCKB1-T before test (b) SCKB1-T after test (c) SCKB1-C before test (d) SCKB1-C after test

Fig. 8 Deformation of SCKB1-T and SCKB1-C

The ductility factor μ of a SCKB is defined by the following expression:

$$\mu=\Delta_u / \Delta_y \tag{7}$$

In which Δ_u and Δ_y are absolute values of the relative displacement δ between the two centers of the two pins corresponding to the ultimate strength and the computed

yield strength respectively. The ductility factors are listed in Table 5. Restricted by the test equipment, the exact value for some specimens was not obtained. It is noticed that all specimens possess ductility factor higher than 4.41. For the same configuration, the ductility factor for the specimen under tension is greater than that under compression, and this difference is more significant for SCKB with a smaller eccentricity.

Table 5 Ductility of specimens

Specimen label	Δ_y	Δ_u	μ
SCKB1-C	3.87	17.93	4.63
SCKB1-T	1.72	>17.70	>10.29
SCKB2-C	9.00	91.75	10.19
SCKB2-T	3.65	>53.89	>14.76
SCKB3-C	15.74	>69.39	>4.41
SCKB3-T	10.10	143.58	14.22

4. CONCLUSION

Steel curved knee brace is proposed for weld-free beam-to-column connections. A simplified model of the proposed SCKB is introduced in this paper together with an experimental study. The following conclusions are drawn:

1. The initial stiffness and yield strength of a SCKB can be designed independently to a certain extent.
2. Appropriate estimation of initial stiffness and yield strength can be obtained by the simplified model.
3. For the same configuration, the ultimate tensile strength is higher than the ultimate compressive strength, and the ductility factor is higher under tension than under compression.
4. The difference between mechanical properties under tension and compression becomes distinguished with the decrease of the curvature of the SCKB.

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