Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2023 Volume 29 Issue 1: 67–76
https://doi.org/10.3846/jcem.2022.17228

SEISMIC RETROFITTING METHOD FOR STEEL STRUCTURES BY KNEE BRACES JOINTED BY HIGH HARDNESS VISES

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Received 14 January 2022; accepted 2 May 2022; first published online 30 November 2022

Abstract. The authors have developed a new method of seismic retrofit for steel structures by adding knee braces which is jointed to the existing structures by vises with screw bolts made of high hardness metal. The slipping strength of the connection had been studied through axial tensile test of steel coupons jointed by the vises. The features of the connection by the vise are easy setup and providing the strength as much as by the normal bolts joint. An experimental study had been conducted for the specimens of steel frames retrofitted by knee braces. The knee brace was jointed to the steel frames by the vises. Two types of failure modes were investigated. One was slipping behavior at the connection and the other was bucking behavior at the knee braces. The strengths of the specimens were estimated by the simple calculations for the two types of failure modes.

Keywords: slipping strength, buckling strength, combined stress states, seismic reinforcement.

Introduction

Buildings of steel structures were damaged by some large-scale earthquakes in Japan. The typical damage under strong ground motions was breaking along the welding line at the beam-column-connection as shown in Figure 1 (Architectural Institute of Japan [AIJ], 1996) and Figure 2 (Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster, 2000). The earthquakes of 1994 Northridge and 1995 Kobe revealed that a large number of steel buildings experienced damage. To avoid the inconvenience and cost due to the damage by earthquakes, significant researches have been conducted on the approaches that enhance structural resilience. Fang et al. (2022) summarized some of the recent technological advances in the field of the seismic resilient steel structures. Among these, MacRae (2013) reported the various brace structures. The plastic deformation performance of steel dampers was investigated by Domenico et al. (2019), Kishiki et al. (2005) and Tamai et al. (2010) as the energy dissipating devices.

The authors have proposed a new method of seismic retrofit for steel structures by adding knee braces which are jointed to the existing structures by vises with screw bolts made of high hardness metal. This seismic retrofitting method is applicable to moment resisting frames of steel structures. A knee brace has the functions to decrease the bending moments at the ends of both of the beam and columns, and to increase the rigidity of the beam-column-connections. The knee braces are effective to prevent the damage of the beam-column-connections, but it is difficult to set them to existing buildings. The authors have proposed to use the vise which is shown in Figure 3 to clip the end plates of the knee brace to the existing beams and columns. There are no works for welding and making holes for bolts by using the vises to retrofit the steel structures. The head of the bolt of the vise is created as high hard-ness metal which bites into the jointed steel plates to prevent the loosening the torque of the bolt.

Figure 1. Steel structure damaged by Kobe earthquake in 1995

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Figure 2. Fracture at beam-column-connection of the steel structure damaged by Kobe earthquake in 1995

Figure 3. Vise used to seismic retrofit of steel structures

The research for seismic retrofitting method by using knee braces was reported by Harada et al. (2012). Also, Yamada et al. (2011) showed that the knee brace damper was adopted to the retrofit of over-track buildings. Our research is different from the studies by Harada et al. (2012) and by Yamada et al. (2011) on the connecting method to add the knee braces to existing buildings.

The basic connecting performance by the vise had been studied at first. The slipping strength of the connections by the vises was estimated through axial tensile tests of steel coupons jointed by the vises. After the estimation of the slipping strength of the connections, an experimental study had been conducted for the practical specimens of steel frames retrofitted by knee braces. The knee braces were jointed to the specimen by the vises. Two types of failure modes were investigated. One was slipping behavior at the connection and the other was yielding and bucking behavior at the knee braces. The strengths of the specimens were estimated by the simple calculations for the two types of failure modes.

1. Tensile test on connection of steel plates clipped by vise

In order to investigate the basic performance of the connections clipped by the vises, the tensile test has been conducted. The test specimens were two steel coupons clipped by the one or two vises. The tensile force versus slipping displacement relations were discussed.

1.1. Specimens

The test specimens were summarized in Table 1. The specimen was named under the rule shown in Figure 4. The parameters were as follows: thickness of steel plates (11 mm, 16 mm, 19 mm), condition of surface of steel plate (unprocessed, rust, shot blast), and number of joint device (one or two). The specimens with the rust surfaces were tested after revealing them at the outside in one month. Figure 5 shows the appearance of the surface of the steel coupons. The influence by the three different conditions of surface and the three different combinations of the thickness, which were 16-16, 19-19, 11-16 (unit is mm), were investigated.

Figure 6 shows the shapes of the specimens. The rust and shot blast parts (50×180 mm) were shading in the figure. Test specimens were made by overlapping two steel coupons as shown in Figure 7. Then they were connected by the vise and subjected to tensile force.

The thickness of both of grip ends of the specimens were made as the same (i.e., the 11–16 mm specimen had 27 mm thickness of the grip ends). In the case of the different thickness of specimens, the bolt-heads of the vises touched on the thinner plates. Figure 8 shows the specimen clipped by the two vises as an example. The all bolts of the vise were introduced to 300 Nm torque by torque-wrench as shown in Figure 9. According to the toque of 300 kN, the average of the compressive force of the bolts was 75 kN.

1.2. Test results

Tensile test was conducted by using 2 MN testing machine shown in Figure 10. As shown in Figure 11, the test specimens were subjected to tensile force and measured the displacement between each steel coupon jointed by the vise by clip gauges in the gauge length of 57 mm. The measured displacement included the elastic deformation of steel coupon in the gauge length. It was necessary to subtract the elastic displacement from measured displacement to obtain the slipping displacement. After the test, the situations of the surface of the steel plates were recorded by the cameras, and the maximum torque was observed when the stress of the bolts were released.

In the Figure 12, the test results of 16–16 mm specimens were shown as examples. The vertical axis showed the tensile force, and the horizontal axis showed the average of the slipping displacements observed by two clip gauges shown in Figure 10. In one figure, two curves were shown and compared by the difference of the number of the vises.

Table 1. Test specimens for tensile test

Surface processing	Specimen	Slipping strength (kN)	Displacement (mm)	Maximum strength (kN)	Slipping strength per a vise (kN)	Average (kN)	Standard deviation (kN)
Unprocessed	16-16N-1	12.3	0.04	73.1	12.3	18.2	3.5
	16-16N-2	40.2	0.14	112.5	20.1		
	19-19N-1	14.6	0.05	62.2	14.6		
	19-19N-2	41.6	0.09	120.7	20.8		
	11-16N-1	22.0	0.08	74.4	22.0		
	11-16N-2	38.5	0.12	128.0 (4.88 mm)	19.3		
Rust	16-16R-1	40.9	0.20	81.9	40.9	35.5	8.6
	16-16R-2	94.7	0.20	118.5 (2.07 mm)	47.3		
	19-19R-1	–	–	–	–		
	19-19R-2	73.6	0.19	135.2	36.8		
	11-16R-1	29.9	0.19	85.4	29.9		
	11-16R-2	45.1	0.17	141.6	22.5		
Shot blast	16-16B-1	37.5	0.16	86.2	37.5	37.7	9.3
	16-16B-2	97.9	0.20	137.3	48.9		
	19-19B-1	45.3	0.19	62.7	45.3		
	19-19B-2	67.8	0.19	117.4	33.9		
	11-16B-1	35.5	0.19	75.4	35.5		
	11-16B-2	50.2	0.19	125.7	25.1		

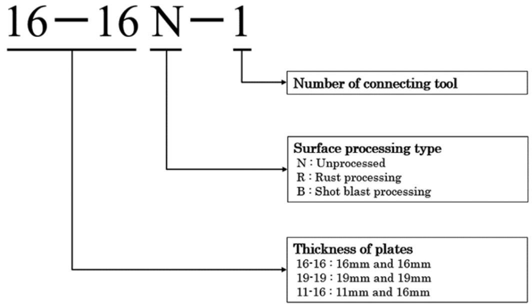

Figure 4. Name of the specimens for tensile test

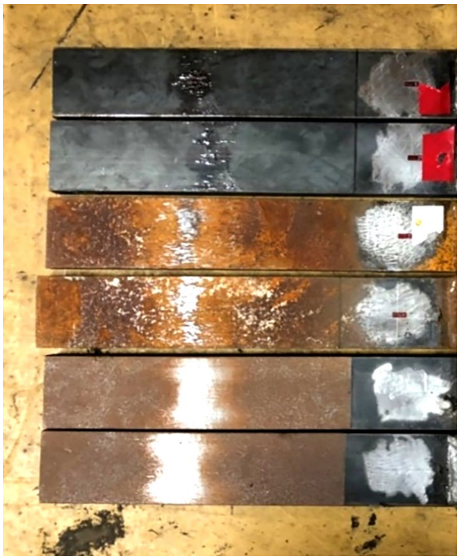

Figure 5. Surface of the specimens (Top 1, 2: unprocessed; middle 3, 4: rust; bottom 5, 6: shot blast)

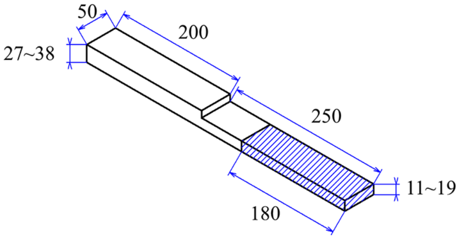

Figure 6. Shape of the steel coupon for tensile test for the connection (unit: mm)

Figure 7. Specimens overlapped of two steel coupons

Figure 8. Specimen clipped by the two vises

Figure 9. Introducing the torque of 300 Nm by torque-wrench

Figure 10. 2MN testing machine

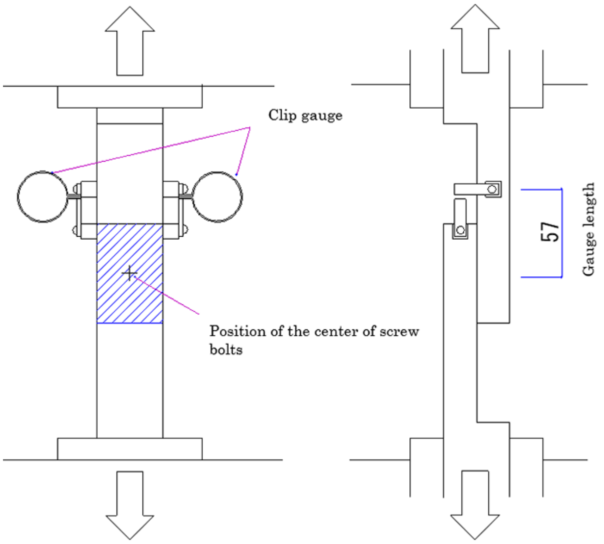

Figure 11. Loading and measuring devices (unit: mm)

The Figures 10a to 10c were compared by the difference of the surface conditions. The slipping strength of the specimens with unprocessed surface were apparently lower than that of the specimens with rust surface and shot blast surface. The slipping behaviors occurred till 1 mm of the slipping displacement, then the tensile force increased gradually on all of the experimental curves. Figure 13 shows the surface of the steel coupon after the tensile test.

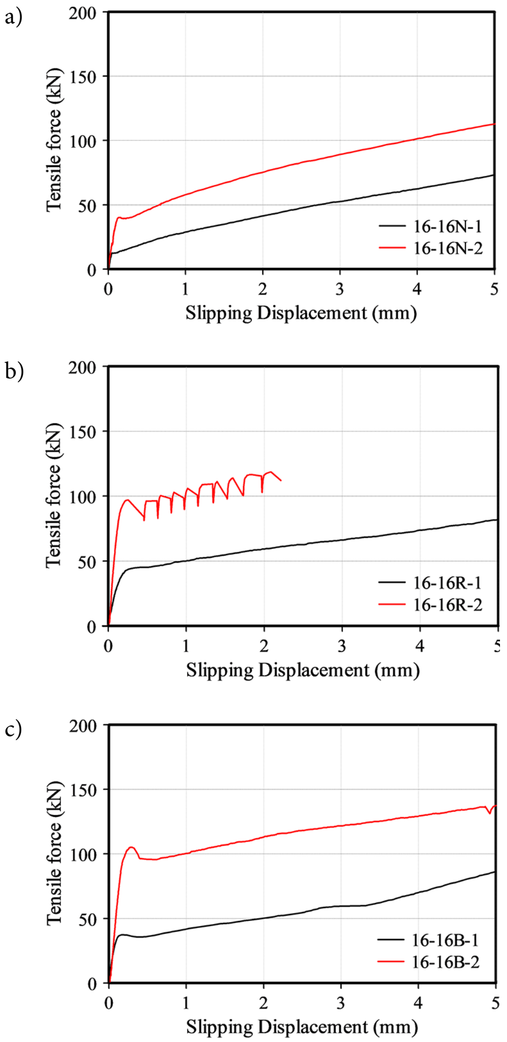

Figure 12. Relationships between tensile force and displacement: a – 16-16N; b – 16-16R; c – 16-16B

Figure 13. Surface of the steel coupon after the tensile test

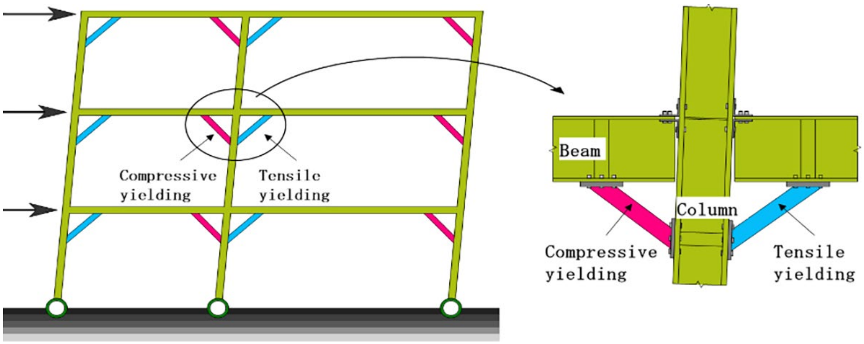

Figure 14. Steel frame with knee braces proposed in the reference

The scratch mark by the high hardness screw bolt was shown in the photograph. The gradual strength enhancement was owing to the digging behavior of the bolt head into the steel coupon as shown in the photograph. The vise did not loosen the connecting performance between the steel plates after the slipping behavior occurred. The test results were already shown in Table 1. There are discussions for slipping displacement corresponding to slipping strength. The limits of displacements of slipping were defined as 0.2 mm in Japan (AIJ, 2016), 0.5 mm in U.S. (AISC-Research Council on Structural Connections, 1994), and 0.15 mm in Europe (ECCS Technical Committee 10. Bolted and Welded Connections, 1985), respectively. In this paper, the slipping strength was defined by the abrupt change of the slope of the experimental curve or tensile strength at slipping displacement of 0.2 mm. The averages of the slipping strength of three different surfaces were obtained as these values: 18.2 kN for unprocessed, 35.5 kN for rust, and 37.7 kN for shot blast, respectively. The rust processing was available practically to use for seismic retrofit. The slipping strength of 35.5 kN by the vise was larger than the strength by high strength bolt (F8T, Japanese Industrial Standard, JIS) of M22, and smaller than that of M24, by referring to the Japanese Guide Book (AIJ, 2016). The frictional coefficient of rust surface became 0.47 which was 75 kN divided by 35.5 kN. This value was bigger than the value of 0.45 defined in Japanese recommendations (AIJ, 2006, 2010). This value of 0.45 was used for design for connection between knee brace and existing steel members, hereafter. There was no information of the loosening of bolt in the use of long-term. The authors have already conducted stress relaxation test, and the loosening was not observed. The detail of the results of relaxation test will be informed in our next paper.

2. Experimental study for steel frames retrofitted by knee braces

The authors proposed a new seismic retrofitting method for steel structure by adding the knee braces. The vises with high hardness bolts heads were used to set the knee braces to the existing structure. The feature of this method is easy setup because there is no welding and/or making the hole for bolts. The knee braces were effective seismic resistant members in the studies by Suita et al. (2003) and by Koetaka et al. (2005). There were important studies of steel structures with knee braces by Byakuno et al. (2003), Chou et al. (2004) and by Takeuchi et al. (2000). In these studies, the steel frames with knee braces shown in Figure 14 were investigated when the knee braces yielded and acted as energy dissipating dampers. The feature of the detail of the studies by Suita et al. (2003) and Koetaka et al. (2005) was that the lower flanges of the steel beams at the beam-to-column-connections did not joint to the column in order to avoid the fracture at those parts.

The experiment has been conducted to the steel frames retrofitted by the knee braces as shown in Figure 15. In this test, the knee braces were set by using the vises. The two types of failure modes were investigated. One was slipping at the connections between the end pates of knee braces and existing steel beams. The other was yielding and bucking at the knee braces. The former was the test for the connecting design by the vises. The latter was conducted for investigation of the energy dissipating performance of the knee braces.

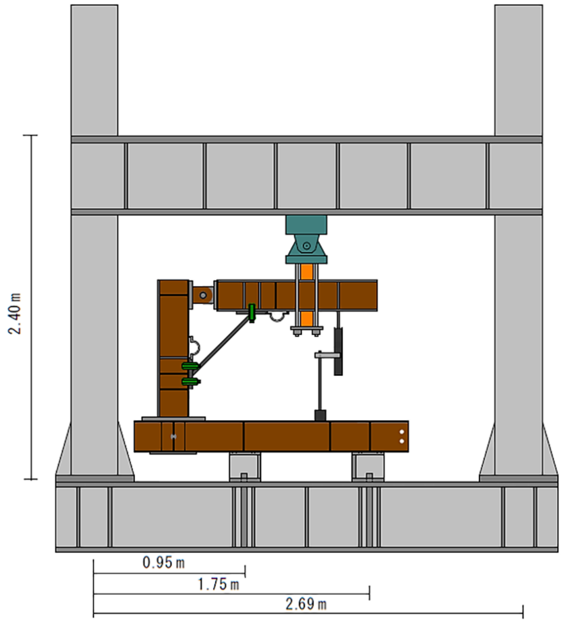

Figure 15. Test setup

2.1. Specimens

Figure 16a shows the knee braces in the specimens for investigation of the slipping failure at the connection. Figure 16b shows the knee braces in the specimen for investigation of the yielding at the knee braces. Material properties and dimensions of the knee braces were summarized in Table 2 and Table 3. The column of the frame was BH-200×180×6×9 which was high strength steel of HSA700. The beam of the frame was BH-200×200×6×9 which was normal strength steel of SM490. The column and the beam were connected by pin-joint. The frame was half part of one span steel frame. The hydraulic jack was used to apply the tensile force and compressive force alternately to the beam vertically.

The thickness of the ends plates was 22 mm. The material properties of all end plates were the same. The surface condition of the end plates was rust. The knee braces were welded to both of the end plates. The specimens with rust surface were revealed in the open air over one month.

The test parameter for the investigation of the slipping behavior was the angle θ between the beams and the knee braces. The angle θ of the specimens of SL-45 and SL-30 were 45 degree and 30 degree, respectively. Specimen of SL-45-0 was applied to alternative force in order to investigate the differences between stress state of the connection. Specimens of SL-45-1, SL-45-2, SL-45-3 were the same and subjected to monotonic tensile force for investigation of the slipping strength. SL-30 was also subjected to monotonic tensile force and verified to the evaluating method for the slipping strength which was explained later. The test parameter for investigation of the yield and buckling at the knee brace was the thickness h of the central part of the knee braces: 6, 9, 12, 15 mm, corresponding to the name of the specimens: nSL-6, nSL-9, nSL-12, nSL-15. The length L, thickness t and height h of the specimens were summarized in Table 4.

The two vises were used to connect the knee brace to the beam as shown in Figure 15. The four vises were used to connect the knee brace to the column. Therefore, the slip occurred at the connection between the end plate of knee brace and the steel beam. Figure 17 shows the specimens with yield and bucking failure, which had four vises each to connect the knee brace to the beam and the column. In the figure, loading and measuring devices were also explained.

2.2. Calculating method for slipping strength

The calculating method for the slipping strength was derived as follows. The clipping force B was 75 kN by the one vise as the same value of the tensile test of steel coupons in the previous section.

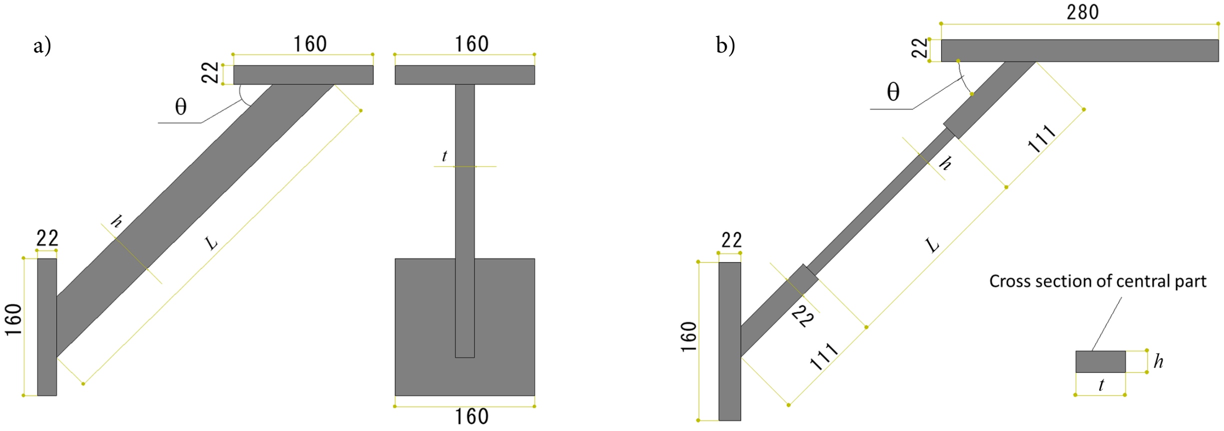

Figure 16. Shapes of the knee braces of the specimens (unit: mm): a – investigation of the slipping failure at the connection; b – investigation of the yielding at the knee braces

Table 2. Material properties of the steel frames of test specimens

	Spec	t_f (mm)	σ_y (N/mm^2)	σ_u (N/mm^2)	ε_{st} (%)
Beam	SM490	8.9	392	520	2.83
Column	H-SA700	9.0	795	862	–

Note. t_f: thickness of flange of H-shape steel, σ_y: yield strength, σ_u: tensile strength, ε_{st}: stain at the strain hardening.

Table 3. Material properties of the steel plates for knee braces

	Spec	t (mm)	σ_y (N/mm^2)	σ_u (N/mm^2)	ε_{st} (%)
SL-45	SM400	21.8	279	428	1.89
SL-30, nSL	SM400	21.5	271	434	1.85

Note. t: thickness of steel plate, σ_y: yield strength, σ_u: tensile strength, ε_{st}: stain at the strain hardening.

When the knee brace was sustaining tensile force in Figure 18, the contact force at the surface between the end plate of the knee brace and the steel beam was decreased by the vertical component T of the axial force N of the knee brace. The frictional force Q at the surface was predicted as follows:

$$Q = (nB - T)\mu, \tag{1}$$

where n was number of the vise, B was axial force of the bolt of the vise, T was vertical component of N, μ was the frictional coefficient, and Q was horizontal component of N.

Table 4. Dimensions of the knee braces in the specimens of retrofiteed steel frames

	L (mm)	t (mm)	h (mm)	Θ (°)
SL-45-0	450	21.8	50.3	45
SL-45-1	450	21.8	50.3	45
SL-45-2	450	21.8	50.3	45
SL-45-3	450	21.8	50.3	45
SL-30	384	21.5	50.0	30
nSL-6	200	21.5	5.9	45
nSL-9	200	21.5	9.0	45
nSL-12	200	21.5	11.9	45
nSL-15	200	21.5	14.8	45

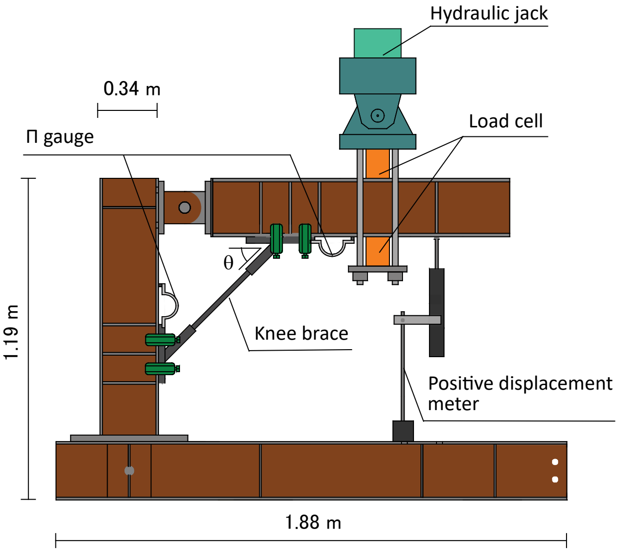

Figure 17. Loading and measuring devices

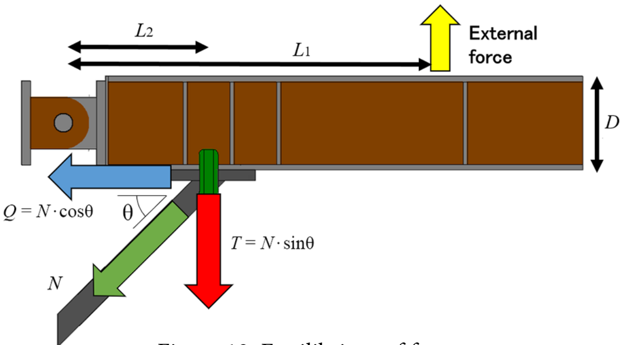

Figure 18. Equilibrium of forces

When the relation of $T = Q\tan\theta$ was substituted into Eqn (1), the slipping strength Q_A was derived as follows:

$$Q_A = \frac{nB\mu}{1 + \mu\tan\theta}. \tag{2}$$

When the axial force was tension, substituting these values: $n = 2$, $B = 75$ kN, $\mu = 0.45$, $\theta = \pi/4$, $\tan\theta = 1$, then $Q_A = 46.6$ kN. When the axial force was compression, $Q_A = 122.7$ kN. The calculated value of the Q_A was compared to the test results in the next section.

2.3. Test results with slipping behavior

The applied force was measured by the load cell of which capacity was 200 kN at the position of the hydraulic jack. The slipping displacement was measured by π gauges laterally at the surface between the end plate of the knee brace and the steel beam. The π gauge was a displacement meter shown in Figure 19. Four wire strain gauges were glued on the surface of the knee brace along its axis. Also, axial deformation of the knee brace was measured by two displacement meters. When the knee brace kept elastic, the axial force N of the knee brace was obtained by multiplying the strain and the axial stiffness. The value of N was also able to be obtained from rotational equilibrium.

The experimental result of SL-45-0 was shown in Figure 20. In the figure, the vertical axis showed the lateral component Q of N; the horizontal axis showed lateral displacement Δ_H, which was the average of two displacement obtained by the π gauges. In the figure, the value of N was obtained from the data of wire strain gauges.

The value of Q varied in positive and negative according to the change of tension and compression of the axial force of knee brace N. The absolute value of peaks of Q in negative was over two times of maximum value in positive. The calculated values Q_A obtained by Eqn (2) were shown in the figures. In the positive side, the envelop curve of the experimental attained Q_A and then declined,

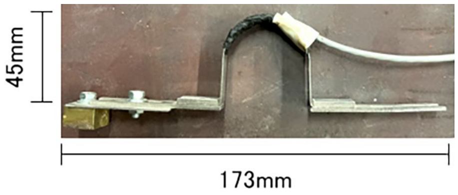

Figure 19. π gauge

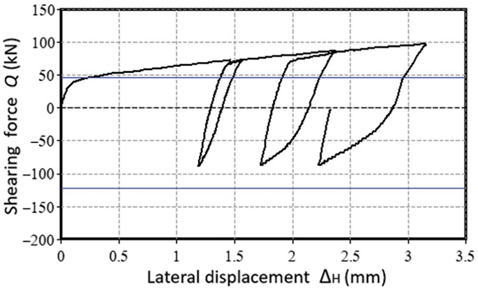

Figure 20. Relations between Q and Δ_H

but kept upward trend. In the negative side, the experimental curve did not attain Q_A without declining manner and slipping behavior did not be observed. When the knee braces in the steel buildings were sustaining tension and compression alternatively under seismic forces, the connection design in which the knee brace sustained tension was important.

The experimental results of SL-45-1, SL-45-2, SL-45-3 were shown in Figures 21a to 21c. The experimental result of SL-30 was shown in Figure 21d. The knee braces of these specimens were subjected to monotonic tensile force to compare between the test and the calculation of the slipping strength. The calculated strength by Eqn (2) were shown in Figure 20. The all of the test results showed gradual enhancement of strength after slipping in the figures, which showed the similar behavior of the results of the simple tensile test. These stable manner of force versus deformation relations realize that the retrofitting design with allowing the slip between the knee brace and existing members.

The slipping strength were summarized in Table 5. he slipping strength were summarized in Table 5. The test results were overestimated by the Eqn (2) except for SL-45-1 and SL-30. But the strengths of all specimens were over the calculated value of Q_A in the loading process. The mean value of four SL-45 specimens was 44.9 kN which was 96% of Q_A. This showed that the slipping strength were precited by the Eqn (2). In the practical use of the retrofit, Eqn (2) were necessary to estimate the slipping strength of the specimen with different angle between the knee brace and the beam. The calculating method of Eqn (2) was able to the slipping strength of the specimens with the different angle. The slipping strength of SL-30 was higher than that of SL-45. As shown in Eqn (2), when the angle θ decreased, the slipping strength increased.

2.4. Test results with yield and buckling behavior

In this section, the test results of specimens which failed in yielding and buckling were discussed. In order to prevent the slipping failure, the four vises were used to connect the knee brace and steel beam. The axial force *N* corresponding to the calculated slipping strength by Eqn (2) was 135 kN. Figures 22a to 22d showed the relations between *N* and axial displacement Δ_A of the knee braces. The test was controlled by the axial displacement. The loading program was shown in Figure 23, where the maximum displacement was 5 mm. The value of *N* was obtained from rotational equilibrium.

As shown in the figures, the knee braces attained its yield strength under tensile force. After that, buckling of the knee braces occurred under compressive force. The redlines showed the calculated yield strength and bucking strength in these figures. The experimental values and calculated values agreed precisely. The value of *N* of all specimens did not attain the 135 kN which was strength of slipping failure. The comparisons between test and calculation were summarized in Table 6. The yielding and buckling mechanism at knee braces was desirable. In this test, the mechanism at knee braces was realized. The load versus deformation relations were discussed deeply from test and analysis in our next paper.

Table 5. Test results of slipping strength

	Test results (kN)	Slipping strength (kN)	
		Average	Calculated value
SL-45-0	40.9	44.9	46.6
SL-45-1	54.0		
SL-45-2	44.9		
SL-45-3	39.6		
SL-30	60.0	60.0	53.6

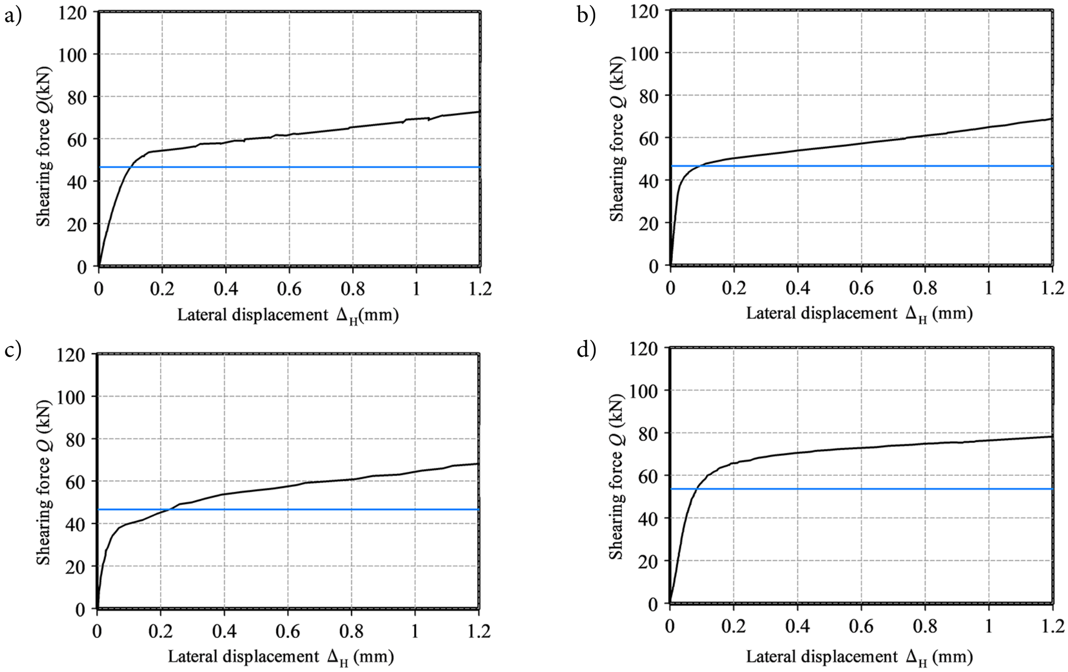

Figure 21. Relations between Q and Δ_H: a – SL-45-1; b – SL-45-2; c – SL-45-3; d – SL-30

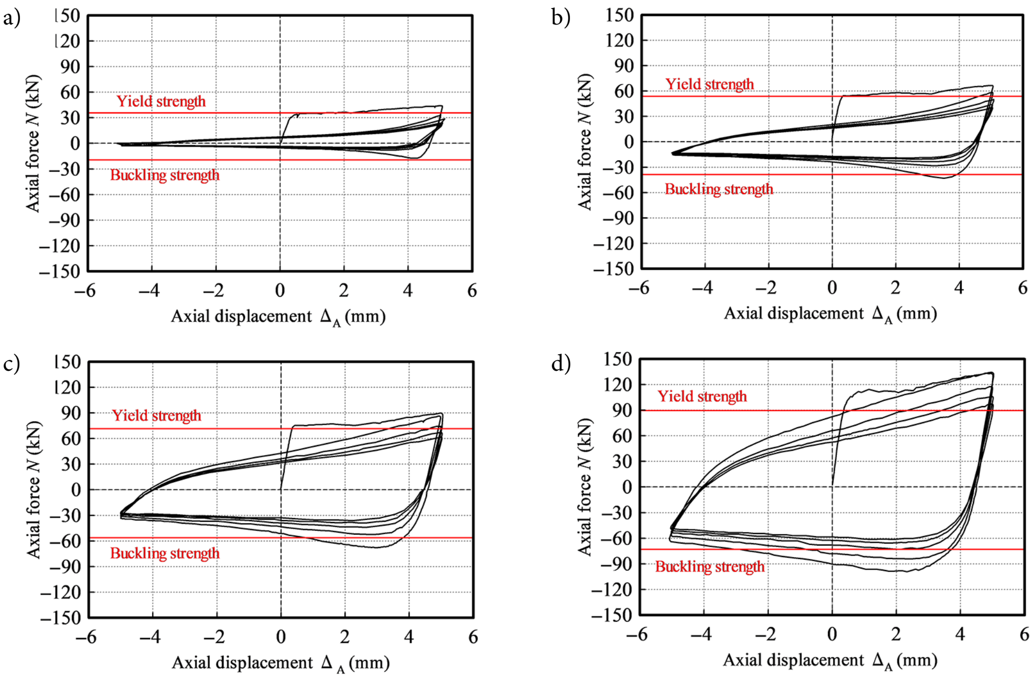

Figure 22. Relations between N and Δ_A: a – SL-45-1; b – SL-45-2; c – SL-45-3; d – SL-30

Table 6. Test results of yield and buckling strength

	Yield strength (kN)			Buckling strength (kN)		
	Experimental value	Calculated value	E/C	Experimental value	Calculated value	E/C
nSL-6	31.1	35.8	0.87	17.4	20.4	0.85
nSL-9	51.8	53.7	0.96	43.1	43.4	0.99
nSL-12	73.8	71.5	1.03	67.9	63.9	1.06
nSL-15	96.4	89.4	1.08	99.1	83.3	1.19

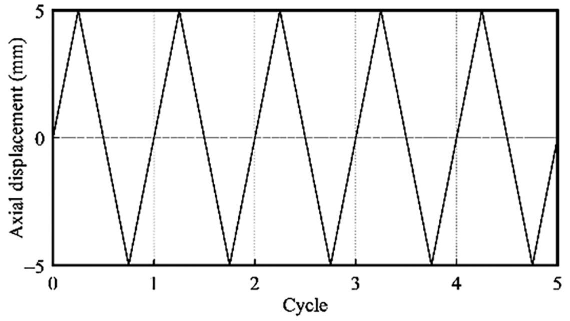

Figure 23. Loading program

Conclusions

From the simple tensile test on the connection by the vises and the practical test on retrofitted steel frames by knee braces, the following conclusions were derived:

- From the tensile test results, the average of the slipping strength of the connection between rust surface of steel coupons by one wise was 35.5 kN, which was corresponding to the value of frictional coefficient of 0.47.
- The two failure modes were observed experimentally by the test of frame specimens retrofitted by the knee braces. One was slipping behavior at the connection. The other was the yielding and bucking behavior at the knee brace.
- The slipping strength between the end plate of the knee brace and the existing steel beam was estimated by the calculating method which was considering to the difference of tensile or compressive force of knee brace.
- The hysteretic behavior of the specimens with yielding and bucking of the knee braces showed energy dissipating performance.
- The yielding and bucking strength of the knee braces were estimated by simple calculations.

Acknowledgements

The experimental study of this paper was assisted by Dr. Chan Iathong who was Assistant Professor of Nagasaki University and Kenta Okamoto who was technician of Nagasaki University. The authors wish to express their gratitude to their contributions.

Funding

This research received no external funding.

Author contributions

Hiroyuki Nakahara was responsible for study design. Hiroyuki Nakahara, Takato Shimomura and Ding Nan were involved in experimental works, calculations and the data interpretation. All authors critically revised the manuscript, commented on drafts of the manuscript, and approved the final manuscript.

Disclosure statement

The authors declare no conflict of interest.

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