Mechanical behavior and design method of weld-free steel structure with knee brace damper using square tube column

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SUMMARY:
This paper suggests a new weld-free system using square tube columns instead of wide-flange columns, in order to construct bi-directional moment frame. An experimental verification of full-scale beam-column subassemblies is conducted to confirm basic mechanical behaviour and to reveal ultimate state, which is out-of-plane buckling of the knee brace damper joint. As a result, it is revealed that the suggested connections can possess stable hysteresis characteristic under a large earthquake in the seismic design code if bolted connections are designed according to a proposed method. However, at the ultimate state, out-of-plane buckling of knee brace damper occurs. In order to prevent out-of-plane buckling of the knee brace damper, based on the test results, a design criteria of the brace joint to remain elastic under axial force and bending moment considering initial imperfection is proposed.

Keywords: Steel structure, Cyclic loading test, Weld-free system, Square tube, Out-of-plane buckling

1. INTRODUCTION

We have proposed an innovative structural system, which is called 'weld-free' system as shown in Fig. 1, in order to provide steel structures with stable construction quality and high plastic deformation capacity compared with conventional welded beam-to-column connections (Suita et al., 2004, Inoue et al., 2006 and Suita et al., 2006). The weld-free system consists of wide-flange columns, wide-flange beams and buckling-restrained braces named 'knee brace damper', and these members are mainly connected by using super high-strength bolts. The knee brace dampers are installed in both the top and

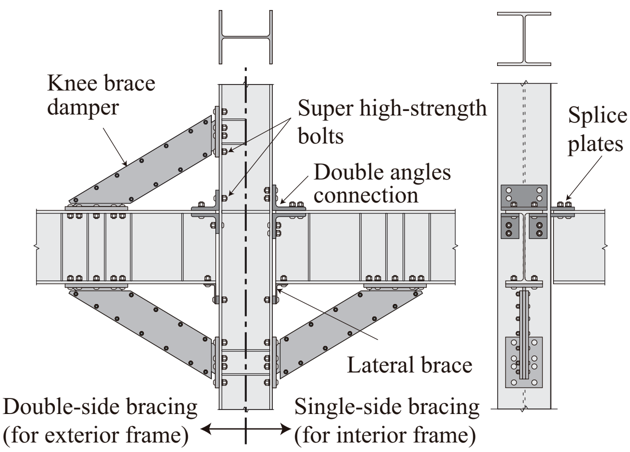

Figure 1. Details of weld-free system (wide-flange column)

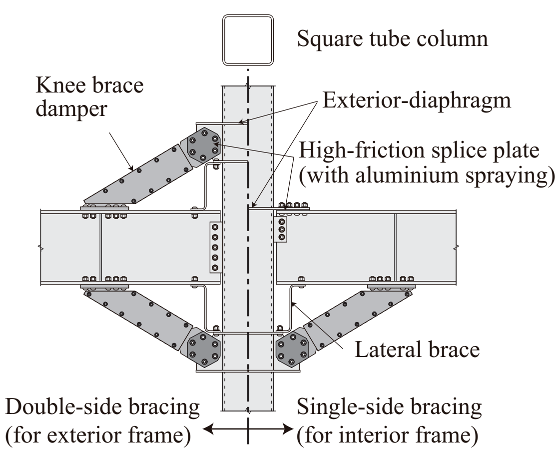

Figure 2. Details of weld-free system (square tube column)

the bottom of the beams or only in the bottom of the beams. Against a strong earthquake, the weld-free system is designed to dissipate seismic input energy by plastic deformation of the core plates at the knee brace dampers and to keep the columns and the beams elastic. The beam-to-column connection of the conventional weld-free system in the direction of the weak axis of the column is regarded as a pin joint because the beam top flange is only bolted to a stiffener of the column by using splice plates. Therefore, the beam-to-column connection of the weld-free system can resist only against uni-directional input, and at the same time the amount of steel used for the weld-free system is larger than that used for the bi-directional moment frame (Chou et al., 2004).

From this viewpoint, this paper suggests a new weld-free system, as shown in Fig. 2, using square tube columns instead of the wide-flange columns in order to construct the bi-directional moment frame. In the new weld-free system, the following connection details are proposed.

- Exterior-diaphragms are welded to the column at connections of both the beam top flange and the knee brace damper, in order to prevent out-of-plane deformation of the column flanges.
- Super high-strength bolts and high-friction splice plates sprayed with melting aluminum are used at the bolted connections, in order to reduce the number of the bolts and save the size of the connections.

In this paper, an experimental verification of full-scale beam-column subassemblies is conducted to confirm basic mechanical behaviour and to reveal ultimate state, which is out-of-plane buckling of the knee brace damper joint. Furthermore, based on these test results, a design method of the bolted connections is verified and a design method to prevent the out-of-plane buckling of the brace joint is proposed.

2. CYCLIC LOADING TEST

2.1. Test specimens

Test specimens are two full-scale beam-column subassemblies as shown in Fig. 3 and 4. One specimen, which is designated as type S, has single-side bracing and the other specimen, which is designated as type D, has double-side bracing. In case of type S, the high-friction plate (thickness is 6

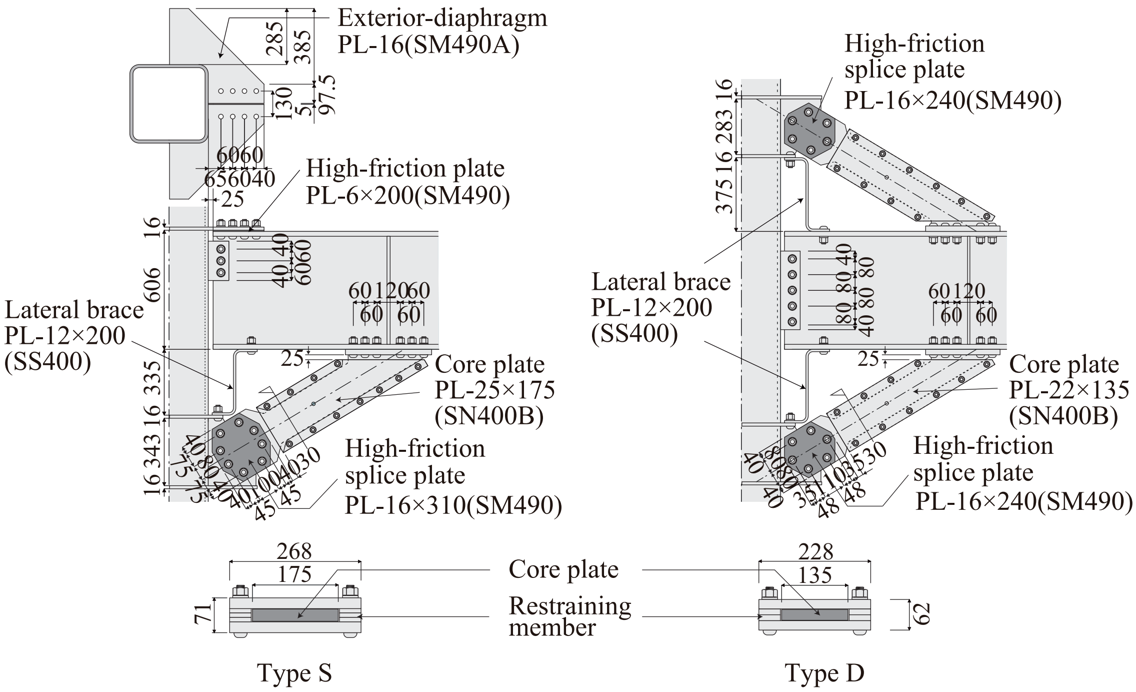

Figure 3. Details of beam-to-column connection (unit: mm)

mm) sprayed with melting aluminum on both sides is installed between the beam top flange and the exterior-diaphragm, and they are bolted in single-shear. And the beam web is bolted to a shear plate, which is welded to the column flange, in single-shear. In case of type D, the beam flanges, on which axial force does not act, are not jointed to the column. And the beam web is bolted to the shear plate, which is welded to the column flange. In all specimens, the sectional area of the column is 400×16 and the sectional area of the beam is 600×200×12×25. The exterior-diaphragms are welded to the column at both the connections of the beam top flange in type S and the connections of the knee brace damper in all specimens. The knee brace damper is connected to a gusset plate, which is welded to the column, by using the high-friction splice plates sprayed with melting aluminum. And lateral braces are installed in the beam flange to which the knee brace damper is connected.

In all specimens, the beams and the column are designed to remain elastic at the level of the yield strength of the braces, and the bolted connections are designed both to remain elastic and to prevent occurrence of significant slip and prying action of the bolts at the level of the maximum strength of the braces. Here, the maximum strength of the braces is assumed 1.4 times of the yield strength based on the nominal strength (Recommendation, 2006). Specification of the friction surfaces at the bolted connections without the high-friction plates is blast or rust, and as the design coefficient of friction, 0.45 is used at these friction surfaces. And also 0.70 is used at the high-friction plate sprayed with melting aluminum (Takada et al., 2008) except for the beam top flange in case of type S (0.55 is used at this friction surface) (Koetaka et al., 2012). In Table 1, mechanical properties of steel plates for the core plates of the knee brace dampers are shown.

2.2. Test setup and loading program

A test setup is illustrated in Fig. 4. Both ends of the column are pinned, and the beam end is loaded by a hydraulic jack. Loading protocol is shown in Fig. 5. The amplitudes of beam rotation angle θ applied for the test and number of cycle are one time in 0.005 rad, and two times in 0.01, 0.02, 0.03 and 0.04 rad until ultimate limit state. It is expected that testing until 0.02 rad will reveal the structural performance under a large earthquake in Japanese seismic design code.

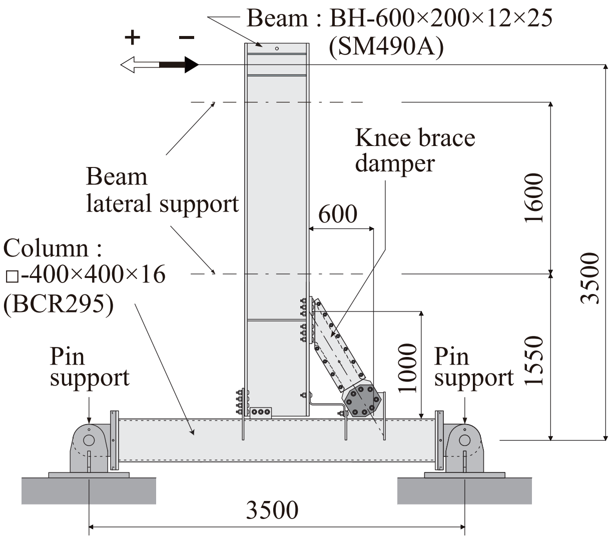

Figure 4. Test setup (unit: mm)

Table 1. Mechanical properties of steel plates for braces (Steel Grade: SN400B)

Specimen	Thickness (mm)	Yield strength (N/mm^2)	Tensile strngth (N/mm^2)	Elongation (%)
Type S	24.9	277	426	34
Type D	21.9	288	437	33

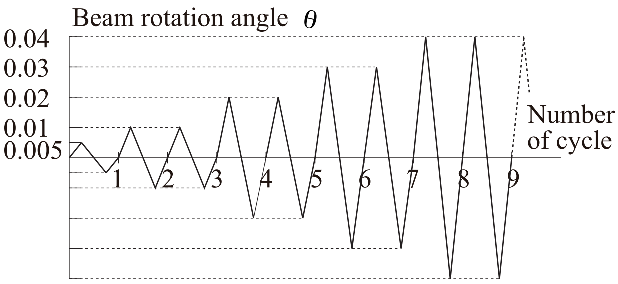

Figure 5. Loading protocol

2.3. Test results

Fig. 6. shows the bending moment at the beam end M versus the beam rotation angle θ relationship. Here, the M_p represents full-plastic moment based on the actual yield strength (see in Table 2). In Fig. 6, the triangular marks ▲ on the hysteresis curve mean the point of reaching maximum bending moment $M_{\max}$, and the bending moment decreased rapidly after reaching $M_{\max}$ because out-of-plane buckling of the knee brace damper joint occurred (see in Fig. 7). Ultimate cycle in Table 2 is identified with the point (▲) and the hysteresis curve after the buckling is shown by dash line. In case of type S after the buckling, the loading of the positive direction, where the tensile force acted on the brace, was continued until 0.067 rad. In all tests, there were no fracture at any joints and no significant yield of the column and the beams. As a result, it is revealed that the suggested connections possessed distinctly high structural performance until the expected level in the design if the bolted connections are designed according to the proposed method.

In Table 2, cumulative plastic deformation capacity until ultimate state are shown. All values are larger than the required plastic deformation under a large earthquake (Chou et al., 2004). However, they are about 10 or 20 percent of the value of the ordinary weld-free system (Koetaka et al., 2006). Thus, the out-of-plane buckling of the brace must be prevented to maintain high plastic deformation capacity.

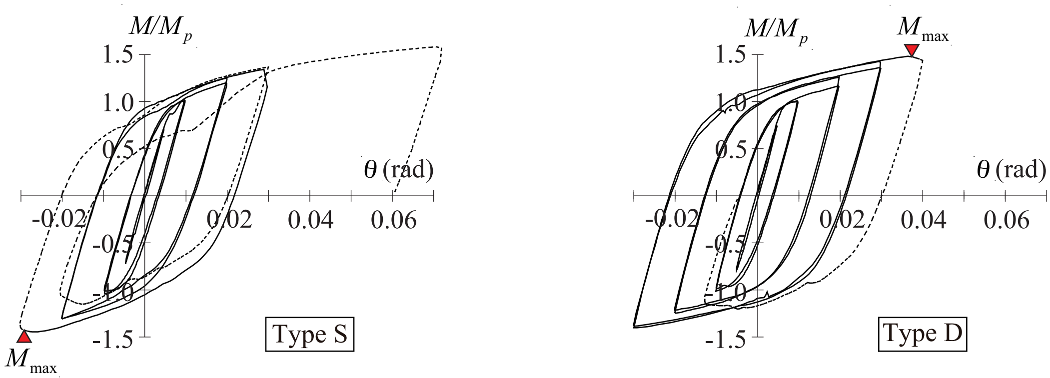

Figure 6. Bending moment at the beam end versus beam rotation angle relationship

Table 2. Test results

Specimen	Full-plastic moment M_p (kNm)	Maximum bending moment $M_{\max}$ (kNm)	Ultimate cycle	Ultimate state	Cumlative plastic deformation of braces η	η_E
Type S	1242	1661 -1803	0.03rad (-1)	buckling	142	149
Type S	1314	1935 -1847	0.04rad (+1)	buckling	222	244

Here, η is a value in which cumlative plastic deformation of the brace is divided by yield deformation, and η_E is a value in which cumlative dissiption energy of the brace is divided by yield axial force and yield deformation.

3. DESIGN METHOD TO PREVENT OUT-OF-PLANE BUCKLING AT BRACE JOINT

3.1. Estimation of out-of-plane buckling load

To estimate out-of-plane buckling load of the brace joint, an analysis model, as shown in Fig. 8, is adopted. In the model, K_c represents torsional stiffness of the column about its longitudinal axis, and K_R represents rotational stiffness of the brace joint, which includes the exterior-diaphragms, the gusset plate, the splice plates, and the brace end, about the column surface. Here, if the hysteresis curve of the brace is given as the perfect elasto-plastic relationship, it can be assumed that the boundary condition at the both ends of restraining member are pins after compressive force of the brace reaches the yield axial force N_y. In Fig. 8, the rotational springs and the pins are connected by rigid body respectively. Then, the out-of-plane buckling load of the brace N_{cr} is derived as the next formula.

$$N_{cr} = \frac{A_1 - \sqrt{A_1^2 - A_2}}{2(l_b + l_R + d_c^*)l_R d_c^*} \tag{1}$$

$$A_1 = (l_b + l_R + d_c^*)(l_R + d_c^*)K_R + (l_b + l_R)l_R K_c \tag{2}$$

$$A_2 = 4(l_b + l_R + d_c^*)l_b l_R d_c^* K_R K_c \tag{3}$$

l_b, l_R and d_c^* are shown in Fig. 8.

Comparison of the buckling load between test results (i.e., maximum axial force of the brace $N_{\max}$) and calculation results (i.e., buckling load N_{cr} obtained from Eqn. (1)) is shown in Table 3. Here, stiffness of rotational springs were obtained from another verification to measure twist of the column and deflection of the brace joint by acting out-of-plane load on the splice plates connected to the column of the specimens as mentioned above. Fig. 9 shows axial force of the knee brace damper N versus rotational angle of the brace joint θ_R relationship. The dot lines in Fig. 9 represent out-of-plane buckling load N_{cr} obtained from Eqn. (1). Rotational angle θ_R increased rapidly as axial force N became close to the buckling load N_{cr}. And buckling load N_{cr} of type S is almost the same as the maximum axial force of the brace $N_{\max}$, and N_{cr} of type D is larger about 20 percent than $N_{\max}$.

Fig. 10 shows relation between axial force and bending moment (refer to Fig. 11) at the splice plates of the knee brace damper. The value of vertical axis is normalized by the yield axial force of the splice plates ${}_{sp}N_y$, and the value of horizontal axis is normalized by yield bending moment of the splice

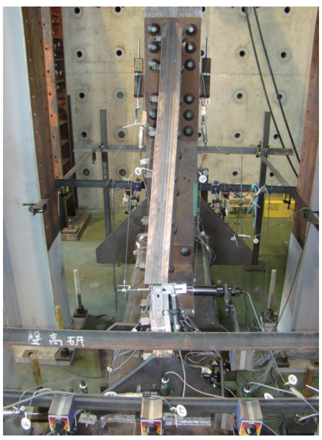

Figure 7. Out-of-plane buckling

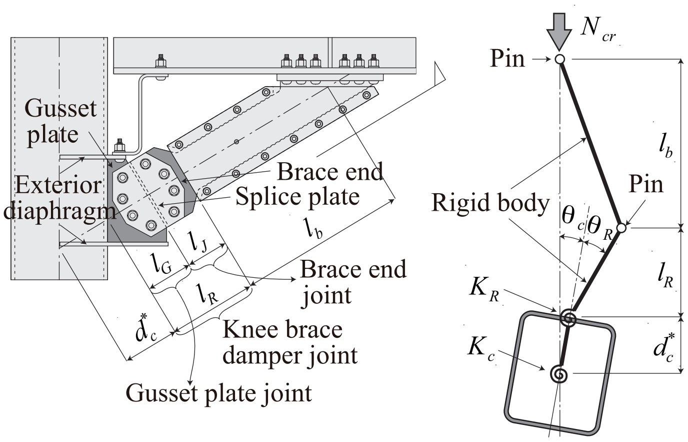

Figure 8. Buckling model

plates ${}_{sp}M_y$. Here, it is assumed that ${}_{sp}M_y$ is two times of yield bending moment of one splice plate, because slip has been occurred when axial force reached $N_{\max}$. In Fig. 10, the heavy lines mean the yield surface of the splice plates, and it can be considered that the splice plates become yield when the solid line reaches the heavy line. And in case of type D, circle marks • represent the point when strain, which is measured by strain gages, of each the splice plate reached the yield strain. Fig. 10 represents that bending moment calculated by Fig. 11 overestimate bending moment at circle marks, and however bending moment when axial force reached $N_{\max}$ is identified with the yield surface. The reason that $N_{\max}$ of type D is smaller than N_{cr} in Fig. 9 would be caused by plasticity of the splice plates and amplitude of initial imperfection. As a result, to prevent out-of-plane buckling of the brace joint, the splice plates must remain elastic under axial force and bending moment.

Table 3. Comparison of out-of-plane buckling load

Specimen	Maximum axial force $N_{\max}$ (kN)	Buckling load N_{cr} (kN)	Stiffness of column K_c (kNm)	Stiffness of brace joint K_R (kNm)
Type S	1752	1755	4822	1481
Type D	1254	1501	4745	1020

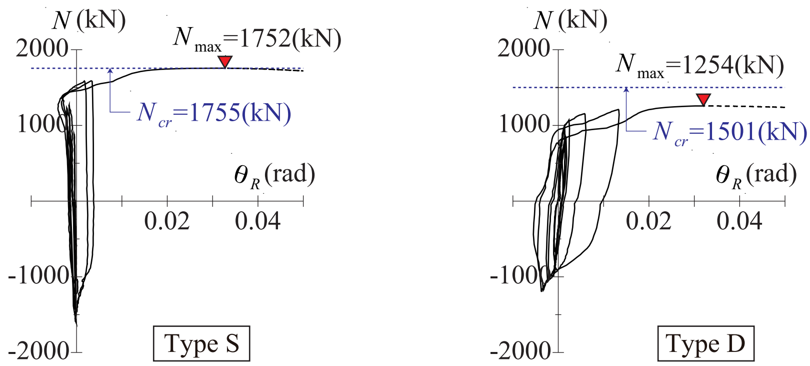

Figure 9. Axial force of knee brace damper versus rotational angle of brace joint relationship

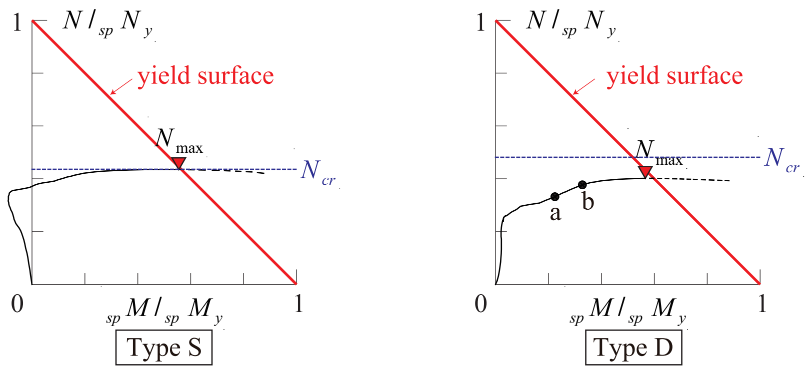

Figure 10. M-N interaction at splice plates of knee brace damper

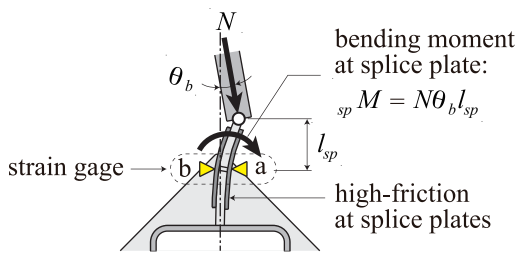

Figure 11. Bending moment at splice plates

3.2. Estimation of out-of-plane stiffness of brace joint

To calculate the out-of-plane buckling load N_{cr}, rotational stiffness of the brace joint K_R must be estimated. From this viewpoint, in order to develop a model for estimation of rotational stiffness of the brace joint, firstly, the knee brace damper joint is divided in the gusset plate joint and the brace end joint, as shown in Fig. 8. The gusset plate joint consists of the exterior-diaphragms, the gusset plate, and the splice plates, and the brace end joint consists of the splice plates and the brace end. Next, to estimate out-of-plane stiffness of the gusset plate joint K_G, the ‘Rigid Bodies-Spring Models’ (Kawai et al., 1977) is adopted. In the model, an analyzed plate is divided in several rigid triangular plates, and each rigid triangular plate is connected by rotational springs at the boundaries.

The gusset plate is divided in three rigid triangular plates A, B, and C as shown in Fig. 12. Degrees of freedom of each node in the rigid triangular plates are limited only in the z-direction (i.e. the out-of-plane direction), and rotational angle θ_{AB} of the rotational spring at the boundary of triangular plates A and B is obtained from the out-of-plane displacement of each node w_1- w_4. Bending moment acting on the rotational spring can be also obtained from the out-of-plane load of each node P_1- P_4. Therefore stiffness matrix $\boldsymbol{K_{AB}}$ in the boundary of triangular plates A and B can be obtained (Kawai et al., 1977). In Fig. 12, assuming that the nodes 2-5 are fixed points and boundary conditions of the sides 2-3, 2-5, and 3-4 are simple supports, out-of-plane stiffness of the gusset plate joint K_G is defined as the ratio of out-of-plane load of node-1 (P_1) to out-of-plane displacement of node-1 (w_1). Therefore K_G is derived by using the elements about the node-1 in the stiffness matrix in the boundary of triangular plates $\boldsymbol{K_{AB}}$ and $\boldsymbol{K_{AC}}$ by the next formula.

$$K_G = \left(\frac{\sqrt{l_{23}^2 - {}_{AB}h_A^2}}{l_{13}\,{}_{AB}h_A} + \frac{\sqrt{l_{34}^2 - {}_{AB}h_B^2}}{l_{13}\,{}_{AB}h_B}\right)^2 k_{AB} + \left(\frac{\sqrt{l_{25}^2 - {}_{AC}h_C^2}}{l_{12}\,{}_{AC}h_C} + \frac{\sqrt{l_{23}^2 - {}_{AC}h_A^2}}{l_{12}\,{}_{AC}h_A}\right)^2 k_{AC} \tag{4}$$

$$k_{AB} = \frac{2l_{13}}{{}_{AB}h_A + {}_{AB}h_B} \cdot \frac{Et_g^3}{12(1-\nu^2)} \tag{5}$$

$$k_{AC} = \frac{2l_{12}}{{}_{AC}h_A + {}_{AC}h_C} \cdot \frac{Et_g^3}{12(1-\nu^2)} \tag{6}$$

Here, t_g is thickness of the gusset plate, E is Young’s modulus, and ν is Poisson's ratio.

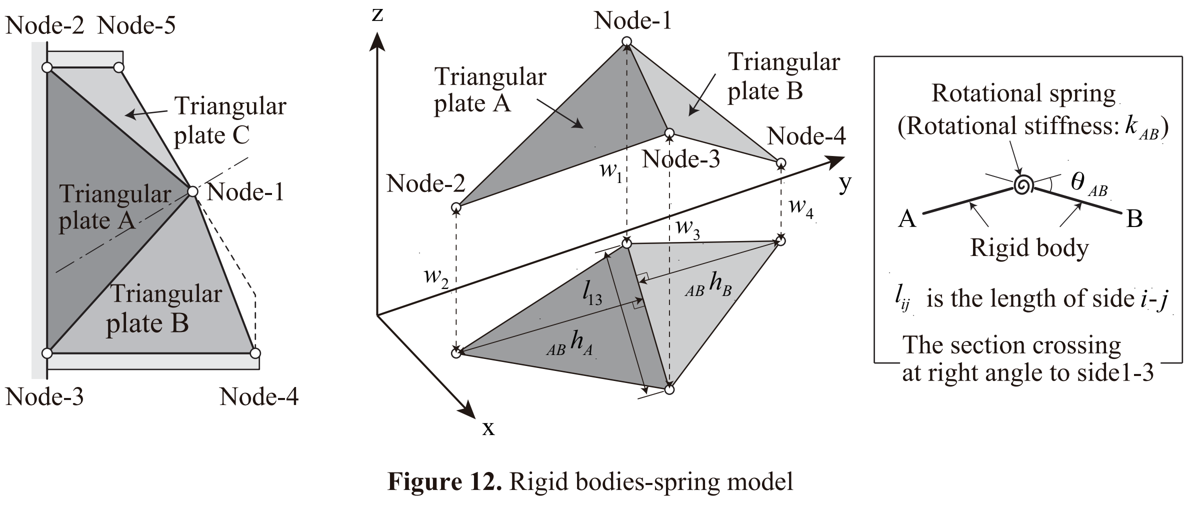

Figure 12. Rigid bodies-spring model

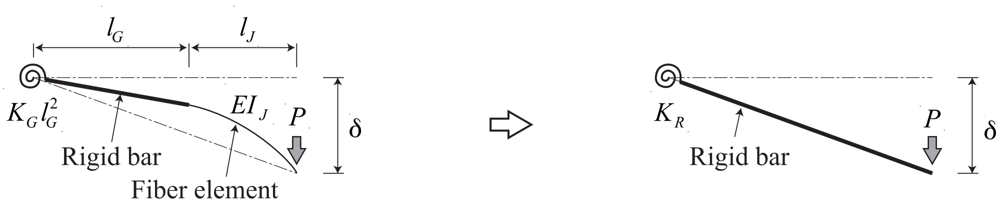

Figure 13. Knee brace damper joint model

Table 4. Comparison of rotational stiffness of knee brace damper joint

Specimen	Calculation result of stiffness of gusset plate joint K_G (kN/mm)	Calculation result of rotational stiffness of brace joint K_R (kNm)	Test result of rotational stiffness of brace joint K_R (kNm)
Type S	58.1	1738	1481
Type D	55.0	1201	1020

Furthermore, it is assumed that the gusset plate joint is represented by a rigid body and a rotational spring and the brace end joint is represented by a fiber element (see left side in Fig. 13). In order to obtain rotational stiffness of the brace joint K_R, the combined model is replaced by a rigid body and a rotational spring (see right side in Fig. 13). It is assumed that out-of-plane displacement δ against out-of-plane load P at the joint end by using left side model in Fig. 13 is identified with that by using the right side model in Fig. 13. Consequently, rotational stiffness of the brace joint K_R is obtained from the next formula.

$$K_R = \left\{ \frac{1}{K_G l_G^2} + \frac{l_J^3/(l_J + l_G)^2}{3EI_J} \right\}^{-1} \tag{7}$$

Here, I_J is the sum of each moment of inertia of the brace end and the splice plates.

Comparison of rotational stiffness of the brace joint K_R between test results, which are shown in Table 3, and calculation results, which are obtained from Eqn. (7), is shown in Table 4. In all specimens, the calculation results of K_R overestimate test results about 20 percent, however it is important that the estimation method is quite simple and easy.

3.3. Design criteria of brace joint

In order to prevent the out-of-plane buckling at the brace joint, the brace joint must remain elastic. If axial force N becomes close to buckling load N_{cr}, out-of-plane deformation similar to the buckling mode increases (Koetaka et al. 2009). At the same time, not only axial force but also bending moment acts on the splice plates of the knee brace damper with initial imperfection. Therefore maximum bending moment acting on the splice plates ${}_{sp}M_{\max}$ is obtained from the next formula, assuming that initial imperfection is the buckling mode shown in Fig. 8.

$${}_{sp}M_{\max} = \frac{N_{\max} l_J \theta_{b0}}{1 - N_{\max}/N_{cr}} \tag{8}$$

Here, $N_{\max}$ is axial force of the knee brace damper joint for design, and θ_{b0} is the angle of initial imperfection of the knee brace damper.

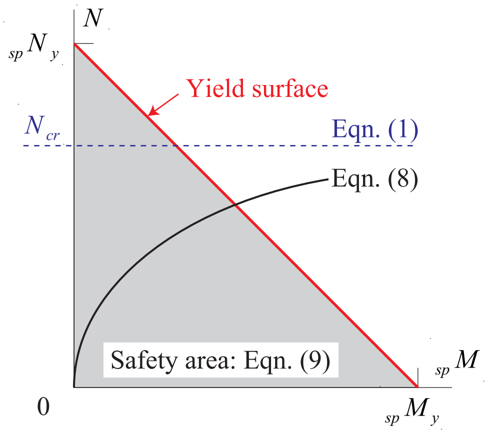

Figure 14. Design criteria of brace joint

In order to prevent the out-of-plane buckling at the brace joint, the splice plates of the brace joint must remain elastic. Therefore the point of $N_{\max}$ and $_{sp}M_{\max}$ must exist in the yield surface of the splice plate as shown in Fig. 14, and this requirement is represented as the next formula.

$$\frac{N_{\max}}{_{sp}N_y} + \frac{_{sp}M_{\max}}{_{sp}M_y} < 1 \tag{9}$$

Here, $_{sp}N_y$ is the yield axial force of splice plates, and $_{sp}M_y$ is two times value of yield bending moment of one splice plate.

4. CONCLUSIONS

The mechanical behavior and the ultimate state, which is out-of-plane buckling of the knee brace damper, of the weld-free system using square tube column have been revealed by the cyclic loading test on the full-scale beam-column subassemblies. Furthermore, based on these test results, a design method of the bolted connections was verified and a design method of the out-of-plane buckling of the brace joint was proposed. The primary findings and conclusions are as follows.

1. It is revealed that the suggested connections can possess stable hysteresis characteristic under a large earthquake in the seismic design code if the bolted connections are designed according to the proposed method.
2. To possess high plastic deformation capacity as well as ordinary weld-free system against unexpected huge earthquake, out-of-plane buckling of the knee brace damper must be prevented.
3. Out-of-plane buckling loads, which are presented in Eqn. (1), almost equal to test results. And, Rotational stiffness of the brace joint, which are presented in Eqn. (7), overestimate test results about 20 percent, however it is important that the estimation method is quite simple and easy.
4. In order to prevent out-of-plane buckling of the knee brace damper, the design criteria of the brace joint to remain elastic under axial force and bending moment in consideration of the initial imperfection was proposed.

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