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BI-DIRECTIONAL DYNAMIC LOADING TESTS OF A STUD-TYPE MULTI-UNIT FRICTION DAMPER USING CONED DISC SPRINGS

Y. Suzui[(1)], T. Sano[(2)], Y. Utsumi[(3)], H. Hirata[(4)], and D. Ode[(5)]

[(1)] *Senior Engineer, Technical Research Institute, Obayashi Corporation, suzui.yasumasa@obayashi.co.jp*
[(2)] *General Manager, Technology Division, Obayashi Corporation, sano.takeshi@obayashi.co.jp*
[(3)] *Deputy General Manager, Specialty Construction Department, Obayashi Corporation, utsumi.yoshikazu@obayashi.co.jp*
[(4)] *Chief, Technical Research Institute, Obayashi Corporation, hirata.hiroshi@obayashi.co.jp*
[(5)] *Engineer, Technology Division, Obayashi Corporation, ode.daisuke@obayashi.co.jp*

Abstract

The authors have developed a multi-unit friction damper which tighten the friction plate and the stainless-steel plate with high-tension bolts via coned disc springs and have applied it to many buildings. The friction damper exhibits a stable sliding frictional force during an earthquake and controls vibration of the building.

The structural performance of the friction damper has already been confirmed by dynamic loading tests in the state of incorporating it in a full-scale steel frame, but they were based on loading in only one direction within the steel frame.

However, in recent years, it has been pointed out that during an actual earthquake, a damper incorporated in the main frame of a building is deformed not only in the in-plane direction but also in the out-of-plane direction. And it is recommended to verify the performance of a damper under bi-directional deformation simulating horizontal deformation during an earthquake.

In this study, bi-directional dynamic loading tests were conducted on the friction damper for the purpose of confirming the structural performance in the state where deformation was simultaneously applied not only in the in-plane direction but also in the out-of-plane direction.

The test specimens were designed with reference to the stud-type multi-unit friction dampers used in actual high-rise buildings. They were composed of three friction units. Since the target frictional force of each friction units was 100kN, the target total frictional force of the stud-type damper specimen was 300kN.

A shaking table was used for dynamic loading. A loading frame composed of upper and lower loading beams and columns with both end pins was assembled on the shaking table, and the stud-type damper specimen in a standing state was incorporated into the frame. The lower side of the specimen was fixed to the shaking table via the lower loading beams, and the upper side of the specimen was subjected to a reaction force on the outside of the shaking table via the upper loading beams. And the dynamic loading to the specimen was performed by giving the dynamic displacement of two horizontal directions to the shaking table.

For the dynamic loading, sine waves and seismic response waves were used. In the case of using sine waves, bi-directional loading was performed so that the horizontal displacement history of the shaking table draws a circle. In the case of using seismic response waves, bi-directional loading was performed so that the horizontal displacement history of the shaking table draws a random shape.

The following conclusions were drawn from the results obtained in this study.

1. In bi-directional dynamic loading test, the stud-type multi-unit friction dampers produced the target frictional force and exhibited a stable energy absorption ability, showing rigid-plastic hysteresis loops in the in-plane direction.
2. The effect of bi-directional loading on the load-deformation relationship of the friction damper was small in both in-plane and out-of-plane directions.

Future research tasks include confirming the structural performance of other types, for example brace-type multi-unit friction dampers under bi-directional dynamic deformation.

Keywords: friction unit; high-tension bolt; bi-directional loading; rigid-plastic hysteresis; out-of-plane deformation

1. Introduction

The authors have developed a multi-unit friction damper which tighten the friction plate and the stainless-steel plate with high-tension bolts via coned disc springs and have applied it to many buildings [1]. The friction damper exhibits a stable sliding frictional force during an earthquake and controls vibration of the building.

The structural performance of the friction damper has already been confirmed by dynamic loading tests in the state of incorporating it in a full-scale steel frame [2, 3], but they were based on loading in only one direction within the steel frame.

However, in recent years, it has been pointed out that during an actual earthquake, a damper incorporated in the main frame of a building is deformed not only in the in-plane direction but also in the out-of-plane direction. And it is recommended to verify the performance of a damper under bi-directional deformation simulating horizontal deformation during an earthquake. As examples of simultaneous horizontal loading tests (in-plane and out-of-plane) for dampers, there are experiments for shear panel dampers [4, 5], but there are few examples of such studies.

Therefore, this time, the authors conducted a dynamic loading experiment in two horizontal directions simultaneously for a stud-type damper member incorporating the multi-unit friction damper. In this report, the experimental plan and the experimental results are reported.

2. Outline of the developed friction damper

Fig. 1 shows the basic configuration of a single friction unit of the developed damper, and Fig. 2 shows main components of each friction unit. In this friction unit, a slotted hole is provided in the inner steel plate of the joint, and a friction plate (brake pad) and a stainless-steel plate are sandwiched between the inner steel plate and the outer steel plate. Then, the joints are tightened with high-tension bolts via the coned disc springs stacked in parallel. The joints repeatedly slide with stable frictional force during an earthquake. As a result, the friction damper efficiently absorbs seismic energy and reduces vibration of the building. Further, the frictional force of the friction damper can be freely adjusted by changing the number of the friction damper unit.

Fig. 3 shows the relationship between the restoring force and the deflection of the coned disc springs in the vertical direction. The axial force of the high-tension bolt can be stabilized by using the coned disc

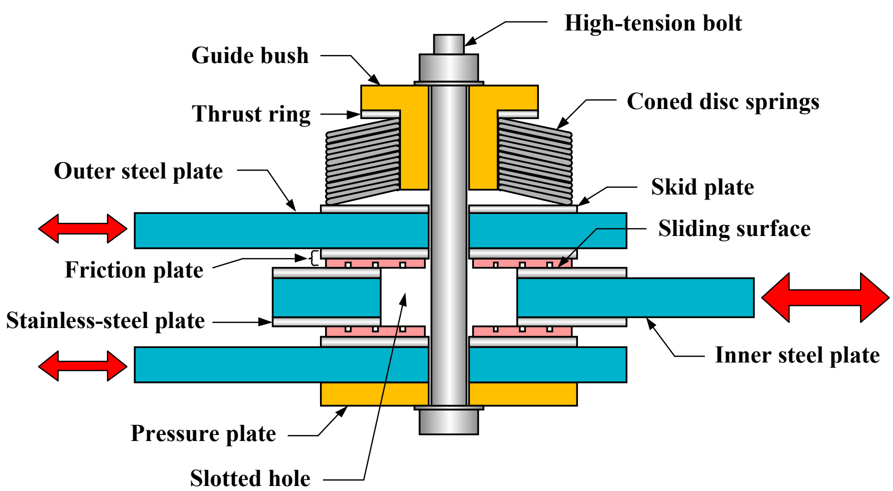


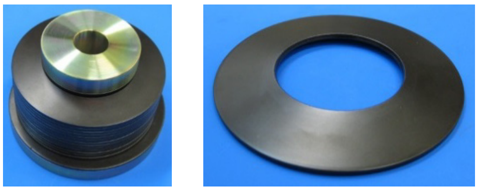
Fig. 1 – Basic configuration of a single friction unit of the developed damper

springs in a region where the change in the restoring force with respect to the change in the deflection is small. The friction coefficient of the sliding surface of the damper is kept constant by combining a stainless-steel plate with a friction plate (brake pad) that has superior durability and little aging.

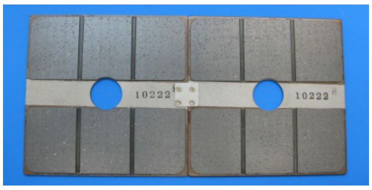
Fig. 4 shows application examples of multi-unit friction dampers installed in actual high-rise buildings. Usually, this damper is incorporated as a brace-type or stud-type damper for seismic control in a beam-column frame of a building.

(a) High-tension bolt (HTB)

(c) Stainless-steel plate



(b) Coned disc spring



(d) Friction plate

Fig. 2 – Components of each friction unit

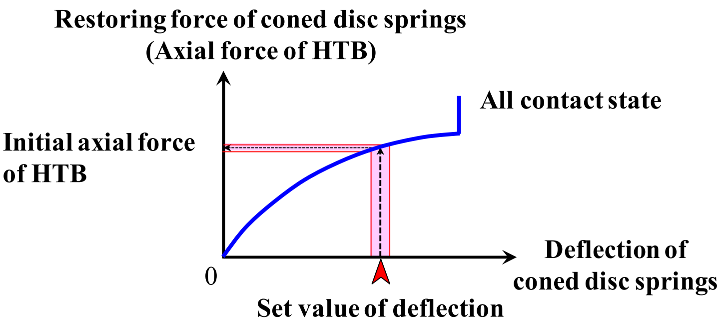


Fig. 3 – Relationship between the restoring force and the deflection of the coned disc springs in the vertical direction

(a) Brace-type

(b) Stud-type

Fig. 4 – Application examples of multi-unit friction dampers installed in actual high-rise buildings

3. Experimental plan

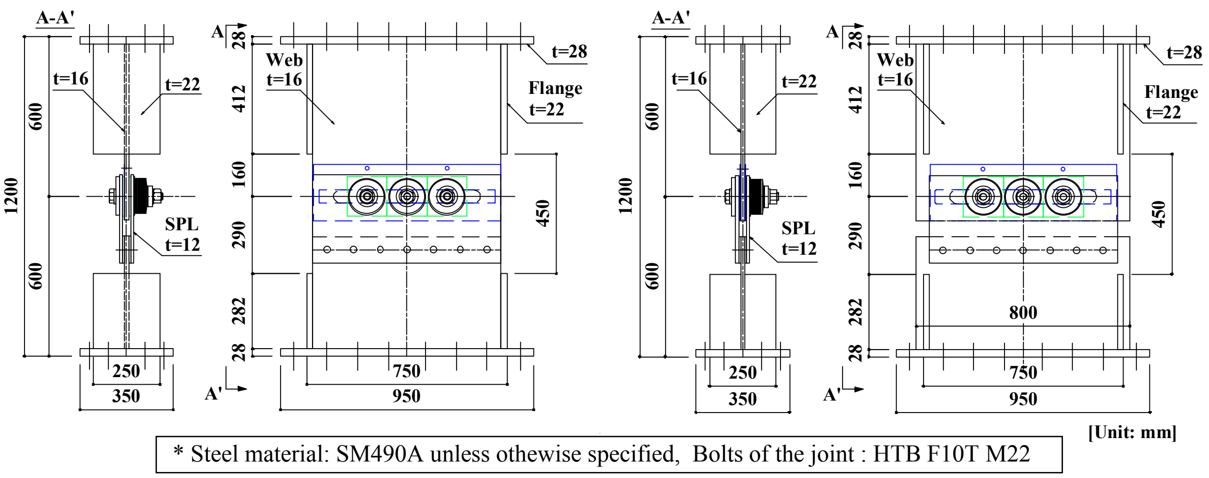
3.1 Test specimen

Table 1 shows a list of test specimens. Fig. 5 shows elevation drawings of the stud-type multi-unit friction damper specimens in the tests. The test specimens were models of stud-type dampers used in actual buildings, and two types of test specimens were used: S2-3-F (flange plate through-type) and S2-3-W (web plate through-type). The specimens were 1200 mm in height and 750 to 800 mm in width, and three friction units with two sliding surfaces were arranged near the center of the stud of each specimen. The target frictional force of one friction unit was 100 kN, and the target frictional force of the stud-type damper was 100 kN × 3 = 300 kN.

For the friction unit, a high-tension bolt (F8T M27) and 12 coned disc springs (outer diameter 130 mm, inner diameter 65 mm, plate thickness 3.6 mm) were combined. The axial force of the high-tension bolt introduced by fastening in the damper part was controlled by the height of the coned disc spring. And the axial force of the bolts was introduced with the target axial force of 150kN. Table 2 shows the tensile test results of the main steel materials used for the test specimen.

Table 1 – List of test specimens

Specimen	Type of Specimen	Number of friction face of damper	Number of friction damper unit	Target frictional force of damper [kN]	Assembly detail of stud
S2-3-F	Stud	2	3	300	Frange plate through-type
S2-3-W					Web plate through-type



(a) Specimen S2-3-F (b) Specimen S2-3-W

Fig. 5 – Elevation drawings of the stud-type multi-unit friction damper specimens in the tests

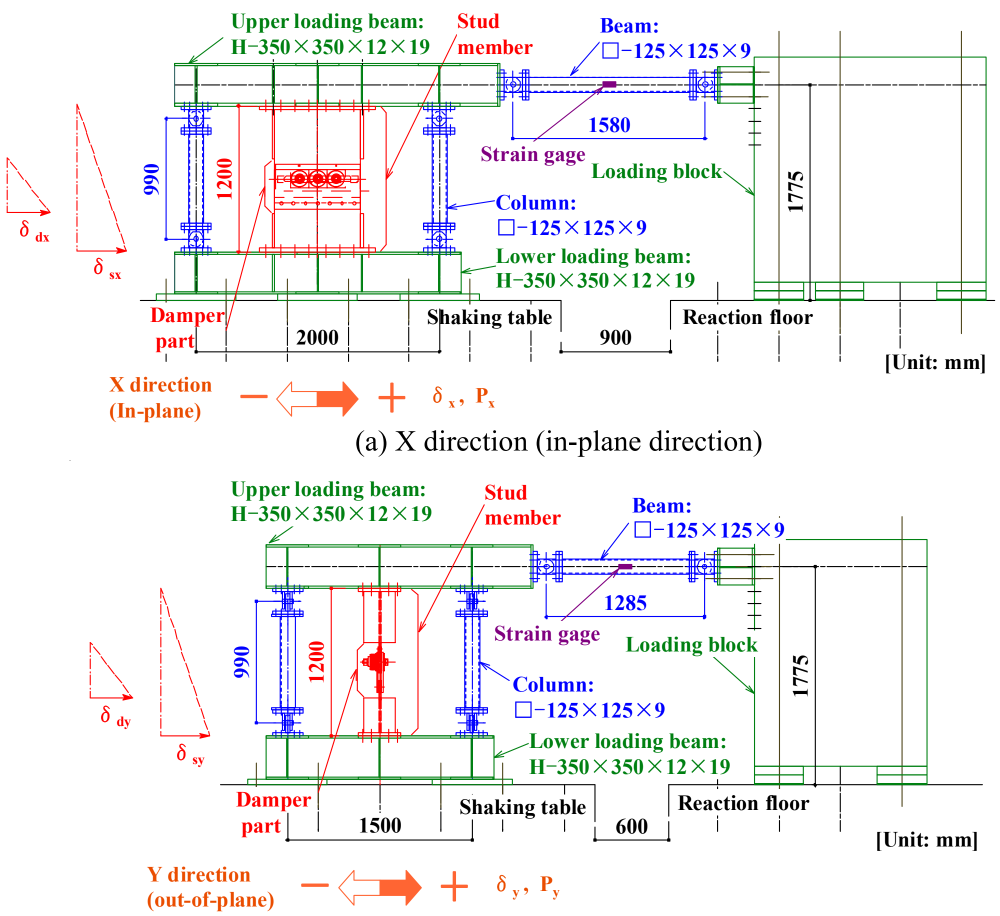
Table 2 – Results of tensile tests of steel material

Steel grade	Thickness of plate [mm]	Yield strength [N/mm²]	Tensile strength [N/mm²]	Elongation [%]	Remarks (main applicated portion)
SM490A	16	357	523	26.3	Web of stud
	22	361	539	27.9	Flange of stud

<Remarks> The test piece shape: JIS Z2241 1A

3.2 Loading method

Fig. 6 shows experimental setup for two-directional dynamic loading tests. A loading device composed of upper and lower loading beams and columns with pin support at the both ends was assembled on the shaking table, and the test specimen was installed in it. And the upper loading beams with pin support at the both ends were attached to the loading blocks installed on the reaction floor. Then, dynamic loading was performed on the test specimen by applying dynamic two horizontal displacements (X and Y directions) to the shaking table.



(a) X direction (in-plane direction)

(b) Y direction (out-of-plane direction)

Fig. 6 – Experimental setup for two-directional dynamic loading tests

Table 3 shows the loading program. The command displacement to the shaking table was adjusted so that the horizontal deformation of the stud member including the damper part reached the target displacement.

Fig. 7 shows the time history of the loading waveform, and Fig. 8 shows the displacement history (target displacement) of the shaking table. Two types of loading waveforms were used: sine wave (period 4 sec, amplitude ± 10, 20, 40, 60, 80 mm) and seismic response wave (maximum deformation 40 mm). For the sine wave, the stationary part was composed of four waves, and the rising part and the damping part before and after it were composed of two waves each. In bi-directional loading (XY loading), the sine waves in the X and Y directions were shifted by π / 2 (1sec in time), and it was targeted that the displacement history of the shaking table drew a circle.

Table 3 – Loading program

Waveform	Loading period T [sec]	Loading direction X*1 , Y*2 XY*3	Taget amplitude of stud		Number of cycles N_c
			δ_{sx} [mm]	δ_{sy} [mm]	
Sine wave	4	X → Y → XY	±10	±10	4
		X → Y → XY	±20	±20	4
		X → Y → XY	±40	±40	4
Seismic response wave	(3.68)	X → Y → XY	[40]	[40]	—
Sine wave	4	XY	±60	±60	4
		XY	±80	±80	4

<Remarks> ( ): The primary natural period of the assumed building, [ ]: Maximum deformation
*1: In-plane direction, *2: Out-of-plane direction, *3: Bi direction

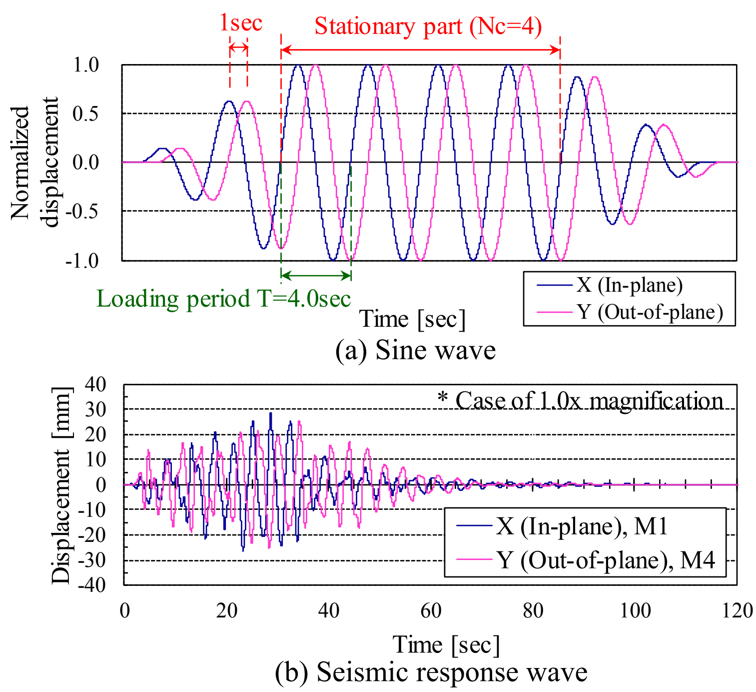
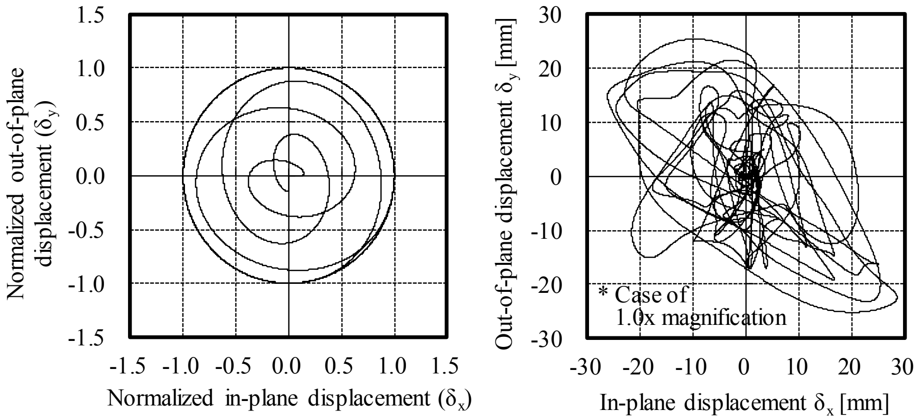


Fig. 7 – Time history of loading waveform



(a) Sine wave (b) Seismic response wave

Fig. 8 – Displacement history of shaking table (target displacement)

The seismic response waves were obtained by a seismic response analysis with damping factor of 5% for a 30-story high-rise steel-frame building (primary natural period 3.68 sec). The wave named the Kokuji wave [6] was used as the input waveform for response analysis. The time history of story drift on the 20th story obtained by response analysis was used for loading tests with adjusting the magnification of the story drift. The phase of the Kokuji wave was a random phase [7] having different characteristics in the X direction and the Y direction, respectively.

And the ratio of the amplitude (or maximum deformation) in the X direction and the Y direction for bi-directional loading (XY loading) was set to 1: 1.

3.3 Measurement method

Load, deformation, etc. of the test specimen were measured by the following method (see Fig. 6).

Load: The axial force of each of the two beams in the X and Y directions from was calculated using the value of the strain gauge attached to the square steel pipe part of the beam with pins at the both ends. The horizontal load (in-plane direction: P_x, out-of-plane direction: P_y) of the test specimen was determined by adding the axial force of the two beams in each direction. The proportional coefficient between the value of the strain gauge and the axial force of the beam was investigated by a calibration test.

Deformation: The horizontal deformation of the stud member (in-plane direction: δ_{sx}, out-of-plane direction: δ_{sy}), the horizontal deformation of the damper part (in-plane direction: δ_{dx}, out-of-plane direction: δ_{dy}), etc. were measured by a laser displacement meter.

Axial force of a high-tension bolt: The axial force of a high-tension bolt in the damper part was calculated from the value of a biaxial strain gauge attached to the bolt head. The proportional coefficient between the value of the strain gauge and the axial force of the high-tension bolt was investigated by a calibration test.

4. Experimental results

4.1 Experiment progress

Fig. 9 shows the overall view of the loading device, and Fig. 10 shows the loading status of the test specimen. In any of the test specimens, it was confirmed that the damper itself smoothly operated in the in-plane direction, which was the operating direction of the damper, in a state where it was subjected to dynamic repetitive out-of-plane deformation.

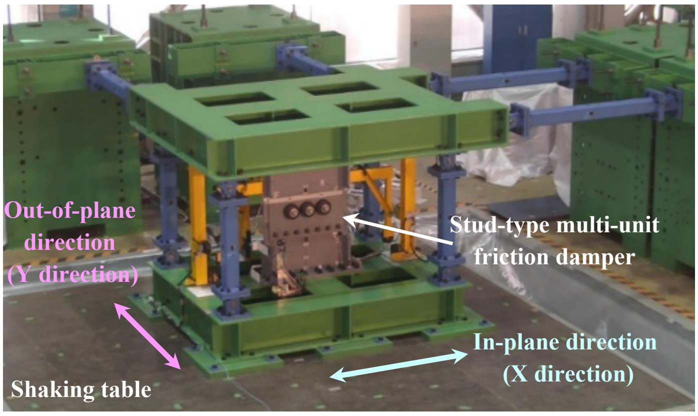


Fig. 9 – Overall view of loading device

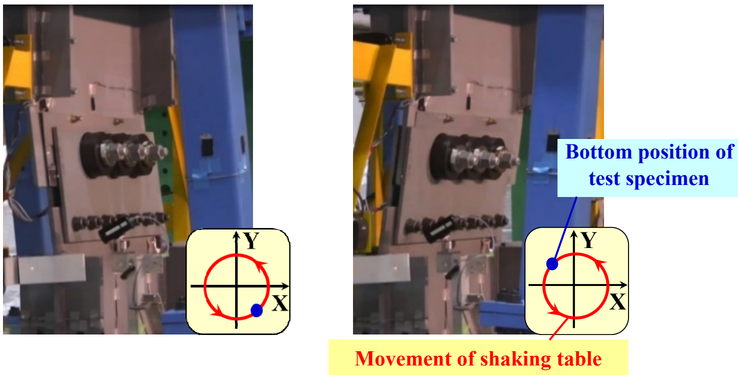


Fig. 10 – Loading status (specimen S2-3-W, sine wave, target amplitude of stud member 80mm)

4.2 Load-deformation relationship

Since the load-deformation relationship of the specimen S2-3-F and S2-3-W had the same tendency, the results of the test piece S2-3-F are described below.

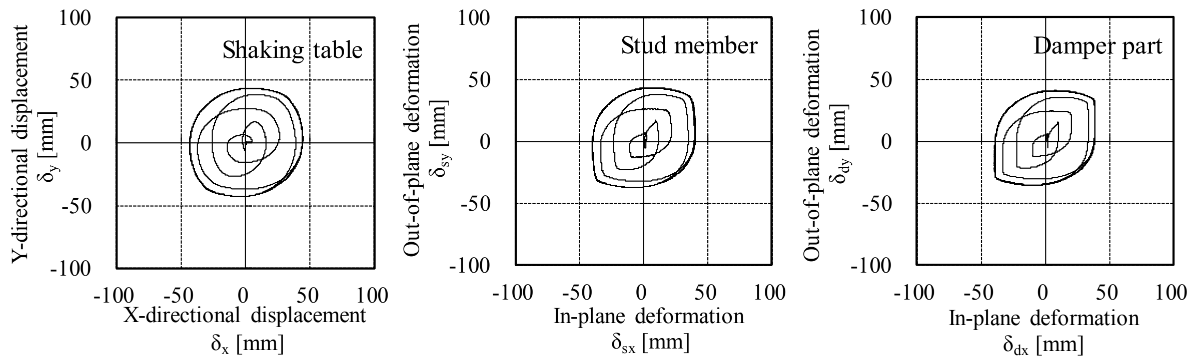
4.2.1 In case of sine wave

Fig. 11 shows the displacement history of the shaking table and the deformation history of the stud member and damper part under bi-directional loading with a sine wave (period 4 sec, target amplitude of the stud member ± 40mm). The displacement history of the shaking table was nearly circular. In the deformation history of the stud member, the maximum deformation in the in-plane direction, which was the damper operation direction, reached a plateau because of the elastic deformation of the loading device.

Fig. 12 shows the load-deformation relationship of the damper with respect to a sine wave (period 4sec, target amplitude of the stud member ± 40mm). Fig. 12(a) is the load-deformation relationship for loading only in the in-plane direction, Fig. 12(b) is the load-deformation relationship for loading only in the out-of-plane direction, and Fig. 12(c) is the load-deformation relationship for bi-directional loading in the in-plane and out-of-plane directions. Fig. 12(d) is a load-deformation relationship in the out-of-plane direction under the same loading as Fig. 12(c).

In the load-deformation relationship in the in-plane direction, the target frictional force of the damper (solid blue line) and a load of ± 10% error bounds (dashed red line) are shown. As can be seen from Fig.

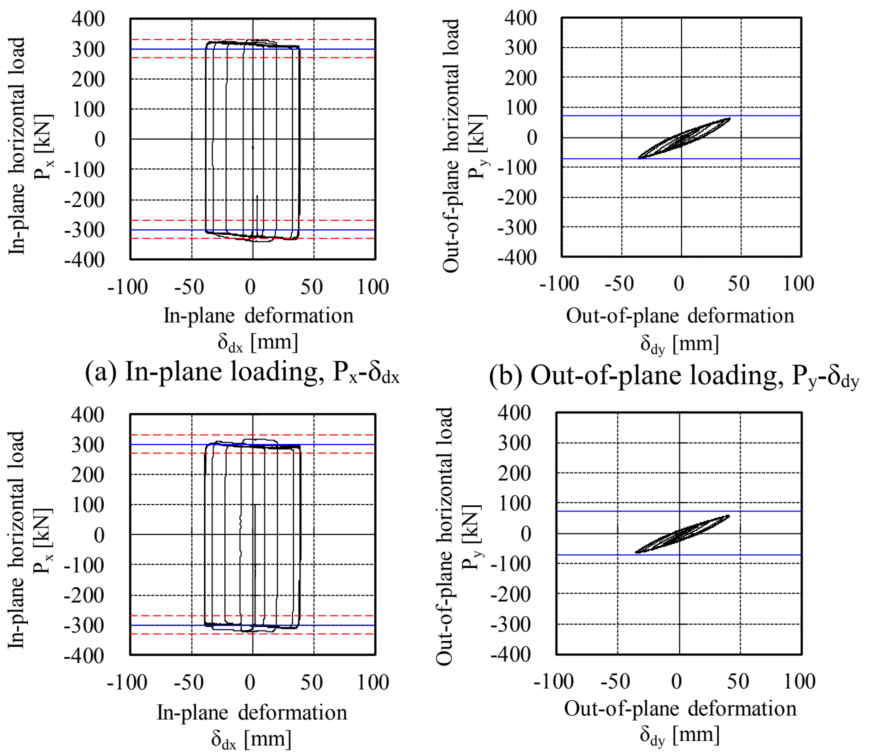
12(c), the load-deformation relationship in the in-plane direction of the damper showed rigid-plastic hysteresis loops even under bi-directional loading, and the frictional force approximately satisfied the target frictional force ± 10%. In the out-of-plane load-deformation relationship, the horizontal load calculation value (solid blue line) at the time of out-of-plane full plastic bending strength of the web plate of the damper part is also shown.



(a) Shaking table (b) Stud member (c) Damper part

* Definitons of δ_x, δ_y, δ_{sx}, δ_{sy}, δ_{dx}, δ_{dy} are shown in Fig. 6

Fig. 11 – Displacement or deformation history in bi-directional loading
(sine wave, target amplitude of stud member 40mm)



(a) In-plane loading, P_x-δ_{dx} (b) Out-of-plane loading, P_y-δ_{dy}

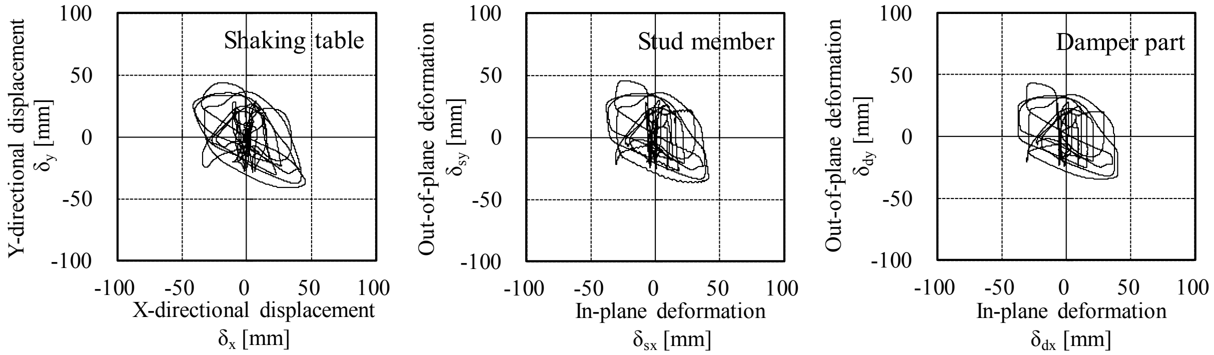
(c) Bi-direcitonal loading, P_x-δ_{dx} (d) Bi-directional loading, P_y-δ_{dy}

Fig. 12 – Load-deformation relationship of damper part
(sine wave, target amplitude of stud member 40mm)

From the comparison between Fig. 12(a) and Fig. 12(c) and the comparison between Fig. 12(b) and Fig. 12(d), it was found that the influence of the bi-directional loading on the load-deformation relationship of the damper part was small. Although the description was omitted in this report, the load-deformation relationship of the stud member had the same tendency.

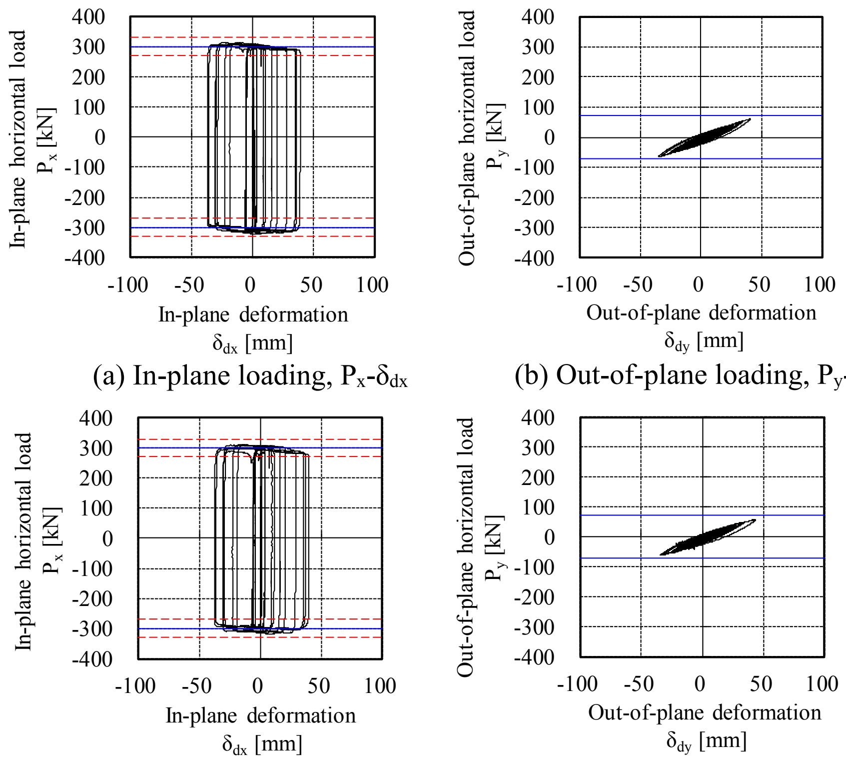
4.2.2 In case of seismic response wave

Fig. 13 shows the displacement history of the shaking table and the deformation history of the stud member



(a) Shaking table (b) Stud member (c) Damper part

Fig. 13 – Displacement or deformation history in bi-directional loading
(seismic response wave, target amplitude of stud member 40mm)



(a) In-plane loading, P_x-δ_{dx} (b) Out-of-plane loading, P_y-δ_{dy}

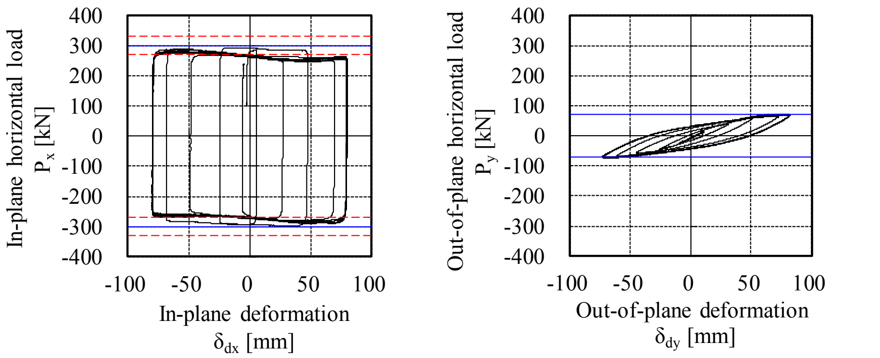
(c) Bi-direcitonal loading, P_x-δ_{dx} (d) Bi-direcitonal loading, P_y-δ_{dy}

Fig. 14 – Load-deformation relationship of damper part
(seismic response wave, target amplitude of stud member 40mm)

and the damper part under bi-directional loading due to the seismic response wave (target deformation of the stud member ±40mm). Fig. 14 shows the load-deformation relationship of the damper with respect to the seismic response wave (target deformation of the stud member ± 40mm). The contents shown in Fig. 14(a), Fig. 14(b), Fig. 14(c), and Fig. 14(d) are the same as those in the case of the sine wave. In the case of seismic response waves, as in the case of sine waves, the load-deformation relationship in the in-plane direction of the damper showed rigid-plastic hysteresis loops, and the frictional force approximately satisfied the target frictional force ± 10%. Also, from the comparison between Fig. 14 (a) and Fig. 14 (c) and the comparison between Fig. 14 (b) and Fig. 14 (d), it was found that that the effect of the bi-directional loading on the load-deformation relationship of the damper part was small.

4.2.3 In case of extremely large out-of-plane deformation

Fig. 15 shows the load-deformation relationship of the damper part for bi-directional loading using a large amplitude sine wave (period 4sec, target amplitude of the stud member ± 80mm). The hysteresis loop in the in-plane direction of the damper part was slightly asymmetrical depending on whether the deformation was positive or negative. It was considered that, when the amplitude in the out-of-plane direction was extremely large, the bending deformation of the stainless-steel plate of the damper part was increased. In addition, the axial force of the high-tension bolts in the damper part slightly changed due to the out-of-plane deformation during loading, but the decrease in axial force of the bolts at the end of loading was small.



(a) Bi-direcitonal loading, P_x-δ_{dx} (b) Bi-direcitonal loading, P_y-δ_{dy}

Fig. 15 – Load-deformation relationship of damper part
(sine wave, target amplitude of stud member 80mm)

5. Conclusions

Bi-directional dynamic loading experiments were performed on the stud-type multi-unit friction dampers. The conclusions obtained for these specimens were as follows.

1. In bi-directional dynamic loading test, the stud-type multi-unit friction dampers produced the target frictional force and exhibited a stable energy absorption ability, showing rigid-plastic hysteresis loops in the in-plane direction.
2. The effect of bi-directional loading on the load-deformation relationship of the friction damper was small in both in-plane and out-of-plane directions. This was true for both cases of sine waves and seismic response waves.

Future research tasks include confirming the structural performance of other types, for example brace-type multi-unit friction dampers under bi-directional dynamic deformation.

6. References

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