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REINFORCING I-BEAMS WITH WEB OPENINGS USING FILLET-WELDED PERFORATED PLATE

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In beam-to-column connections in steel structures, it is crucial for stresses to be transmitted from the beam to column smoothly. However, openings of I-section steel beam web are often made at the end of the beam when piping facilities pass through the beam. Openings at the end of the I-section steel beam reduce its flexural strength, shear strength, and deformation capacity of the steel beam ends. If the openings are made at the end of a beam, the beam should somehow be reinforced to achieve acceptable stress transmission performance and good deformation capacity. There are several existing ways of reinforcing openings at the end of a beam in Japan; however, simpler and more economical reinforcing methods are desired. In this paper, a new reinforcing method of openings at the beam ends is proposed. The proposed reinforcement is a perforated steel plate connected to the beam web using fillet welding. The proposed method is simple, easier to produce, and easier to construct compared to conventional methods. An experiment was conducted to verify the performance of the proposed reinforcing method. The results of the experiments showed that the proposed reinforcing method can be designed conservatively using Kato's formula.

Keywords: Steel structures, Reinforcement with perforated plate, Opening at beam ends, Failure mode, Shear span ratio.

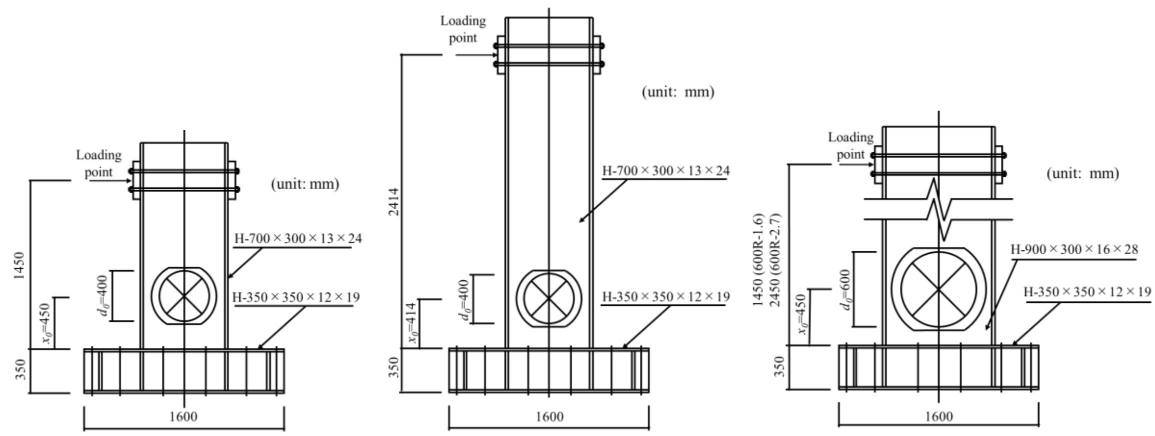
1 INTRODUCTION

In beam-to-column connections in steel structures, it is crucial for stresses to be transmitted from the beam to column smoothly. However, openings of I-section steel beam web are often made at the end of the beam when piping facilities pass through the beam. Openings at the end of the I-section steel beam reduce its flexural strength, shear strength, and deformation capacity. If the openings are made at the end of a beam, the beam should somehow be reinforced to achieve acceptable stress transmission performance and good deformation capacity (Darwin 1990, AISC 2016). Many widely known studies have been conducted on how to reinforce the opening at beam ends (Kato and Kaneko 1997); however, simpler and more economical reinforcing methods are desired.

Casting rings are a common method for reinforcing web openings in Japan. Herein, a new, simpler, and more economically efficient reinforcement is proposed, which is a perforated steel plate fillet welded to the beam web. The shape of the perforated steel plate is adequate considering the stress transmission. An experiment was conducted to verify the reinforcing performance of the proposed method.

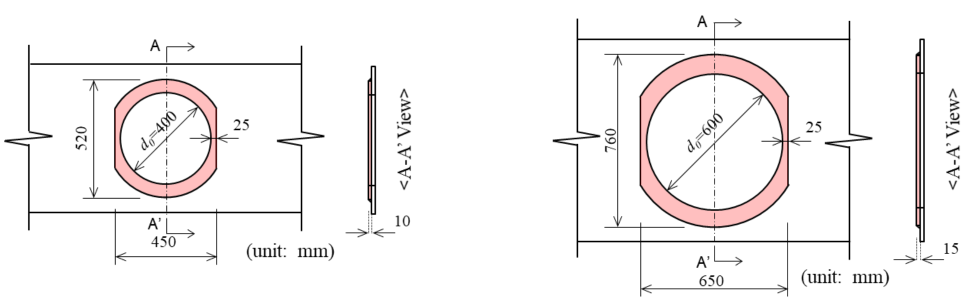
2 OUTLINE OF EXPERIMENT

The outlines of the test specimens are listed in Table 1. A total of six specimens were made and tested, including a specimen without an opening and an unreinforced perforated specimen. The experimental parameters were the depth of the I-section beam (diameter of the perforation), shear span ratio, and loading type. The loading condition was a cantilever-type with five monotonic loadings and one cyclic loading. Figure 1 shows examples of the dimensions of the specimens and Figure 2 shows the details of the perforated steel plate for reinforcement. The ratio of the opening diameter to the depth of the I-section was 0.57 (400 Series) and 0.67 (600 Series). The distance from the beam end to the opening perforation's center (position of opening center) was 414 mm (400R-3.4C) and 450 mm (400N-2.1, 400R-2.1, 600 Series). The perforated steel plate was connected to the web opening by fillet welding for reinforcement. The parts of the perforated steel plates considered to be unnecessary for stress transmission were cut off vertically. Two of the I-section steel beams' cross-sectional sizes were H-700 × 300 × 13 × 24 and H-900 × 300 × 16 × 28, and the steel type was SM490B. The reinforcing steel plate was made of TMCP550C. One reinforcement plate had an opening diameter of 400 mm and was 10 mm thick. The other reinforcement plate had an opening diameter of 600 mm and was 15 mm thick. The material properties of the steels are shown in Table 2.



(a) 400R-2.1 (b) 400R-3.4C (c) 600R-1.6 and 600R-2.7

Figure 1. Dimensions of specimens



(a) Type 400 (b) Type 600

Figure 2. Shape of perforated steel plates for reinforcement

Table 1. Outline of the test specimens.

Specimen	Beam	Reinforcement	Diameter of opening d_0(mm)	Position of opening center x_0(mm)	Shear span (mm) (Shear span ratio)	Remarks
N-2.1	H-700x300x13x24	-	-	-	1450 (2.07)	Without opening
400N-2.1		Type400 (t=10mm)	400	450		No reinforcement
400R-2.1						-
400R-3.4C				414	2414 (3.45)	Cyclic loading
600R-1.6	H-900x300x16x28	Type600 (t=15mm)	600	450	1450 (1.61)	-
600R-2.7					2450 (2.72)	-

Table 2. Material properties of steels.

		Steel type	$_sE$ (GPa)	f_y (MPa)	f_u (MPa)	ε_y	Yield ratio
Ring		TMCP550C	213.7	369.0	550.1	0.00173	0.671
H-700	web	SM490B	204.7	441.0	569.5	0.00215	0.774
	flange		209.3	377.1	535.6	0.00180	0.704
H-900	web		214.6	482.6	611.0	0.00225	0.790
	flange		207.7	389.4	542.6	0.00188	0.718

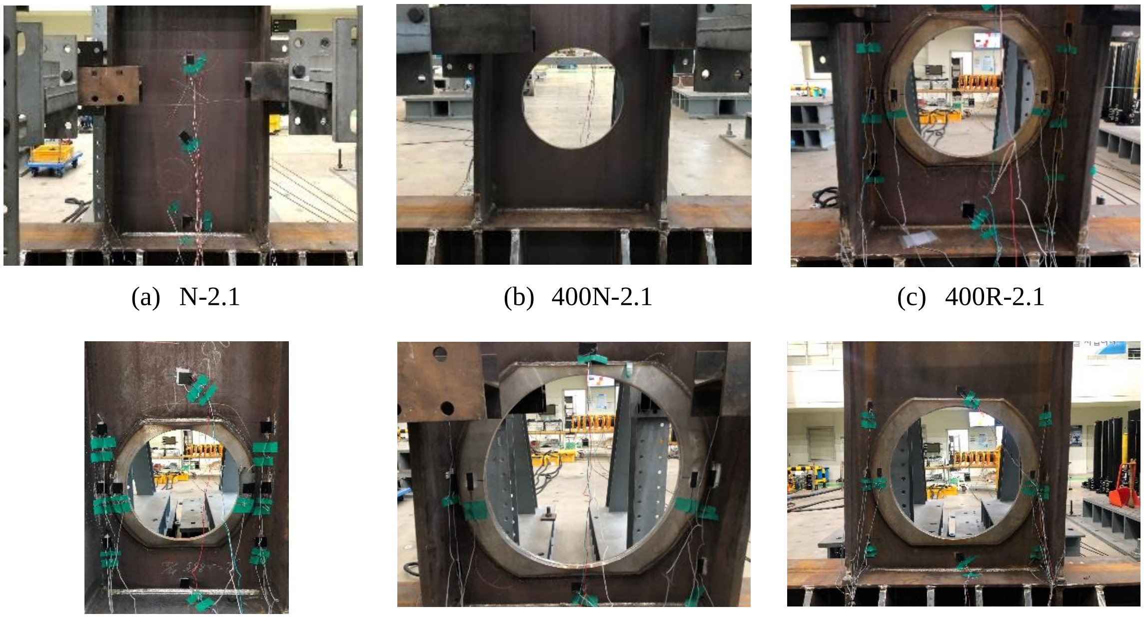
Note: $_sE$=Young's modulus, f_y=yield stress, f_u=ultimate strength, ε_y=yield stress

3 EXPERIMENTAL RESULTS

Figure 3 shows the shear force-deformation angle relations. Figure 3 shows the specimens' state at the maximum strength, and Figure 4 shows the failure mode of the specimens at the end of the experiment. For specimens 400N-2.1, the web started to yield prior to the flange at R = 0.01 rad, and the failure mechanism was shear failure at the beam-end opening. In the other five specimens, it is inferred that the failure mechanism was flexural failure. The yielding of the flange was observed before the yielding of the web; however, a large shear deformation at the beam-end opening was observed at the end of the experiment. As shown in Figure 3, a large shear deformation was not observed at the beam end opening at the maximum strength in the four specimens that were reinforced with the perforated steel plates. No separation between the reinforcing steel plate and beam web was observed. However, at the very end of the experiment, the openings of all the specimens with the exception of 600R-2.7 were greatly deformed in shear, as shown in Figure 4. Local buckling at the beam web and a large separation between the reinforcing steel plate and beam web were observed. Figure 5 shows the shear force-deformation angle relations and Figure 6 shows the state of the principal strain of the web at the maximum strength. Overall, the shear deformation was small when the shear span ratio was large.

Only specimen 400R-3.4C was cyclically loaded; however, the strength did not decrease depending on the cyclic load. The maximum strength exceeded the strength obtained from the full-plastic flexural strength.

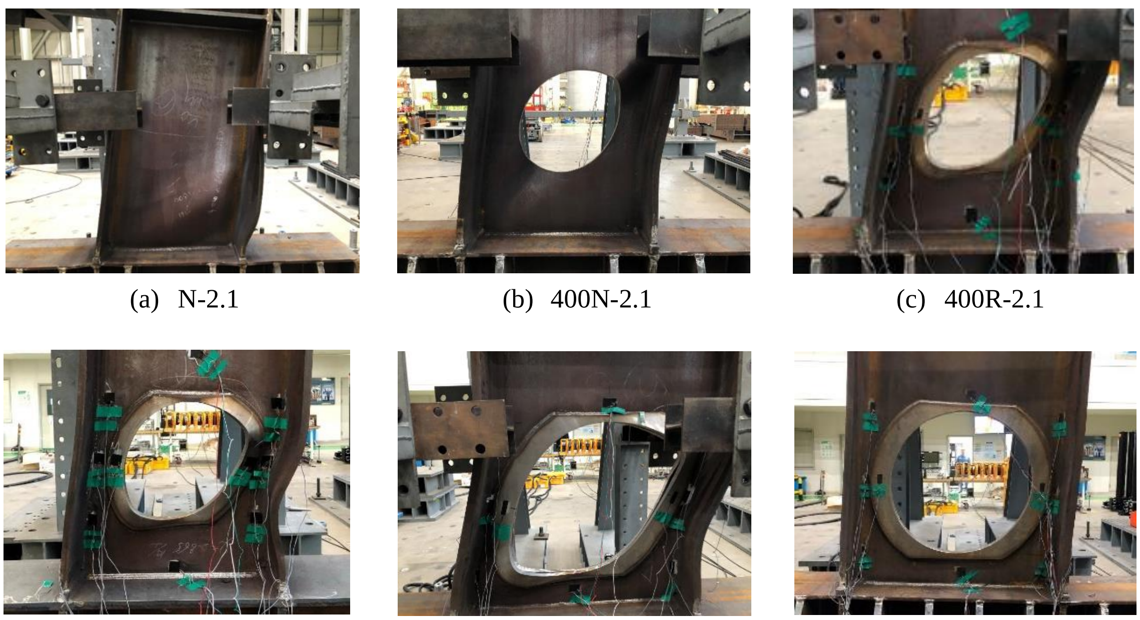
Compared with specimen 400N-2.1, the specimen 400R-2.1 with a reinforcement steel plate showed a higher load-carrying capacity with a gradual decrease in strength after the maximum strength.



(a) N-2.1 (b) 400N-2.1 (c) 400R-2.1

(d) 400R-3.4C (e) 600R-1.6 (f) 600R-2.7

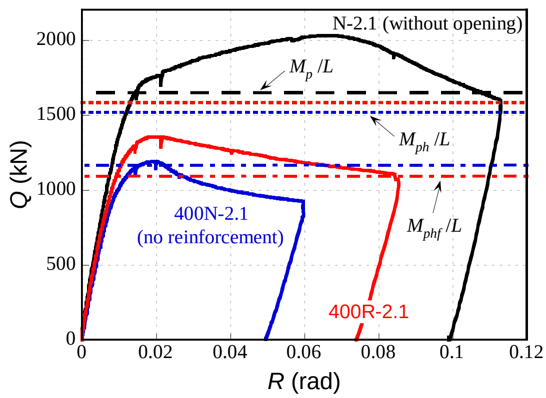
Figure 3. Specimens' state at the maximum strength.



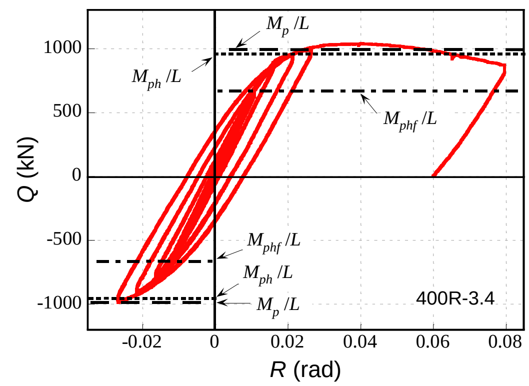
(a) N-2.1 (b) 400N-2.1 (c) 400R-2.1

(d) 400R-3.4C (e) 600R-1.6 (f) 600R-2.7

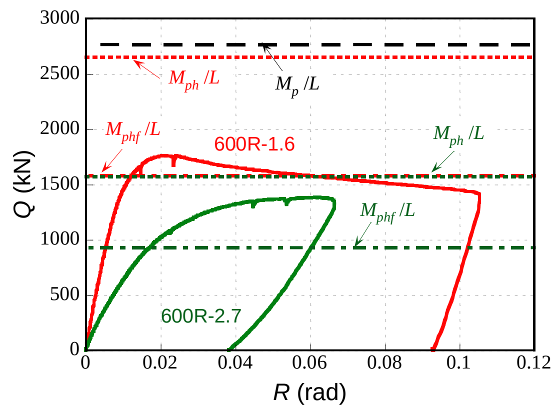
Figure 4. Failure mode of the specimens.



(a) 400 Series.

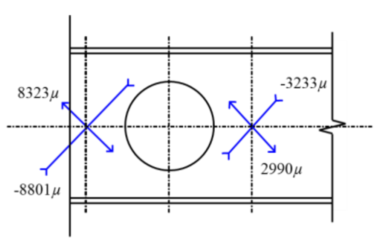


(b) 400 Series (cyclic loading).

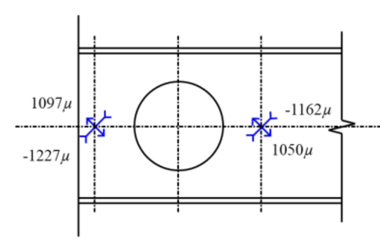


(c) 600 Series.

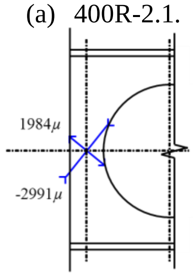
Figure 5. Shear force-deformation angle relations.



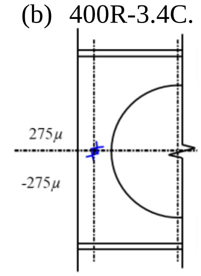
(a) 400R-2.1.



(b) 400R-3.4C.

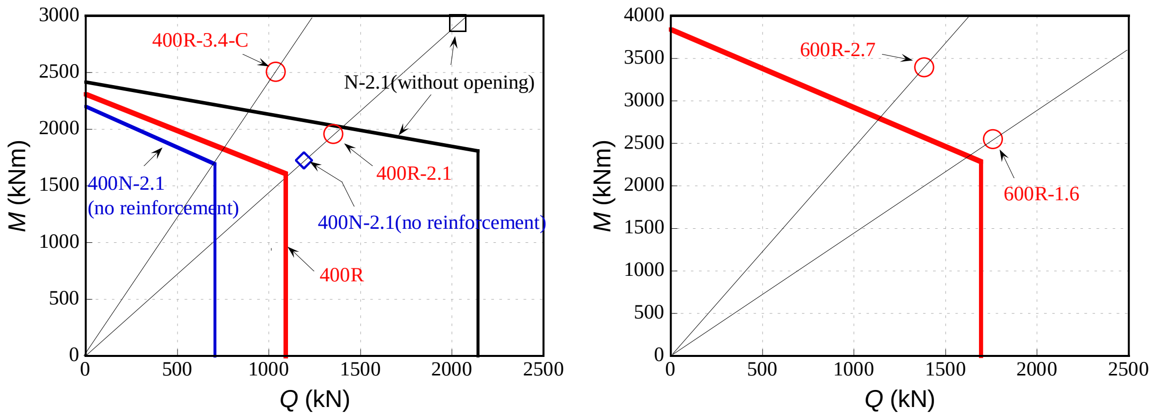


(c) 600R-1.6.



(d) 600R-2.7.

Figure 6. State of the principal strain of the web at the maximum strength.



(a) 400 Series. (b) 600 Series.

Figure 7. *M-Q* interaction diagram.

4 COMPARISON OF STRENGTH

Figure 7 shows the interaction between the bending moment and shear force at the beam end. The experimental values and Kato's strength formula (Kato and Kaneko 1997) were compared and examined. Kato's formula can be drawn using the full plastic moment at hole part and the full plastic moment of flange at hole part, and the shear yield strength of web at hole part. In this case, β in the formula was set to 0.20 for the 400 Series and 0.25 for the 600 Series.

The experimental maximum strength values are circled in the figures. These values exceed the calculated strength for all specimens. According to these results, the proposed reinforcing method can be designed conservatively using Kato's formula.

5 CONCLUDING REMARKS

The following results were observed during the experiment:

1) The specimens reinforced with the proposed perforated plate had an improved maximum strength and showed a higher load-carrying capacity with a gradual decrease after the maximum strength.
2) Separation between the reinforcing steel plate and beam web was not observed until the maximum strength range.
3) The cyclically loaded specimen showed stable behavior and failed in flexure.
4) The experimental values of all specimens exceeded the values based on Kato's formula. The proposed reinforcing method can be designed conservatively using Kato's formula.

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