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Experimental Study on Reinforced Concrete Beams with Web Openings

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Abstract

Recently, although lots of studies on Reinforced Concrete beams with web openings have been performed to realize flexible equipment plan for RC buildings in Japan, there are several unclear points, which are especially shear strength of beam with several web openings and flexural performance of beam with web opening at the beam-end. Therefore, shear test and flexural test were carried out in this study.

Specimens were eleven beams with web openings. Experimental factors were number of openings, the strength of concrete and amount of the reinforcement for shear test and diameter size of opening, with or without Y-bar and the strength of concrete. All specimens with a beam part and two loading stub at the both ends of beam were 1/2.5 scale and subjected to reversal shear force and antisymmetric moment.

As a result, it showed shear strength of beam with three openings was almost the same as that of a beam with single opening. Additionally, although deformation capability after member yielding was improved by Y-bar, the relationship between amount of reinforcement around opening and deformation capability couldn't be identified clearly.

Keywords: R/C beam with web openings, Reinforcement for opening, Shear crack width

1. Introduction

In spite of the frequent earthquakes in Japan, a lot of reinforced concrete (RC) high-rise buildings have been built. Although various equipment in order to provide a comfortable living space is installed, it is necessary to provide openings at some of the beams for pipe arrangement and electrical cable of the equipment. As shown in an example in Figure 1, beams with web openings (perforated beam) is reinforced by reinforcement for opening to ensure the seismic performance.

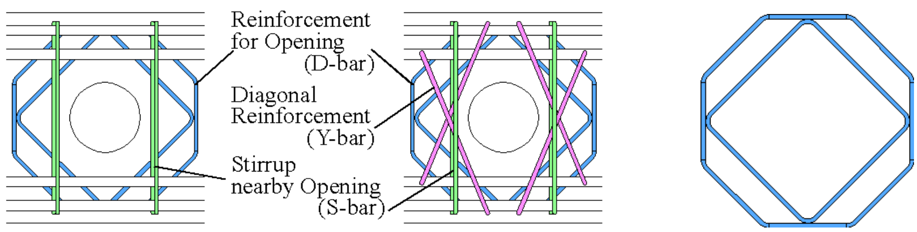
In Japan, a lot of studies on RC perforated beams have been performed in order to realize the flexible equipment plan for RC buildings. We also have researched reinforcing methods for RC perforated beams using relatively simple reinforcing method as a combination of reinforcement for opening(D-bar) and stirrup nearby opening (S-bar) with or without diagonal reinforcement (Y-bar) as shown in Figure 1 [1].

Two kinds of problems are existed to use more effective as a reinforced perforated beam. One is the shear strength of a perforated beam with several openings and the other is the flexural capacity of a perforated beam with the beam-end opening.

Although Prof. Ichinose suggested an evaluation formula of shear strength for perforated beams with three openings [2], the distance of each opening did not satisfy that defined in AIJ RC Standard [3]. However, there is questionable matter when the satisfied distance. Therefore, it is necessary to grasp shear strength of perforated beam with several openings (two or three) more clearly.

On the other hand, the openings at the beam-end is required from an equipment designer for rationally settings. However, stress concentration is likely to occur in the opening of perforated beam at the beam-end, good flexural performance is required in huge earthquakes. Although many past studies have suggested the necessity of complicated reinforcement for opening at the beam-end, the complicated reinforcement causes the deterioration of construction workability.

Therefore, two series of tests, shear test and flexural test, were conducted to evaluate shear strength and deformation capability of perforated beams. #



(a) Reinforcing Method 1 (b) Reinforcing Method 2 (c) Shape of D-bar

Fig. 1 – Arrangement of reinforcing bars for web opening

2. Outline of test plan

Specimens for each test are listed in Tables 1 and 2. The shape and bar arrangements of specimens are shown in Figure 2. Figure 3 shows loading setup.

2.1 Specimens

The specimens with nearly half scale model were a total of eleven (five shear test specimens, six flexural test specimens) of NS-M1 ~ NS-M11. The span L was 1320mm, cross-sectional shape was width 250mm × depth 330mm, shear span ratio $M/(Q \cdot D)$ was 2.0, and each web opening was reinforced with reinforcing method 1 or method 2 as shown in Figure 1(a) and (b). The nominal yielding strength of D-bar and Y-bar was 785N/mm^2 and 345N/mm^2, respectively.

Shear test specimens were five (M1, M2, M3, M9 and M10, NS is omitted). The experimental factors were number of openings (1 to 3) and nominal compressive strength of concrete (30, 60N/mm^2). All opening diameter was D/3 (110mm, D : depth of beam), the center-to-center distance of each opening was 3H (330mm, H : diameter of opening). All shear test specimens were reinforced by method 1 as shown in Figure 1(a). Because the nominal yield strength of longitudinal bars was 1000 N/mm^2 grade, all shear test specimens were designed as shear failure mode prior to the longitudinal bar yield.

Flexural test specimens were six (M4, M5, M6, M7, M8 and M11). The experimental factors were opening diameter (D/3, D/4), nominal compressive strength of concrete (30, 60N/mm^2), and amount of reinforcement for opening. Each flexural test specimen had two openings at both ends of the beam and the distance between beam end and edge of opening was arranged as D/2 (165mm). Opening diameter of M9 and M10 was D/4 (82.5mm) and that of the other flexural test specimens was D/3 (110mm). Method 1 and method 2 as shown in Figure 1 were adopted for flexural test to improve deformation capability. All flexural test specimens were designed as shear failure around opening after the yielding of longitudinal bars.

2.2 Loading Method

Experimental apparatus including the loading equipment for specimens is shown in Figure 3. The specimen was set in a loading frame. All specimens were subjected to reversal shear force and antisymmetric moment as a seismic motion of a frame structure. The loading method of the shear forces comprised one cycle of the rotation angle R=1.25x10^{-3} rad and two cycles of 2.5, 5, 10, 20, 30 and 50 x10^{-3} rad.

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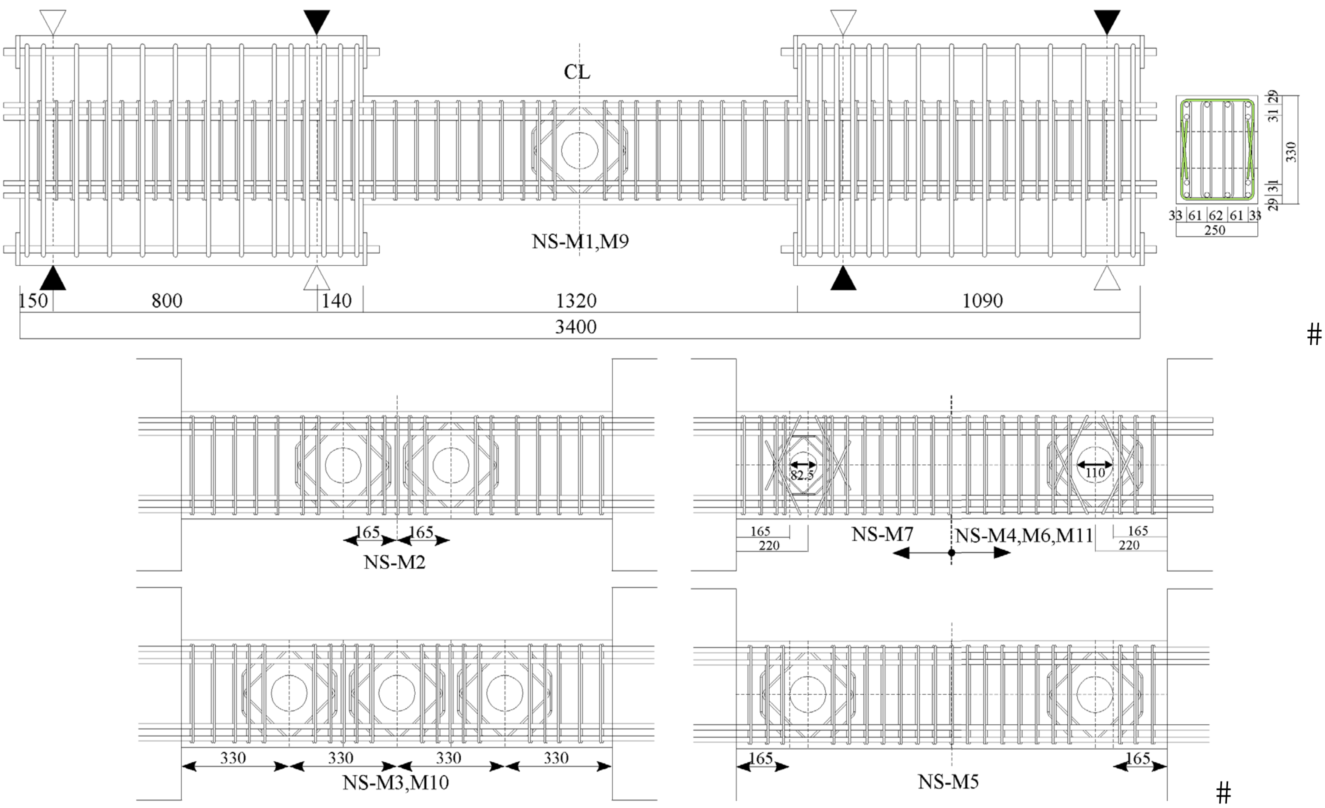

Fig. 2 – Shape and bar arrangement of specimens and loading apparatus

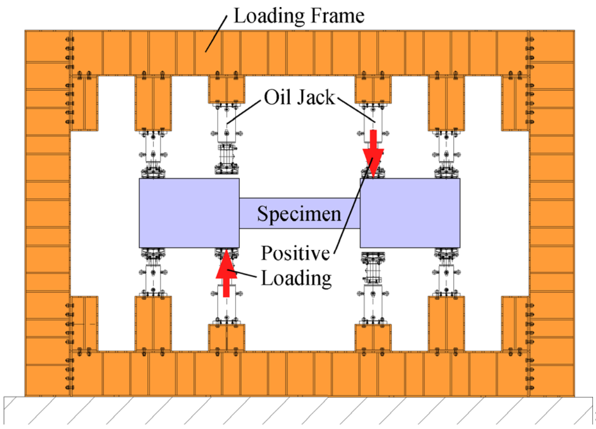

Fig. 3 – Loading setup

Table 1 – Specimens of shear test

Specimen	Shape (mm)	Opening Diameter (mm) [Number]	Lomgitudinal Reinforcement	Stirrup Reinforcement	Reinforcement for Opening (D-bar)	Stirrup nearby Opening (S-bar)	Diagonal Reinforcement (Y-bar)	Concrete Comp. Strength S_B(N/mm²)	Concrete Young's Modulus E_c(N/mm²)
NS-M1	Section B250 x D330 Span L1320	110 [1]	12-D16 SD1000 [1020N/mm²]	4-D6SD785 @65 (p_w=0.78%) [930N/mm²]	D6SD785×3 (p_{ws}=0.78%) [930N/mm²]	4-D6SD785×2 (p_{ws}=0.74%) [930N/mm²]	---	37.6	27400
NS-M2		110 [2]						39.2	28900
NS-M3		110 [3]						36.2	28700
NS-M9		110 [1]		4-D6SD785 @60 (p_w=0.84%) [930N/mm²]	D6SD785×2 (p_{wd}=0.52%) [930N/mm²]			56.1	32800
NS-M10		110 [3]						58.6	33300

Table 2 – Specimens of flexural test

Specimen	Shape (mm)	Opening Diameter (mm)	Lomgitudinal Reinforcement	Stirrup Reinforcement	Reinforcement for Opening (D-bar)	Stirrup nearby Opening (S-bar)	Diagonal Reinforcement (Y-bar)	Concrete Comp. Strength S_B(N/mm²)	Concrete Young's Modulus E_c(N/mm²)
NS-M4	Section B250 x D330 Span L1320	110	12-D16 SD390 [431N/mm²]	4-D6SD345 @52.5 (p_w=0.97%) [345N/mm²]	D8SD785×3 (p_{ws}=1.24%) [1005N/mm²]	4-D6SD345×2 (p_{ws}=0.75%) [345N/mm²]	D6SD345 [345N/mm²]	37.2	28700
NS-M5							---	37.3	29000
NS-M6					D8SD785×4 (p_{wd}=1.65%) [1010N/mm²]	4-D6SD345×3 (p_{ws}=1.12%) [345N/mm²]	D6SD345 [345N/mm²]	27.7	24300
NS-M7		82.5			D6SD785×4 (p_{wd}=1.05%) [930N/mm²]	4-D6SD345×2 (p_{ws}=0.75%) [345N/mm²]		30.8	24600
NS-M8							---	30.6	24600
NS-M11		110	12-D16 SD490 [533N/mm²]	4-D6SD785 @44 (p_w=1.15%) [930N/mm²]		4-D6SD785×3 (p_{ws}=1.12%) [930N/mm²]	D6SD345 [345N/mm²]	53.1	32200

3. Test results

The relationships between shear force Q and rotation angle R are shown in Figure 4 and Figure 5. Figure 6 shows damage condition. Numerical evaluation of shear strength Q_{HI} for perforated beam and flexural strength Q_{fu} according to AIJ Standard for Structural Calculation of Reinforced Concrete Structures [3] are also shown in Figure 4 and Figure 5. Each of the calculation method is described in Chapter 4 in this paper.

3.1 Failure behavior

In shear test specimen M1~M3 with different opening numbers, on the way to the peak of rotation angle R=20x10^{-3} rad cycle, shear cracks were generated diagonally through the opening and diagonal cracks were generated tangentially above and below the opening. Then shear failure was occurred because those cracks developed wider and longer. Although M2 and M3 had two and three openings respectively, shear failure was occurred around one of the openings. The failure process of M9 and M10 was almost the same as that of M1 and M3, respectively. But the spalling of cover concrete around opening was observed in M9 and M10.

In all of the flexural test specimens except for the M11, with the increase of plastic deformation after the beam yielding, diagonal cracks occurred tangentially above and below the opening expanded, then shear failure was observed. In M4, M6 and M7 with Y-bar, the shear failure was observed on the way to the peak of rotation angle R=50x10^{-3} rad, but the same failure was observed on the way to R=-30x10^{-3} rad in M5 and M8. On the other hand, the diagonal cracks did not occur at the same time above and below the opening like other specimens and shear failure did not occur in M11.

3.2 Shear force - rotation angle relationships

The shear force - rotation angle relationships of M1~M3, nominal concrete strength of 30N/mm^2, showed almost the same behavior regardless of the number of openings. Although the maximum strength showed 300~330kN in R= 15×10^{-3}rad, that of M2 (two opening) was slightly lower than that of M3 (three openings). The reason for this, compared to S-bar of M3, the S-bar of M2 was a little widely placed around the openings. On the other hand, the maximum strength of M9 and M10 using nominal concrete strength of 60 N/mm^2 was exhibited 378kN and 413kN in R=18×10^{-3}rad, respectively. Compared to lower concrete strength specimens, deformation at maximum strength of M9 and M10 was increased and the maximum strength was greatly exceeded. The maximum strength ratio of M3 (three openings) to M1 (one opening) was 96.7%, but the ratio of M10 (three openings) to M9 (one opening) was 91.5%.

In flexural test, the shear force – rotation angle relationships and failure mode of M4, M6 and M7 with Y-bar is almost the same. The maximum strength was almost the same of about 230kN at R=30×10^{-3}rad because these specimens yielded. After that, shear failure around opening was observed at 50×10^{-3}rad, then shear force was reduced. Influence of the experimental factors, amount of reinforcement and diameter of opening, was not observed. On the other hand, the shear force – rotation angle relationships of M5 and M8 without Y-bar is almost the same. The maximum strength was 220kN (M5) and 232kN (M8). However, after shear crack around opening occurred in R=-30 × 10^{-3}rad cycle, the lower deformation capability was observed, than the capability of specimens with Y-bar. There were no differences of opening size from the results of M5 and M8.

The M11 with nominal concrete strength 60 N/mm^2 and high strength longitudinal bar 490 N/mm^2 showed good deformation capability until the end of loading test.

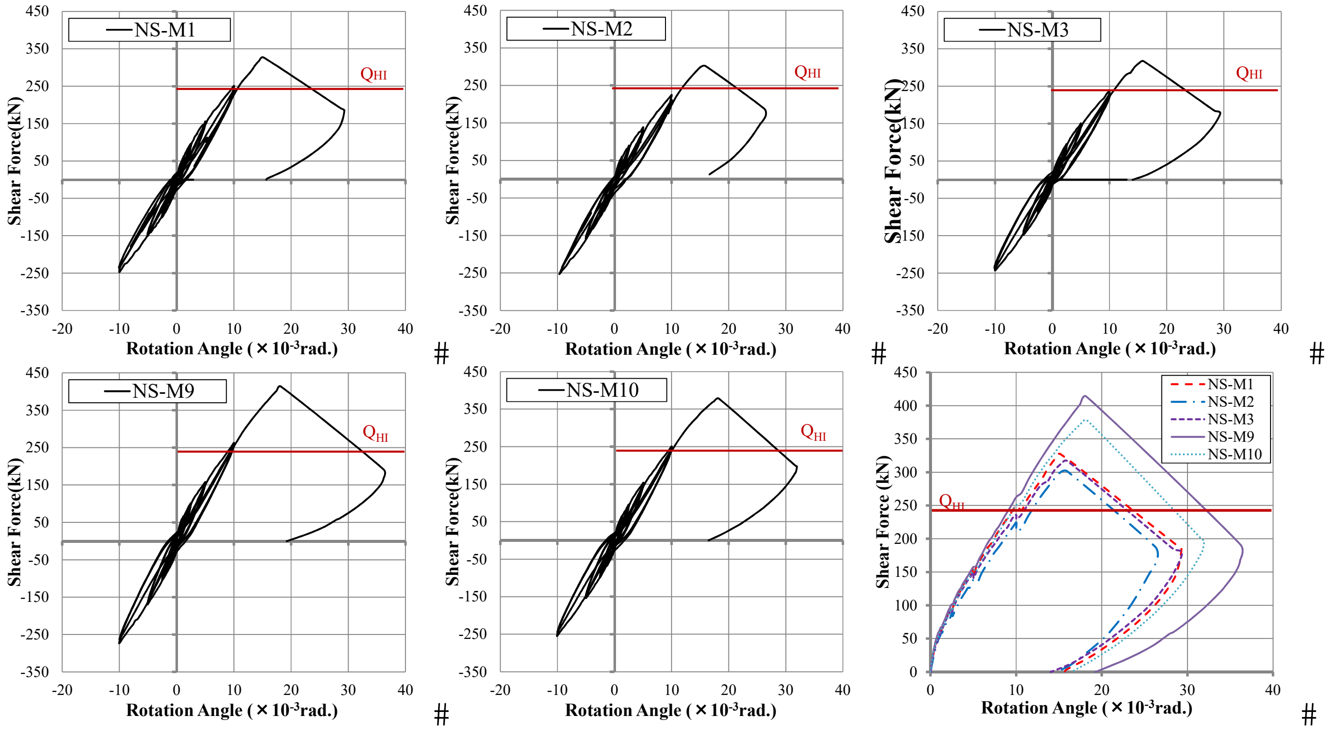

Fig. 4 – Shear force and rotation angle relationships of shear test

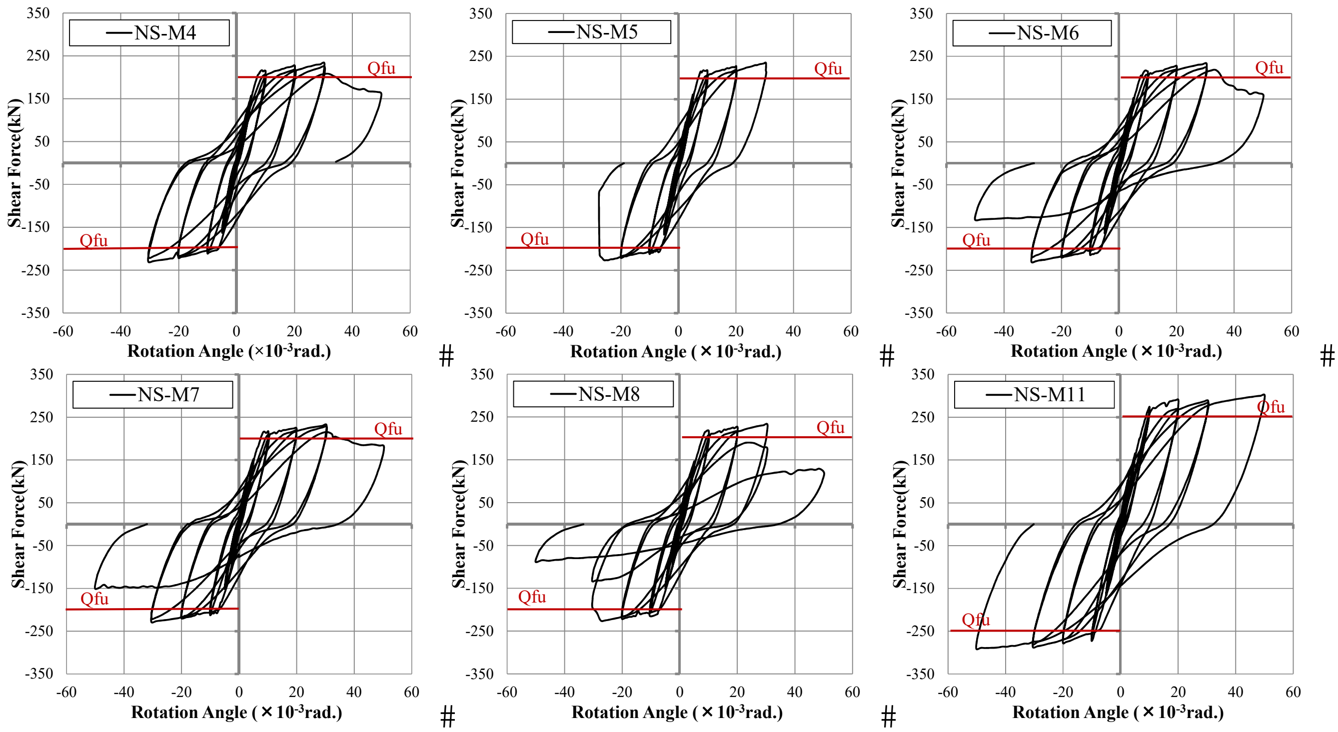

Fig. 5 – Shear force and rotation angle relationships of flexural test

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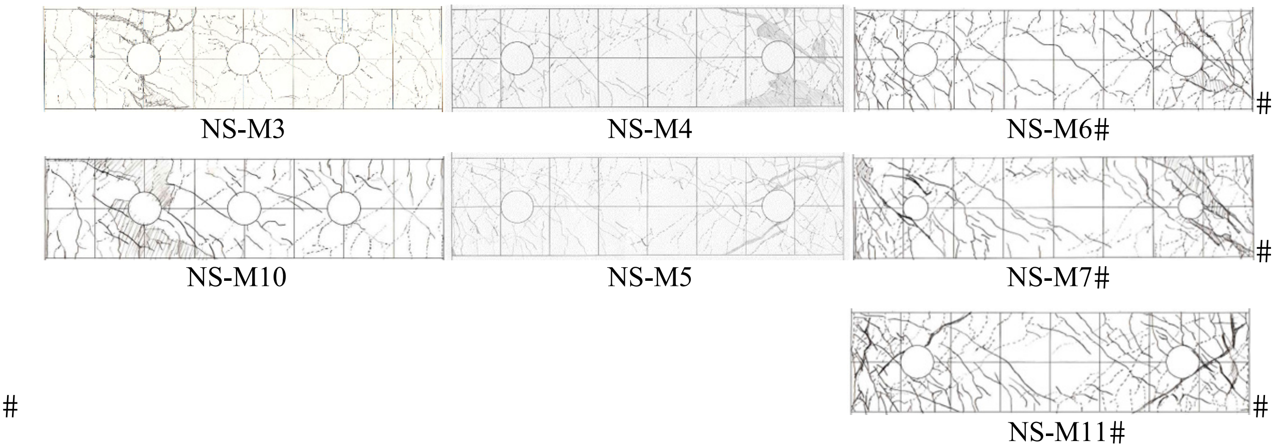

Fig. 6 – Damage condition

3.3 Relationships between Shear force – strain of reinforcements for opening

For a typical specimen, relationships between shear force and strain of reinforcements around the failed opening are shown in Figure 7. Dotted line drawn in the opening reinforcement diagram shows the crack direction. It shows the value of the rebar strain gauge locations which intersect the crack.

In shear test specimen of M3 and M10, of which shear failure around opening were observed before beam yielding, although strain of D-bar and S-bar with yielding strength 785N/mm^2 did not attain yielding strain, there showed large strain near 3000μ at maximum shear force. However, since the enough high stress occurred, it was considered that D-bar and S-bar contributed to the shear resistance efficiently. Other shear failure specimens, M1, M2 and M10, also showed a similar behavior.

In flexural specimens of M4 and M6, of which shear failure around opening were observed after beam yielding, the behavior showed almost the same. Although strain of D-bar showed about 2000μ at maximum strength, D-bar was not yielded. On the other hand, because strain of Y-bar and S-bar exceeded about 5000μ, Y-bar and S-bar were yielded.

Since the M11 did not display shear failure until the end of the test, shear force – strain relationships are shown in Figure 7(c) for both opening at the end of the beam. Strain behavior were almost the same in both openings. Though D-bar showed a relatively large strain about 3000μ, S-bar showed a relatively small about 1500μ. On the other hand, though Y-bar yielded early, shear failure was not observed after yielding of Y-bar. Therefore, it is considered that though Y-bar resisted the initial crack, D-bar contributed to shear resistance mechanism according to increasing crack width.

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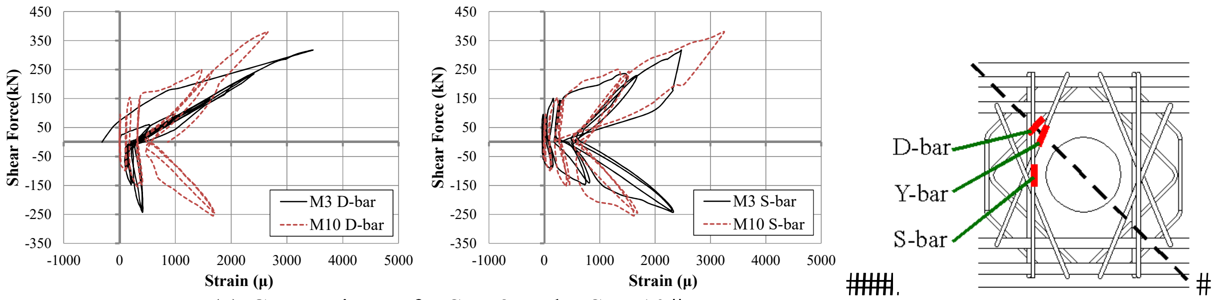

####. #

(a) Comparison of NS-M3 and NS-M10#

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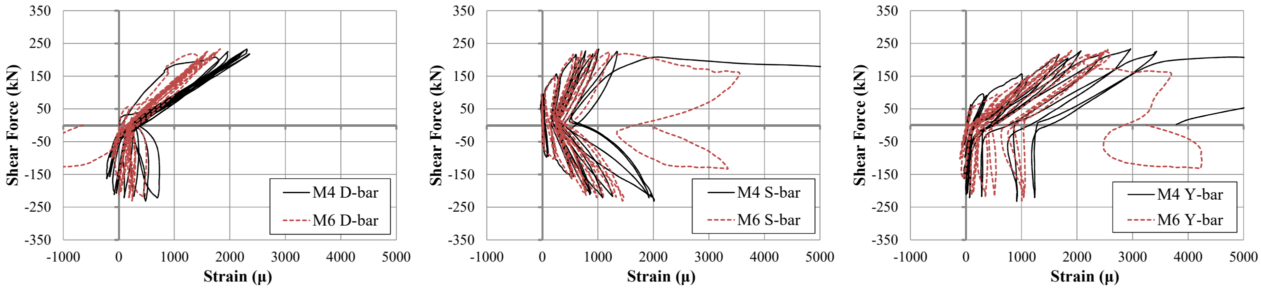

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(b) Comparison of NS-M4 and NS-M6#

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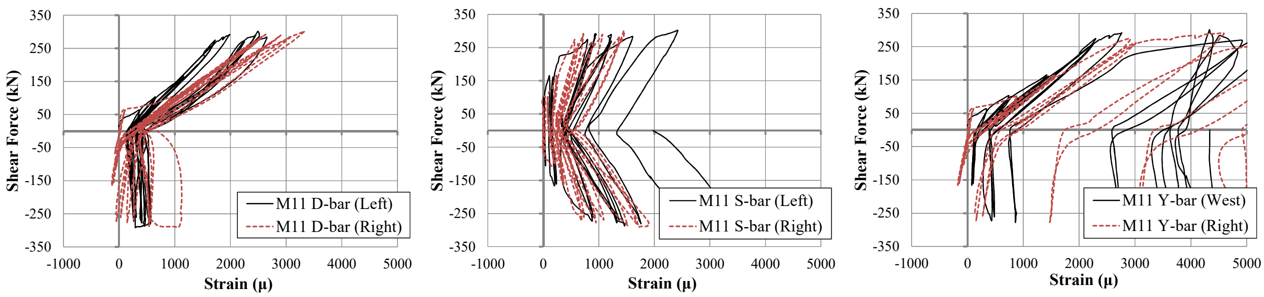

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(c) NS-M11#

Fig. 7 – Relationships between shear force and strain of reinforcements around the failed opening

3.4 Shear crack width around opening

Figure 8 shows changes of shear crack width around opening. Throughout all flexural specimens, maximum shear crack width around opening was about 0.4mm at peak and 0.15mm as residue at unloading. The crack width tended to increase in case with the opening of larger diameter, without Y-bar and with lower ratio of calculated shear strength to calculated flexural strength.

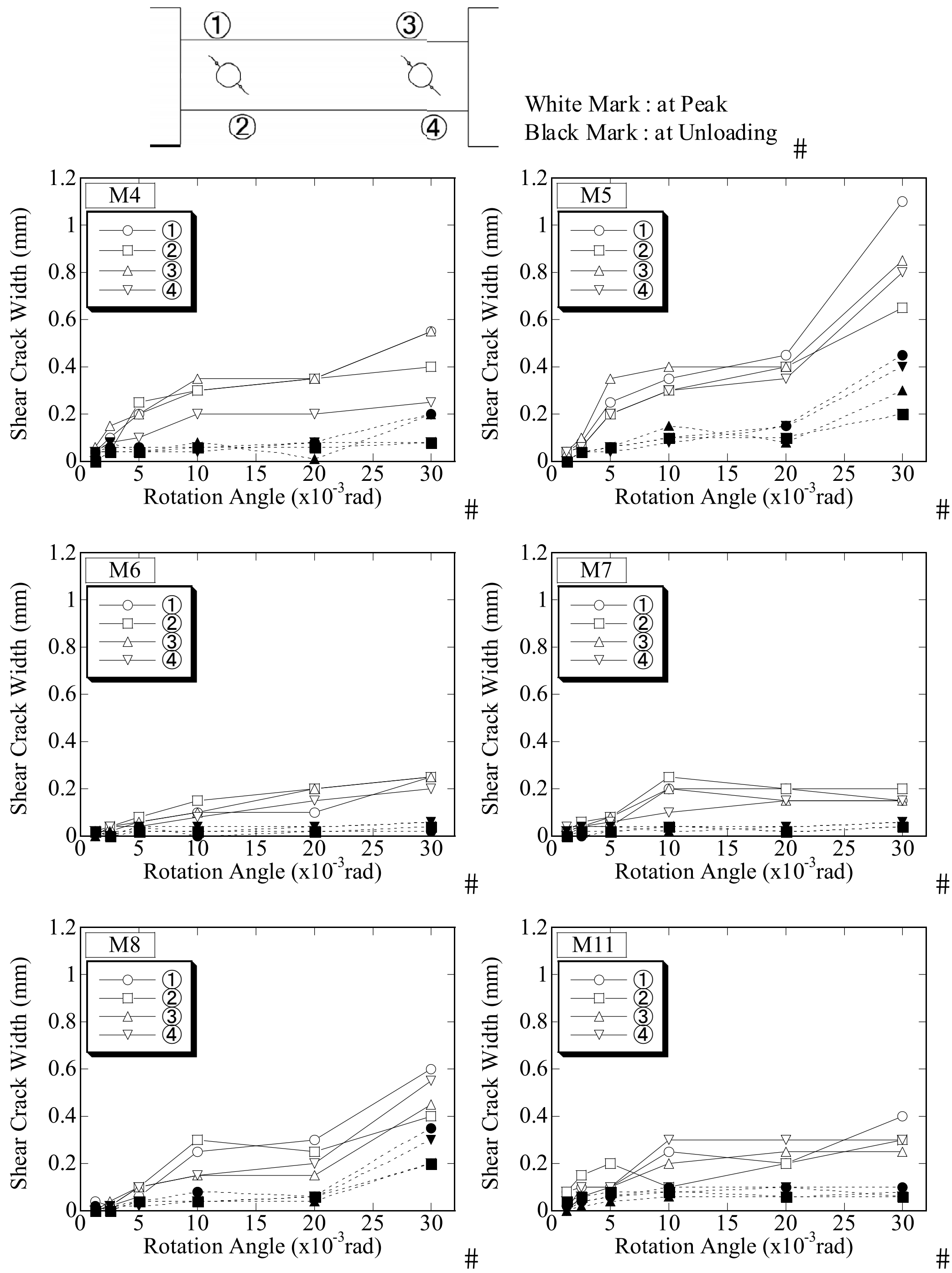


Fig. 8 – Changes of shear crack width around opening

4. Structural performance evaluation

Ultimate flexural strength Q_{fu} is calculated by Equation (1) in accordance with AIJ RC Standard [3]. Ultimate shear strength Q_{HI} and Q_{su} of the beam with web opening is calculated by Equation (2) and Equation (3) respectively. Equation (2) of AIJ RC Standard [3] proposed by Dr. Hirosawa was empirical formula using a lot of experimental results. On the other hand, Equation (3) is theoretical formula based on the truss-model [4].

$$Q_{fu} = \frac{M_{fu}}{L/2} \quad , \quad M_{fu} = 0.9 a_t \cdot \sigma_y \cdot d \tag{1}$$

$$Q_{HI} = \left\{ \frac{0.053 p_t^{0.23} (F_c + 18)}{M/Qd + 0.12} \left(1 - 1.61 \frac{H}{D} \right) + 0.85 \sqrt{p_s \cdot {}_s\sigma_y} \right\} b \cdot j \tag{2}$$

$$Q_{su} = b \cdot j_{tw} \cdot p_{ws} \cdot \sigma_{wy} \cdot \cot \phi_s + A_x \cdot \sigma_{xy} \cdot \sin \theta_x \tag{3}$$

Where Q_{fu} is ultimate flexural strength, a_t and σ_y are sectional area and yield strength of tensile longitudinal bar, d is effective beam depth, Q_{HI} and Q_{su} are ultimate shear strength, p_t ($= a_t / (b \cdot d)$ (%)) is tensile reinforcement ratio, b is beam width, j is a stress center distance ($7/8d$), F_c is the compressive strength of concrete, H is the diameter of opening, D is the beam depth, M and Q are maximum moment and shear force of beam, p_s is reinforcement ratio for opening, ${}_s\sigma_y$ is yield strength of reinforcement for opening, j_{tw} is an effective beam depth, p_{ws} and σ_{wy} are the reinforcement ratio of both sides of the opening and the yield strength of the reinforcement, ϕ_s is angle of truss model against beam axis, A_x and σ_{xy} are cross sectional area and the yield strength of reinforcement for opening and θ_x is angle of reinforcement for opening. In this study, p_s is the summation of reinforcement ratio of D-bar and S-bar.

Firstly, it is seen that the maximum strength obtained from the flexural test is larger than its calculated ultimate flexural strength Q_{fu} as shown in Figure 5. The calculated flexural strength may well be evaluated with Equation (1).

Then, results of this study and past studies [5]-[7] are used for the evaluation of ultimate shear strength of beams with opening. Figure 9 and Figure 10 show the relationships between calculated and experimental shear strength by Equation (2) and Equation (3), respectively.

Average of the ratio of experimental shear strength to shear strength Q_{HI} calculated by Equation (2) is 1.36 and its coefficient of variation is 11.5%. The calculated value is a result that can be enough safe to evaluate the experimental value.

On the other hand, in this experiment, although the stress of D-bar at shear failure did not reach the yield strength, however, reached high stress of more than half of the yield strength. Therefore, when ultimate shear strength is calculated by Equation (3), the three combinations of sectional area of reinforcement A_x, and tensile strength of D-bar are assumed for calculation as follows. In addition, Y-bar is not taken into consideration.

(a) ${}_1Q_{su}$: 4 sections and real yield stress of D-bar,

(b) ${}_2Q_{su}$: 4 sections and maximum stress of 390 N/mm^2 of D-bar

(c) ${}_3Q_{su}$: 2 sections and real yield stress of D-bar.

Although the calculated values by ${}_1Q_{su}$ compared with the experimental values give average, but there are several specimens of the higher calculated value including M1~M3 specimens. On the other hand, the calculated values by ${}_2Q_{su}$ and ${}_3Q_{su}$ are compared with the experimental values, there give the safe evaluation. As a phenomenon of the experiment, the stress of D-bar at shear failure did not yield but indicated high stress over almost half of yield strength. Therefore, as a method of evaluating shear strength of beam with opening, ${}_2Q_{su}$ which is taken into account 4 sections and upper limit of 390 N/mm^2 for D-bar, can be evaluated the experimental values and given the safe evaluation.

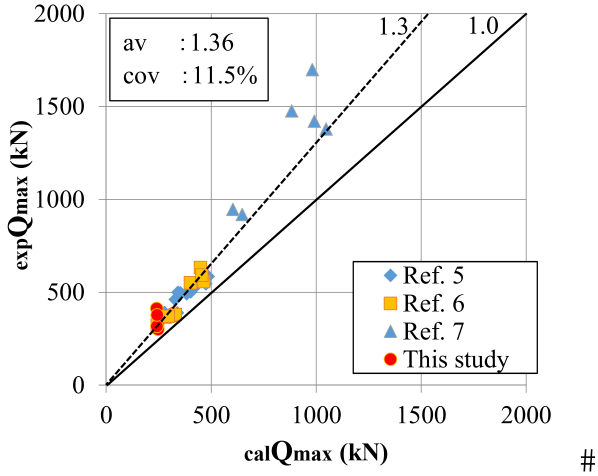
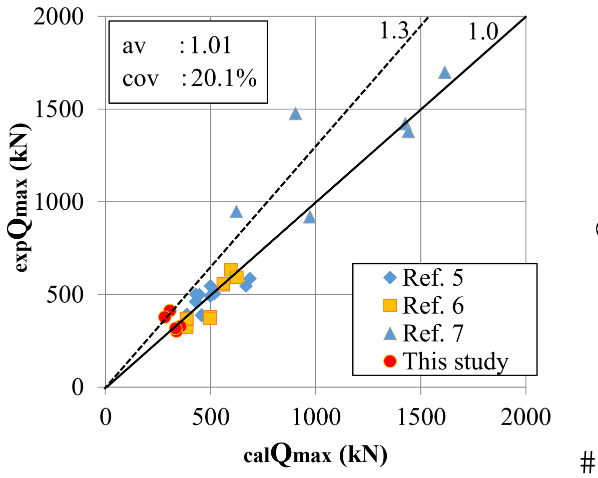
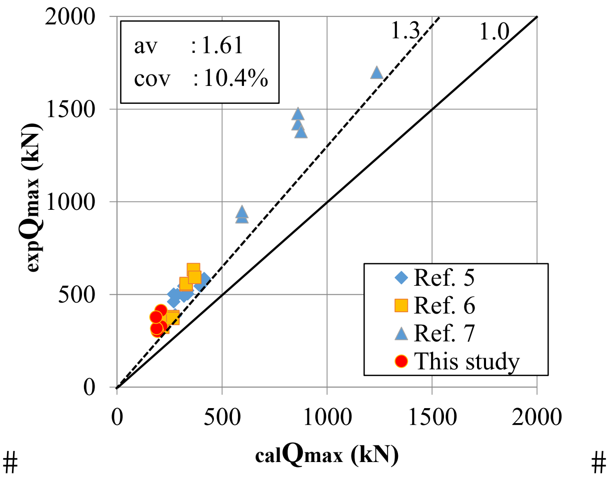


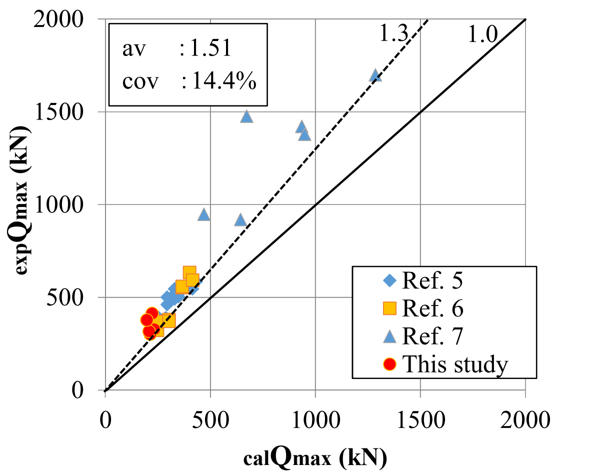
Fig. 9 – Relationships between calculated and experimental shear ultimate strength by Equation (2)



(a) case of $_1Q_{su}$



(b) case of $_2Q_{su}$



(c) case of $_3Q_{su}$

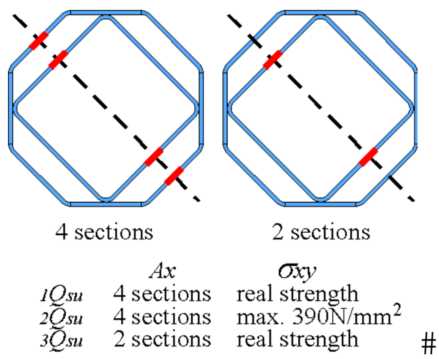


Fig. 10 – Relationships between calculated and experimental shear ultimate strength by Equation (3)

5. Concluding Remarks

Shear test of beams with web openings and flexural test of beams with web openings in the hinge area were carried out to confirm the structural performance in this study. The following findings are obtained.

1. Even if the number of opening with the large diameter like $D/3$ is 2 or 3, shear strength and failure properties do not differ significantly from those of beams with single opening, by separating each opening over $3H$ (H : distance of opening) and by also applying a suitable reinforcement.
2. Specimens with Y-bar of flexural test improved ultimate deformation compared with specimens without Y-bar. In addition, Y-bar acted effectively to improve the structural performance, large deformation capacity of 40×10^{-3} rad after flexural yielding was exhibited. It is clear from the measured strain of Y-bar.
3. Expected improved deformation capacity by down size of the opening wan no observed. The almost similar shear force-rotation angle relationship was shown.
4. M11 with high-strength concrete and longitudinal bar showed the high deformation capacity compared with the other flexural specimens and did not fail until $R=50\times10^{-3}$ rad. It shows good capacity.
5. The calculated ultimate shear strength of beam with web opening by Equation (2), proposed by Dr. Hirosawa, can be evaluated experimental shear strength safely.
6. Due to the calculate ultimate shear strength by Equation (3) based on truss-model, the three combinations of sectional area of reinforcement A_x, and tensile strength of D-bar are used. As a result, ${}_1Q_{su}$ can almost evaluate experimental shear strength on average. On the other hand, ${}_2Q_{su}$ taken into account 4 sections and upper limit of 390 N/mm^2 for D-bar can give the safe evaluation of the experimental values.

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