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High Strength Deformed Bar-in-Coil “HDC800” for Shear Reinforcement of RC Beam with Web-opening

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Abstract

High strength deformed bar-in-coil “HDC800” was developed for shear reinforcement of RC beam with web-opening. This paper reports on the development of material for HDC800, the results of structural experiment and design method of RC beam with web-opening strengthened by HDC800.

1. Introduction

In recent years, super high-rise buildings constructed with reinforced concrete (RC) structure have sharply been on the increase. In the field of multiple dwelling housing, in particular, RC construction has become the most popular form. In order to secure sufficient resistance and toughness of the structural members, which are subject to a large shearing force, efforts have been made to increase the strength of shear reinforcement bars. This is due to it being difficult to secure required volumes of reinforcement bars if conventional reinforcing bars of ordinary strength are to be used. For the same reason, increasing the strength of shear reinforcement for web-opening has been called for. Beams and other structural members are provided with web-openings through which to pass piping, ducts, etc. Shear reinforcement for web-openings comprise of the reinforcing bars that are arranged around those web-openings (**Photo 1**). When there is a web-opening in a beam, a concentration of stress occurs around the opening. This stress concentration can cause a deterioration in the shear strength and deformation-performance the beam and cause cracks in it around the opening, etc. Shear reinforcements for web-openings are arranged to prevent those problems from occurring.

This paper describes the material characteristics of the high strength deformed bar-in-coil “HDC800” for shear reinforcement of RC beams with web-openings that Kamaishi Works of Nippon Steel has started to manufacture. It also describes the shear experimentation that Kirii Construction Materials Co. carried out with RC members which used HDC800 for shear reinforcement for web-openings. In addition, a method of design of shear reinforcement for web-openings, validated by the results of experimentation, is discussed.

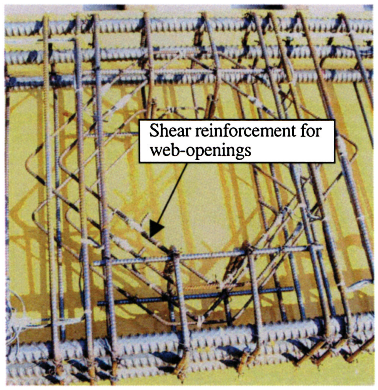

Photo 1 Arrangement of shear reinforcement for web-openings

2. Development of High Strength Deformed Bar-in-Coil HDC800

The shear reinforcements of RC beams with web-openings (product name: NS JYOBU-REN®) for which HDC800 is used, are factory-processed products which are manufactured through straightening a deformed bar-in-coil and subjecting them to a repeated and continuous bending process. Therefore, the deformed bar-in-coil that is used in creation of the product is required to have high strength, good stretch deformability and stable bending workability. In deciding the mechanical properties required of the material, reference was made to the specifications of the high strength deformed bar-in-coil,

Note: JYOBU-REN is a registered trademark of Metal System Co., Ltd.

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Table 1 Mechanical properties

Proof stress by offset method * (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Bending property	
			Bending angle	Pin diameter for bending test
800 min.	1 000 min.	8 min.	180 deg.	Nominal dia. × 3

* Proof stress shall be calculated on the basis of permanent deformation of 0.20%.

Table 2 Chemical compositions

C	Si	Mn	P	S	Cu	Cr	B	Carbon equivalent
0.20 max.	1.10 max.	2.00 max.	0.035 max.	0.030 max.	0.10 max.	0.50 max.	0.0030 max.	0.65 max.

where, carbon equivalent (%)=C+Mn/6+Si/24+Cr/5

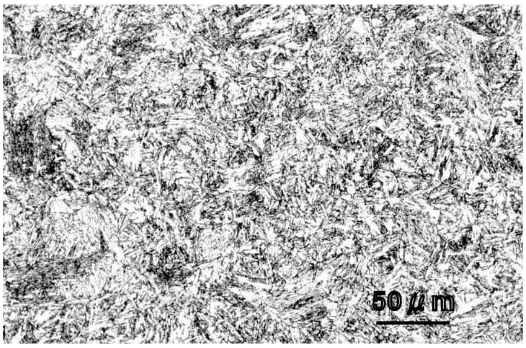

Photo 2 Microstructure of HDC800

Photo 3 Result of bending test for HDC800/D8

HDC685, a construction material for which Muroran Works has obtained official approval, and an existing deformed bar-in-coil of 785 N/mm^2 class. Ultimately, it was decided that the 0.2% proof stress should be 800 N/mm^2 or more and the elongation should be 8% or more as shown in **Table 1**. The material was named HDC800. The dimensions, weight and deformation of the deformed bar-in-coil were decided in accordance with JIS G 3112: Steel bars for concrete reinforcement. HDC800 is available in three different diameters–D6, D8 and D10. In consideration of the bending workability of the product, an "oblique deformation" was adopted. It helps secure good adhesion with concrete.

The basic chemical composition of HDC800 is shown in **Table 2**. NS JYOBU-REN is manufactured by a continuous bending process and therefore, it does not require any welding operation. However, since weldability might be required of HDC800 through product development in the future, the carbon content was kept at a low. Because of this, manganese and other suitable elements are added to HDC800 to secure high strength and good hardenability of the product.

In the hot rolling process, the material is deformed during finish rolling. In the subsequent cooling process, the material is subjected to air-cooling which is necessary to allow the product to achieve high strength. In the case of a steel grade having good hardenability, when the material wound in a coil in a hot process is transported on a conveyor, a variance in its strength can occur. Since such variance in strength can cause defective forming during the continuous bending work, the cooling conditions are adjusted so as to reduce the variance in strength as much as possible.

The HDC800 that is manufactured in this way is of upper bainite structure (**Photo 2**) and has excellent bending workability (**Photo 3**).

3. Structural Experiment on RC Beams with Web-Openings Reinforced with Shear Reinforcement Made of HDC800

A structural experiment was carried out to confirm the effect of reinforcement of RC beams with round web-openings by shear reinforcement "NS JYOBU-REN" made from HDC800. The experiment was carried out to examine the condition of fracture propagation, the influence of repetitive application of load, etc.. RC beams without web-openings and non-reinforced RC beams with web-openings were also subjected to the same experiment for the purpose of comparison.

3.1 Experiment plan

3.1.1 Specimens

The specimens used are shown in **Table 3**. In planning the specimens, consideration was given to the following factors. Eventually, a total of 10 specimens were prepared.

(1) Presence or absence of web-openings
(2) Method of reinforcement of beam with web-openings: Difference between beam without shear reinforcement, beam with shear reinforcement only, and beam with shear reinforcement and stirrups
(3) Amount of shear reinforcement: Difference by web-opening reinforcement ratio
(4) Concrete compressive strength: Two levels of concrete design strength (*Fc*)–36 N/mm^2 and 60 Nmm^2
(5) Method of load application: Difference between multi-cyclic loading and monotonic loading
(6) Amount of main rebar: 2 levels (The amount of main rebar is increased so that shear fracture always precedes bending fracture.)

The specimen sizes were 300 mm (W) × 450 mm (H). Each specimen was provided with one round opening 150 mm in diameter in the center of the span of the tested part and in the center in height direction. The specimens were planned on the assumption that two

Table 3 List of test specimens

Specimen ID	Design strength of concrete Fc (N/mm^2)	Web-opening: Diameter H (mm)	Web-opening: Ratio of opening H/D	Volume of rebars for web-opening: Stirrup	Volume of rebars for web-opening: Shear reinforcement (HDC800)	Volume of rebars for web-opening: Stirrup at web-opening	Volume of rebars for web-opening: Ratio of reinforcement for web opening p_{w0}	Vol. of main rebars (rebar ratio) p_t(%)	Type of loading
No. 1	36	No opening	-	2-D10	-	-	-	3-D25 (1.27%)	Multi-cyclic
No. 2		150	1/3	2-D10	-	-	0.27		
No. 3		150	1/3	2-D10	4-D6	-	0.62		
No. 4		150	1/3	2-D10	4-D6	2-D10	0.89		
No. 5	60	No opening	-	2-D10	-	-	-		
No. 6		150	1/3	2-D10	-	-	0.27		
No. 7		150	1/3	2-D10	4-D6	-	0.62		
No. 8		150	1/3	2-D10	4-D6	2-D10	0.89		
No. 9		150	1/3	2-D10	4-D6	-	0.62	4-D25 (1.69%)	Monotonic
No. 10		150	1/3	2-D10	4-D6	2-D10	0.89		
Remarks	Beam-width×height (effective-height) $b \times D$ (d) = 300×450 (400)mm, Distance between centers of tension and compression j = 350mm, stirrup D10@100(stirrup-ratio p_w = 0.48%), bending-span a = 450mm, shear-span (shear span ratio M/Qd) = 900mm (1.125)								

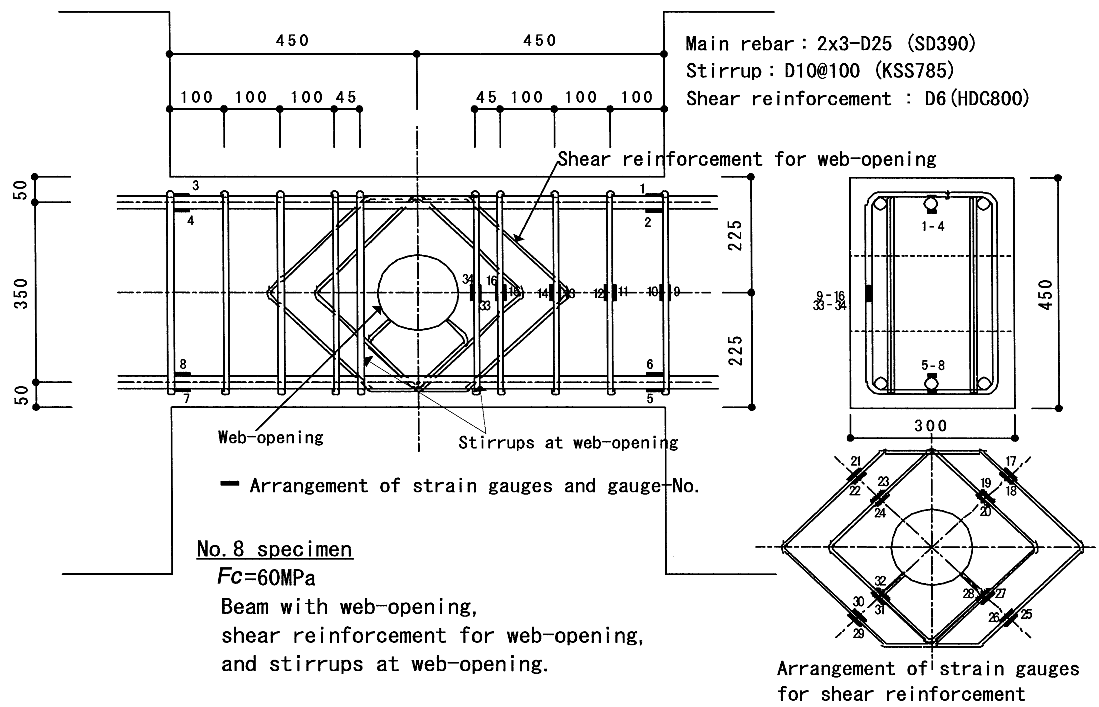

Fig. 1 Details of No.8 specimen

pairs of stirrups were cut by the opening in order to accurately evaluate the influence of the stirrups cut to provide the opening. One stage of main rebar was arranged on both the upper and lower sides. No slab was provided in order to eliminate the effect of constraint of the main rebar by slab. In planning the specimens, the amounts of main rebar and stirrups were decided on so that the shear fracture of the beam around the opening would always precede the bending fracture. The shear span ratio was decided to be about 1.1. As an example, the shape and the arrangement of rebar of the No. 8 specimen are shown in **Fig. 1**.

3.1.2 Materials used

The results of material tests on the concrete and reinforcing bars used for the specimens are shown in **Tables 4 and 5**. For the concrete, two levels of design strength–36 N/mm^2 and 60 N/mm^2–were

Table 4 Results of material test of concrete

For specimen ID	Design strength (N/mm²)	Curing period (day)	Compressive strength (N/mm²)	Tensile strength (N/mm²)
No.1-4	36	28	40.9	2.88
		52	43.3	2.74
No.5-10	60	28	68.1	4.37
		52	70.3	4.46

Table 5 Results of material test of reinforcing bars

Rebar	Type	HDC800	KSS785	SD390
	Designation	D6	D10	D25
	Nominal cross-sectional area (mm²)	31.67	71.33	506.7
Yield point or proof stress (N/mm²)		984	900	433
Strain at yield stress or proof stress (μ)		7359	6672	2458
Tensile stress (N/mm²)		1110	1051	605

adopted. Test pieces which were prepared during the placement of specimen concrete were subjected to a compressive strength test and a cleavage strength test when at the age of 28 days and 52 days, near the timing of the structural experiment. SD390 was used for the main rebar and KSS785 was used for the stirrups.

3.1.3 Method of load application and method of measurement

The loading apparatus of the type developed by the Building Research Institute (see **Fig. 2**) was used to apply anti-symmetric flexural shear force to each specimen. The No. 1 - No. 8 specimens were subjected to cyclic positive-negative load, and the No. 9 and No. 10 specimens were subjected to monotonic load. The repetitive application of load was controlled by means of displacement of the member rotation angle. At the member rotation angle of 1/500, 1/250 and 1/100, respectively, cyclic positive-negative load was applied three times before being set to the forward direction. The axial load to each specimen was zero, and the influence of the weight of the specimen itself was neglected. At each loading cycle, the amount of relative displacement between points of load application was measured by using a displacement gauge. The strains that occurred in the main rebar, stirrups and shear reinforcement were measured by using strain gauges at the same time as measuring the displacement.

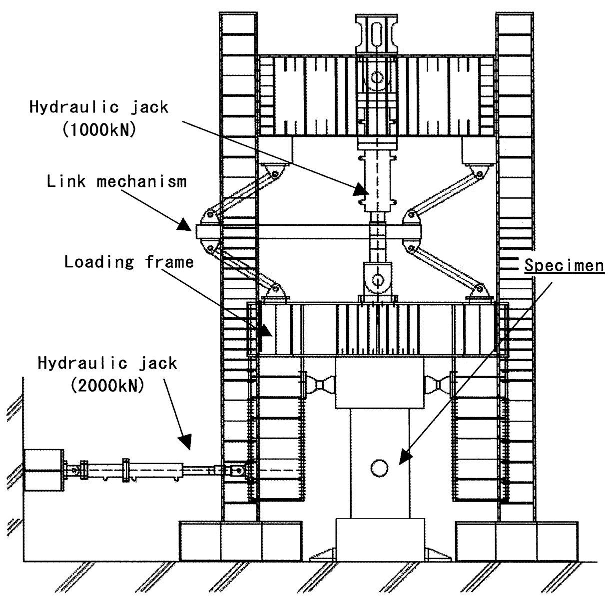

Fig. 2 Loading apparatus

3.2 Experimental results

3.2.1 Conditions of cracking and fracture

The condition of the cracking of the No. 8 specimen is shown in **Photo 4**. After the application of a load was started, a flexural crack occurred in the beam end firstly, followed by a crack in a 45-degree direction from the center of the opening and the crack stopped propagating at the shear reinforcement. As the rotation angle was increased, another crack appeared from the edge of the opening and propagated tangentially toward the specimen corner. This crack became predominant, ultimately causing shear fracture of the right and left sides of the opening.

3.2.2 Load-displacement relationship

The load-displacement relationship obtained with the No. 8 specimen is shown in **Fig. 3**. With this specimen, the load-displacement relationship remained almost linear until the rotation angle was set to 1/250. During the first cycle of load application at the rotation angle of 1/100, the maximum yield strength was reached. Thereafter, the load continued decreasing.

Fig. 4 shows the load-displacement relationships (envelopes of cyclic responses of specimens) obtained when the concrete design strength, *Fc*, was 60 N/mm². The No. 5 specimen without an opening retained 90% or more of its maximum yield even after the maximum yield was reached, whereas the maximum yield of the non-reinforced No. 6 specimen with an opening was less than 50% of that of the No. 5 specimen. On the other hand, the No. 6 - No. 10 specimens with an opening and with shear reinforcement, tested under various conditions, did not decline so much in yield strength. Thus, the effect of the shear reinforcement was confirmed.

3.2.3 Strain in shear reinforcement

The relationship between the load and the strain in the shear reinforcement of the No. 8 specimen is shown in **Fig. 5**. The arrangement of strain gauges is shown in Fig. 1. It was confirmed that the strain in the inner periphery of the shear reinforcement was greater

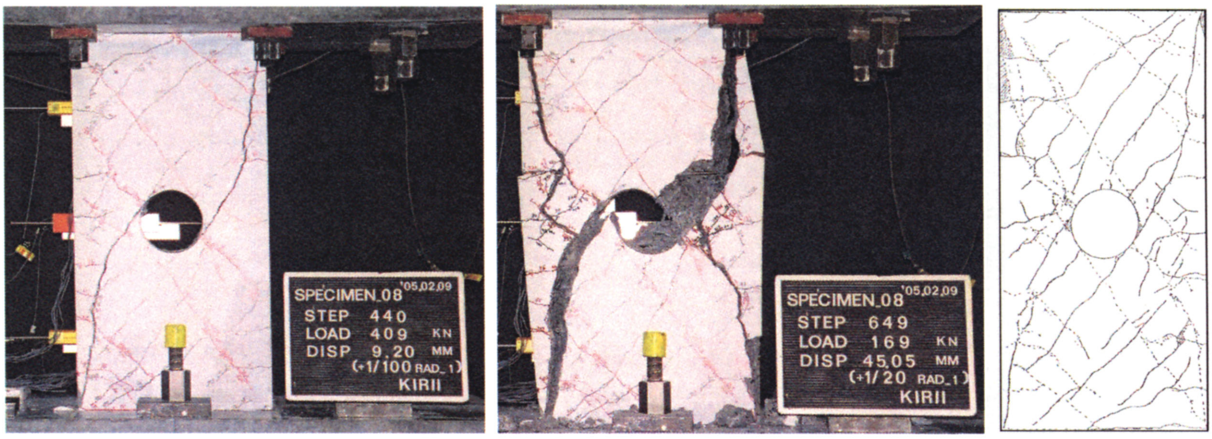

Photo 4 Crack distribution of No.8 specimen (from left-side: rotation angle at 1/100, 1/20, and crack-pattern)

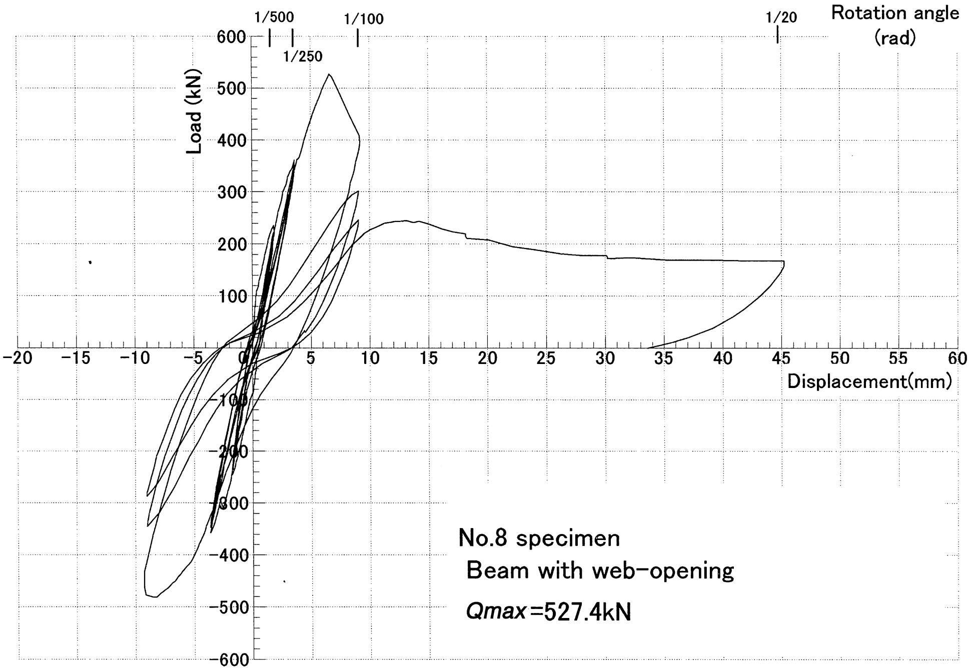

Fig. 3 Load-displacement relations of No.8 specimen

than that in the outer periphery and that both the inner and outer peripheries displayed the effect of the shear reinforcement markedly.

3.2.4 Discussion on effect of shear reinforcement

To discuss the effect of reinforcement by the shear reinforcement, Arakawa's formula for evaluating shear strength (1) was applied to the beams without opening and Hirosawa's formula (2) was applied to the beams with an opening[1-3].

$$Q_{su} = \left\{ \frac{0.092\,K_u \cdot K_p\,(Fc+18)}{M/Qd + 0.12} + 0.85\sqrt{{}_sP_{w0} \cdot {}_s\sigma_y} \right\} \cdot bj \qquad (1)$$

$$Q_{su0} = \left\{ \frac{0.092\,K_u \cdot K_p\,(Fc+18)}{M/Qd + 0.12} \left(1 - 1.61\frac{H}{D}\right) + 0.85\sqrt{{}_wP_{w0} \cdot {}_w\sigma_y + {}_sP_{w0} \cdot {}_s\sigma_y} \right\} \cdot bj \qquad (2)$$

Where,
H: Diameter of round opening (mm)
D: Beam height (mm)
K_u: Correctional coefficient for cross section dimension (K_u = 0.72 when $d \geqq 400$ mm)
K_p: Correctional coefficient for tensile reinforcement ratio pt
$K_p = 2.36\,p_t^{0.23}$
b: Beam width (mm)
d: Effective beam height (mm)
Fc: Concrete design strength (N/mm^2)
M/Qd: Shear/span ratio ($1 < M/Qd \leqq 3$; when M/Qd is greater than 3, it is assumed to be 3)
${}_wP_{w0}$: Reinforcement ratio of diagonal NS JYOBU-REN
${}_sP_{w0}$: Reinforcement ratio of stirrups within an effective range of reinforcement
P_{w0}: Reinforcement ratio of shear reinforcement (sum of reinforce-

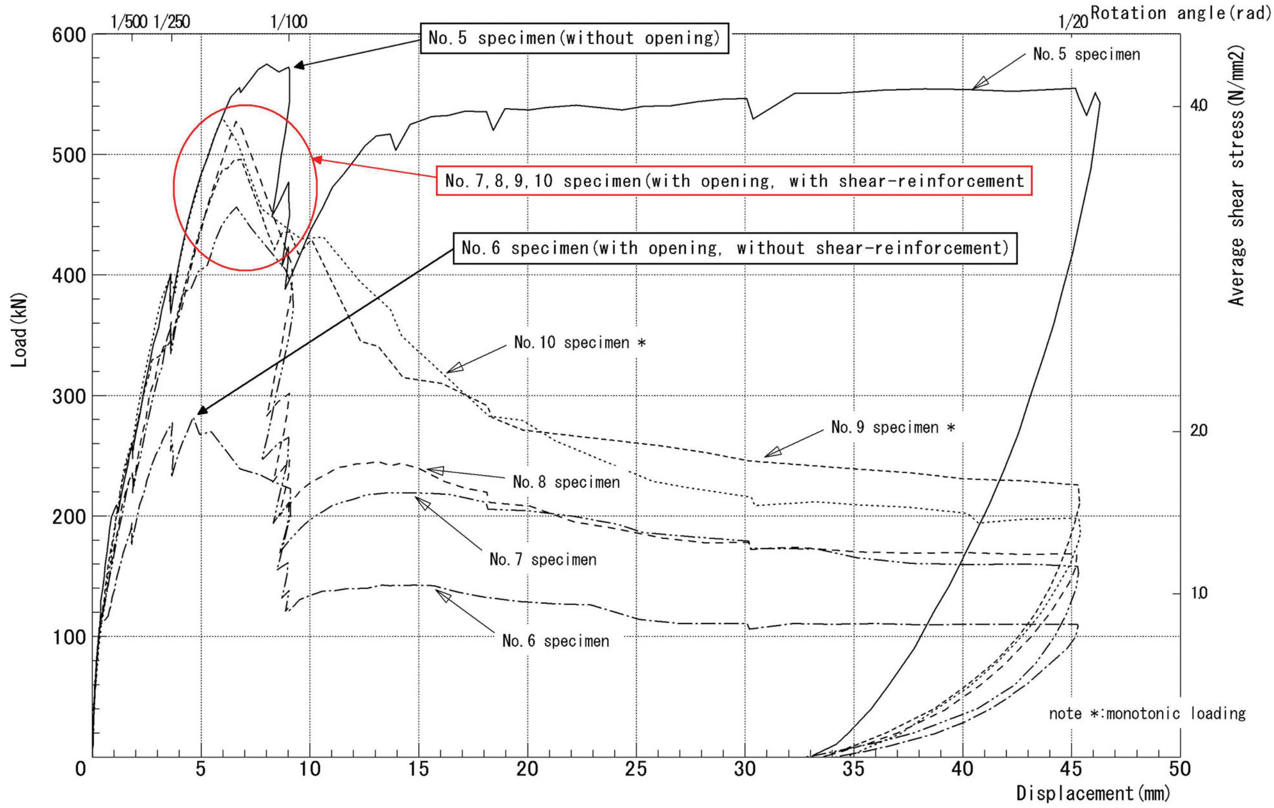

Fig. 4 Load-displacement relations (envelopes of cyclic response of specimens)

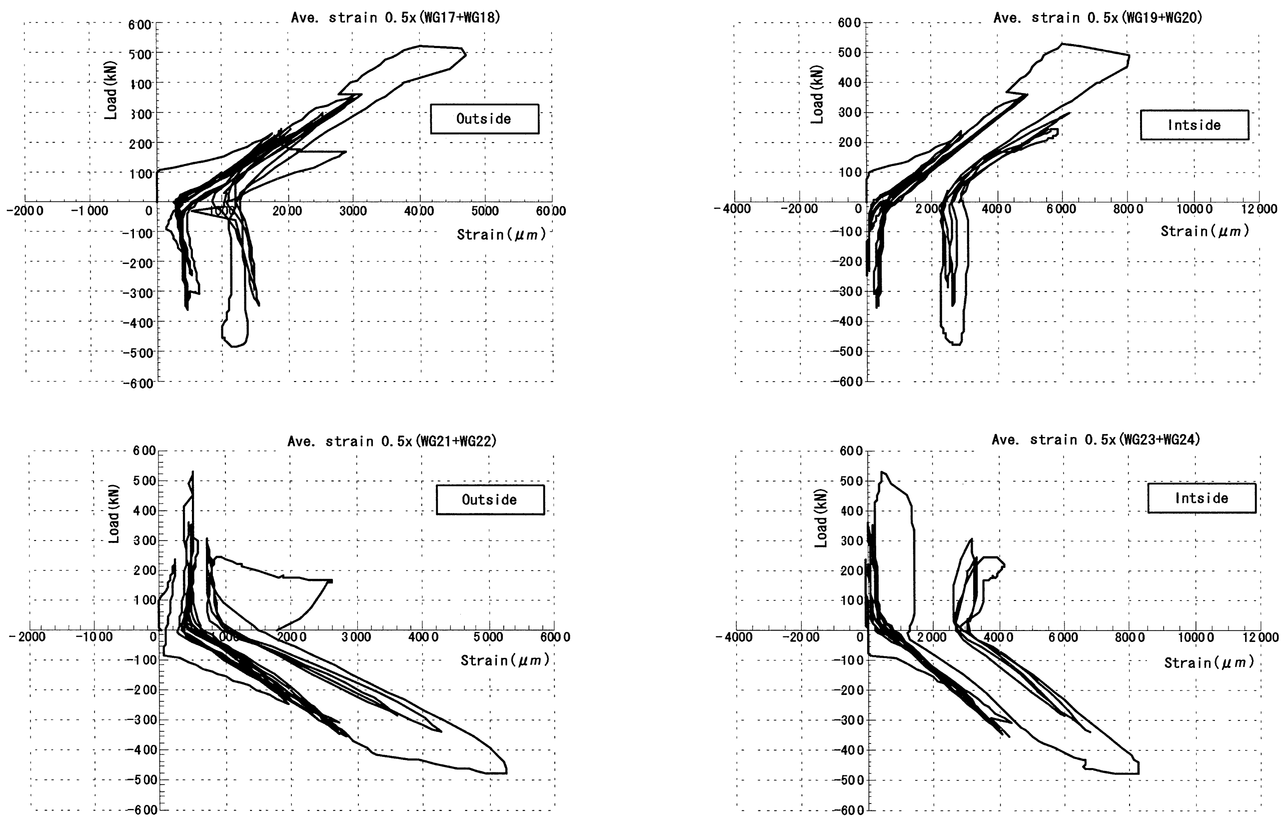

Fig. 5 Load-strain relations of shear reinforcement for web-openings

Table 6 Comparison of shear resistance between experiment and calculation

Specimen ID	Compressive strength of concrete (N/mm²)	Shear resistance (kN)		Comparison $_eQ_{su}/_cQ_{su}$	Web-opening and reinforcements		
		Experiment $_eQ_{su}$	Calculated $_cQ_{su}$		Web-opening	Reinforcement for web-opening	Stirrup at web-opening
No. 1	43.3	507.4	480.7	1.06	×	×	×
No. 2		245.2	276.8	0.89	○	×	×
No. 3		354.3	352.8	1.00	○	○	×
No. 4		414.3	394.1	1.05	○	○	○
No. 5	70.3	574.9	611.2	0.94	×	×	×
No. 6		282.2	337.3	0.84	○	×	×
No. 7		456.3	413.3	1.10	○	○	×
No. 8		527.4	454.6	1.16	○	○	○
No. 9		495.9	426.8	1.16	○	○	×
No.10		530.4	468.1	1.13	○	○	○

Remarks: ○: exist, ×: not exist

ment ratio of NS JYOBU-REN within an effective range of reinforcement and reinforcement ratio of stirrups within an effective range of reinforcement) $P_{w0} = {}_wP_{w0} + {}_sP_{w0}$

${}_w\sigma_y$: Material strength of NS JYOBU-REN shear reinforcement (N/mm²)

${}_s\sigma_y$: Material strength of stirrup shear reinforcement (N/mm²) (material strength of ordinary beam stirrup)

j: Distance between centers of tension and compression (= $(7/8)\,d$) (mm)

Table 6 compares the experimental and calculated values of shear strength. The calculated values of shear strength are derived from the results of the material tests on concrete and rebar.

RC beams with web-openings reinforced by NS JYOBU-REN were subjected to a load test. The test results obtained are as follows.

(1) Shear resistance

The non-reinforced No. 2 and No. 6 specimens with openings showed a marked decline in shear resistance compared with the other specimens. In contrast to this, the specimens provided with shear reinforcement and reinforcement near the opening were measured to have a higher shear resistance than the calculated shear resistance.

(2) Effect of arrangement of reinforcing bars around opening

Even the shear reinforcement alone proved to have a considerable reinforcing effect. However, it was confirmed that the shear resistance could be further improved by arranging additional stirrups around the web-opening.

4. Design Method for Shear Reinforcement NS JYOBU-REN[4)]

It was decided that Equation 2 should be used as the formula for designing the ultimate shear resistance of shear reinforcement using high strength bar-in-coil HDC800, but that the allowance for the ultimate shear resistance should be increased by providing safety factor α. Considering that the allowance for the measured ultimate shear resistance of beams without opening against the ultimate shear resistance calculated by Arakawa's formula (Equation 1) was approximately 1.16, it was decided that for the NS JYOBU-REN using high strength reinforcing bar, too, the same level of allowance for ultimate shear resistance should be secured even for the No. 3 specimen that showed the smallest value in the above experiment. Eventually, the value of α was decided to be 0.85. As a result, the following equation was obtained.

$$Q_{HU} = \alpha \cdot \left\{ \frac{0.092\, K_u \cdot K_p\, (Fc + 18)}{M / Qd + 0.12} \left(1 - 1.61 \frac{H}{D}\right) + 0.85 \sqrt{{}_wP_{w0} \cdot {}_w\sigma_y + {}_sP_{w0} \cdot {}_s\sigma_y} \right\} \cdot bj \tag{3}$$

Where,

Q_{HU}: Ultimate shear resistance of beam with web-opening using NS JYOBU-REN

α : Safety factor when NS JYOBU-REN is used (α = 0.85)

${}_w\sigma_y$: Material strength of NS JYOBU-REN shear reinforcement (N/mm²) (${}_w\sigma_y$ = 800 N/mm²)

The meanings of the other symbols are the same as those in Equation 2.

The scope of application of Equation 3 is as follows (**Figs. 6 and 7**).

(1) Shape of opening: Round (circumscribed circle when the opening is square).

(2) Diameter of opening: Maximum diameter is 1/3 of the beam height. It shall be between 100 mm and 450 mm in size.

(3) Position of opening: In beam horizontal direction, the opening shall not be positioned within the range from the column face to the distance of beam height at the beam edge. In the beam vertical direction, the opening shall not be positioned within the range from the beam (top or bottom) to 1/4 of the beam height or 200 mm, whichever is greater.

(4) Continuous opening center-to-center distance: When two or more openings are provided side by side in the beam horizontal direction, the opening center-to-center distance shall be expressed by distance projected onto the horizontal plane. The center-to-center distance shall not be smaller than three times of the opening diameter. Continuous openings must not be provided in the beam vertical direction.

(5) Positions of continuous openings: There shall not be more than one opening in the range between 45-degree tangential lines.

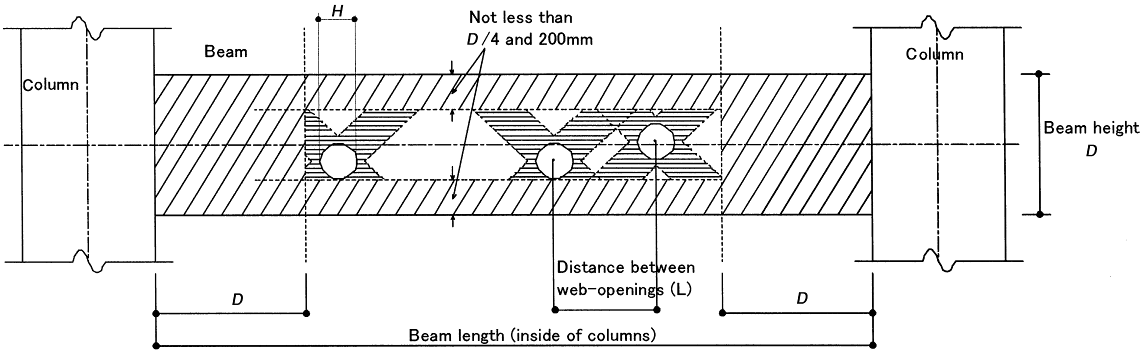

Fig. 6 Rules on the location of web-openings

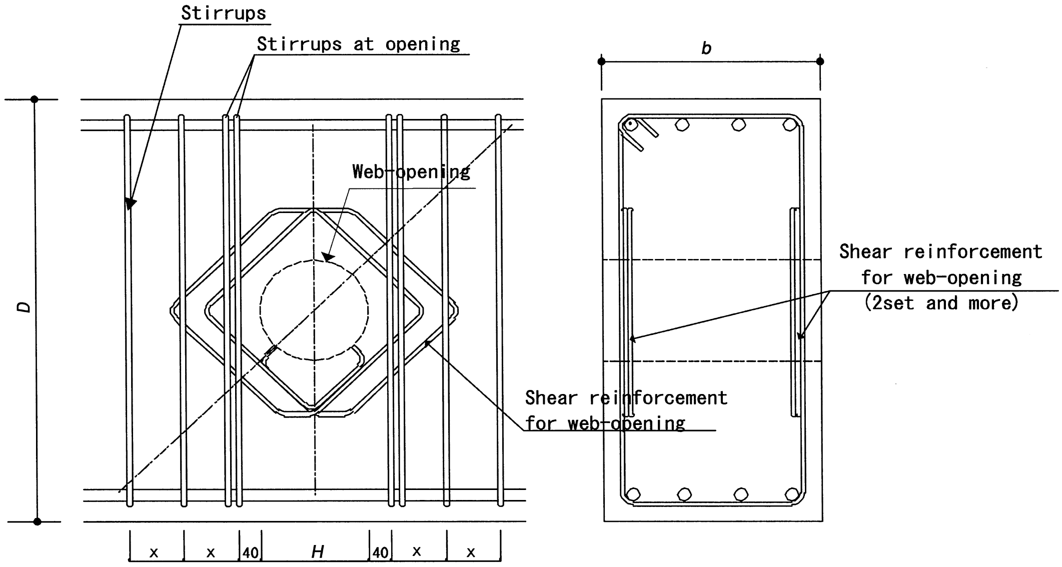

Fig. 7 Arrangement of stirrups at web-opening

(6) Design strength of concrete: Between 36 N/mm^2 and 60 N/mm^2.
(7) Arrangement of additional stirrups around opening: Stirrups of the same specifications as of ordinary stirrups shall be arranged on both sides of the opening.

5. Conclusion

The authors developed a high strength deformed bar-in-coil HDC800 that has a 0.2% proof stress of 800 N/mm^2 or more. In addition, a shear reinforcement NS JYOBU-REN for web-openings was attained using HDC800. By shear tests on RC beams with web-openings applying NS JYOBU-REN, it was confirmed that the shear reinforcement was effective to reinforce RC beams with web-openings. In addition, an equation for evaluating the ultimate shear resistance was formulated. It is expected that the improvement in resistance and the reduction in size of the shear reinforcement of RC beams with web-openings will not only justify the design of the shear reinforcement, but also enhance the efficiency of transportation and arrangement of reinforcing bars at construction sites.

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