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1 Introduction

It has recently been pointed out[1,2] that, because the beam and column members of the reinforced concrete (RC) structure of high-rise buildings are subjected to high axial and shear stresses, effective aseismic performance can be obtained by increasing the strength of the materials and, at the same time, using shear reinforcement consisting of peripheral and internal hoops. The structural design procedure for using high-strength Riverbon prestressed concrete (PC) steel bar as the shear reinforcement for RC beams and columns has already been established.[3] However, considerable time and labor are needed to assemble the internal hoops on the construction site, and the high-strength material makes it difficult to arrange the internal hoops.

To increase the assembly efficiency on the site and save labor, and to improve the structural reliability of the shear reinforcement, the authors developed a new type of transversal reinforcement system consisting of a peripheral hoop and internal hoops, which are made from a one-piece steel bar without breaks or welded joints. This reinforcement system is called Riverbon MULTI TYPE and is available in two forms: Riverbon MULTI HOOP, which consists of only one formed hoop, and Riverbon MULTI SPIRAL HOOP, which consists of a series of continuously formed hoops.

The results of an experiment conducted to demonstrate that Riverbon MULTI TYPE has a shear reinforcing effect equal to or better than that of conventional hoop reinforcement will be described. Furthermore, an outline of the equipment for efficiently manufacturing Riverbon MULTI TYPE and how the efficiency of site work is increased with Riverbon MULTI TYPE will also be described. The PC steel bar used is Riverbon manufactured by Kawasaki Steel Techno-Wire that conforms to SBP D1 275/1 422 specified in JIS G3109.

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2 Structural Experiment

The effects of experimental parameters on the ductility of conventional and Riverbon MULTI TYPE hoops were investigated by using RC columns of the shear failure and flexural yielding types, and the performance of each reinforcement was examined and compared. Riverbon of 1 275 N/mm^2 yield strength was used for the shear reinforcement.

2.1 Experimental Method

2.1.1 Secimens

Fourteen shear test specimens[4)] and 14 flexure test specimens[5)] were used in the experiment **(Table 1)**. Principal test variables were the configuration of the reinforcement, ratio of shear reinforcement (p_w), axial force coefficient (n), and ratio of tensile reinforcement (p_t).

Table 1 Test specimen details

	Specimen	Types of hoop	L/D	n (N/bDF_c)	p_w (%)	p_t (%)	
Shear test	N-E-70		2.5	0.3	0.19	3.54	Conventional
	N-E-35		2.5	0.3	0.38	3.54	
	N-S1-70		2.5	0.3	0.29	3.54	Conventional
	M-S1-70		2.5	0.3	0.57	3.54	Riverbon MULTI
	M-S1-35		2.5	0.3	0.57	3.54	
	N-S2-70		2.5	0.3	0.38	3.54	Conventional
	M-S2-70		2.5	0.3	0.76	3.54	Riverbon MULTI
	M-S2-35		2.5	0.3	0.76	3.54	
	M-D-70		2.5	0.3	0.33	3.54	
	M-D-35		2.5	0.3	0.65	3.54	
	M-O-70		2.5	0.3	0.35	3.54	
	M-O-35		2.5	0.3	0.71	3.54	
	N-ES-35-3		4.0	0.3	0.38	2.26	Conventional
	N-E-35-3		4.0	0.3	0.38	2.26	
Flexure test	M-S2-70-3		4.0	0.3	0.38	2.26	Riverbon MULTI
	M-S2-70-6		4.0	0.6	0.38	2.26	
	M-S2-35-3		4.0	0.3	0.76	2.26	
	M-S2-35-6		4.0	0.6	0.76	2.26	
	N-S2-35-3		4.0	0.3	0.76	2.26	Conventional
	N-S2-35-6		4.0	0.6	0.76	2.26	
	M-S2S-35-3		4.0	0.3	0.76	2.26	Riverbon MULTI
	M-S2S-35-6		4.0	0.6	0.76	2.26	
	M-D-35-3		4.0	0.3	0.65	2.26	
	M-O-35-3		4.0	0.3	0.71	2.26	
	M-S2-70-3L		4.0	0.3	0.38	3.54	
	M-S2-35-3L		4.0	0.3	0.76	3.54	

b : Section width
D : Section hight
L : Column length
N : Axial force
p_w : Ratio of shear reinforcement (5 mmφ)
p_t : Ratio of tensile reinforcement
F_c : Maximum strength of concrete

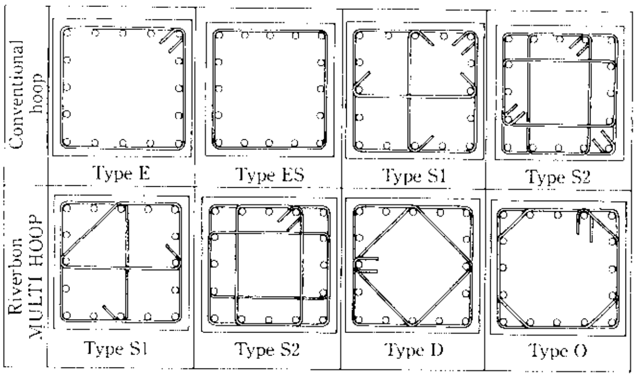


Fig. 1 Provided hoop configuration

Figure 1 shows the various configurations of the Riverbon MULTI TYPE and conventional hoop reinforcement. The conventional hoops were type E, in which only a square peripheral hoop with a 135° hook anchor is provided, type ES, which is type E in a spiral form, and types S1 and S2, in which a square peripheral hoop and two overlapping internal hoops are used. Riverbon MULTI TYPE consists of types S1 and S2, type D, which uses a square peripheral hoop and a square internal hoop, and type O, which uses a square peripheral hoop and an octagonal internal hoop bent-worked in a one-piece steel bar. Type S2S was also tested, in which Riverbon MULTI HOOP of type S2 is continuously formed from the top to the base of the column; this is Riverbon MULTI SPIRAL HOOP.

The sizes of specimens for the shear and flexure tests are shown in **Fig. 2**. Column length L was 750 mm for

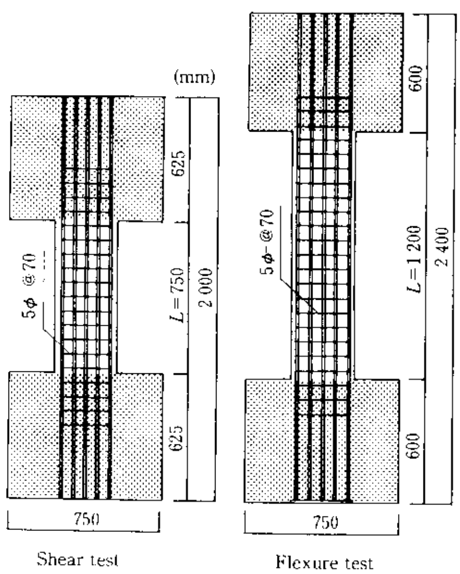


Fig. 2 Details of spacimens

Table 2 Mechanical properties of reinforcing bars

Standard	Bars (mm)	YS*1 (N/mm²)	TS*2 (N/mm²)	El*3 (%)
Riverbon*4	RB5.0	1 407	1 419	10.9
JIS SD40*5	D13 D16	418 428	595 647	23.4 21.0

*1 Yield stress or 0.2% proof stress
*2 Tensile strength
*3 Elongation
*4 Transverse reinforcing
*5 Longitudinal reinforcing

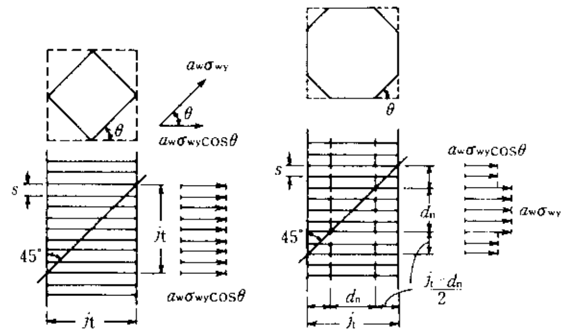


Fig. 3 Definition of reinfocement ratio

the shear test specimens and 1 200 mm for the flexure test specimens. The same cross-sectional dimensions of 300 mm × 300 mm were used for each specimen. The mechanical properties of the reinforcement used are shown in **Table 2**.

The ratio of shear reinforcement, p_w, is defined by the following equation:

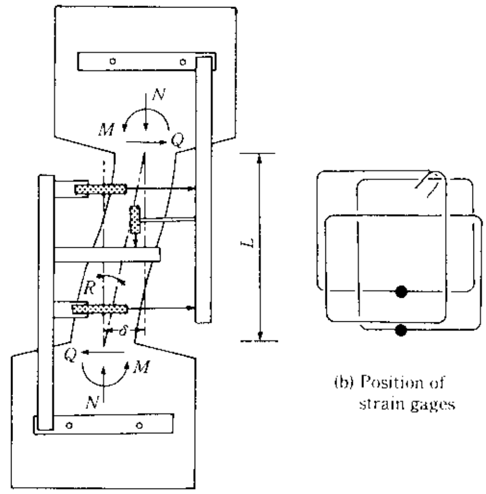
$$p_w = \frac{a_w}{Bs} \cdots\cdots\cdots\cdots\cdots (1)$$

where a_w: cross sectional area of one set of shear reinforcement bars
B: column width
S: Spacing between adjacent sets of shear reinforcement bars

This p_w can be associated with the shearing stress born by the shear reinforcement by assuming that the shear reinforcement that intersects an oblique crack in the 45° direction yields under tensile stress, forming a truss. Based on this concept, the ratio of shear reinforcement for internal hoops of type D and type O is defined by Eq. (2)[4] (**Fig. 3**):

$$p_w = \frac{a_w}{Bs}\left\{\frac{d_n}{j_t} + \left(1 - \frac{d_n}{j_t}\right)\cos\theta\right\} \cdots\cdots\cdots (2)$$

where d_n: Length of the parallel portions (type D: $d_n = 0$)
j_t: Distance between the main reinforcing bars
θ: Angle between the section axis of the column and the internal hoop (45°)



(a) Method of loading

(b) Position of strain gages

Fig. 4 Basic test method

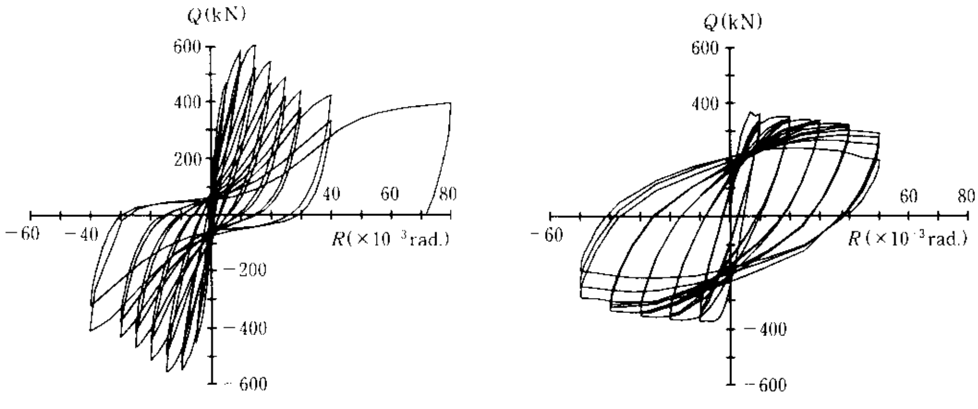
2.1.2 Method of loading

The experiment was conducted by loading the column with a constant central compressive force, and repeating this twice with the same displacement amplitude. The working axial and working shear stresses were measured with 2 940 kN and 1 960 kN load cells installed on hydraulic jacks. **Figure 4** (a) and (b) show the positions of the displacement gages and the strain measuring positions for type S2 reinforcement, respectively. Deflection angle R was calculated by $R = \delta/L$ (where δ is the horizontal displacement, and L is the column length).

2.2 Failure Characteristics

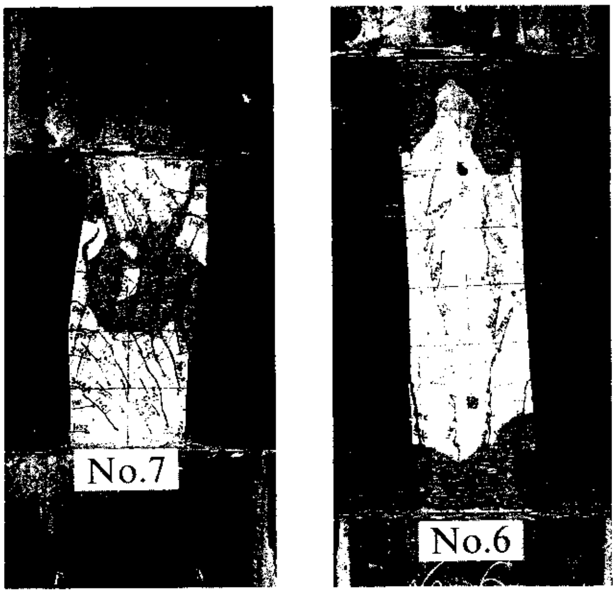
Figure 5 and **Photo 1** show examples of the hysteresis loops and failure characteristic of the shear test specimens and flexure test specimens. The ordinate of Fig. 5 is working shear proof stress Q(kN), and the abscissa is deflection angle $R(\times 10^{-3}$ rad).

In each specimen subjected to the shear test, a bending crack was first formed, and then diagonal tensile cracks were formed in the corners at the top and base of the column. When the diagonal tensile cracks had propagated and the end concrete been crushed, the maximum proof stress was reached, and the specimen assumed the condition of shear compression failure. In each specimen subjected to the flexure test, a bending crack was first formed, and then oblique cracks were formed at the ends of the member. With compressive and tensile yield in the main reinforcement occurring, the end concrete was crushed and the maximum proof stress was reached; the specimen assumed the condition of flexural compression failure. After the maximum proof stress had been reached, the main reinforcement at the end buckled. The buckled parts were finally bro-



Shear test (Specimen M-S2-35)　　Flexure test (Specimen M-S2-35-6)

Fig. 5 Horizontal load—horizontal deflection hysteresis loops



Shear test (Specimen M-S2-35)　　Flexure test (Specimen M-S2-35-6)

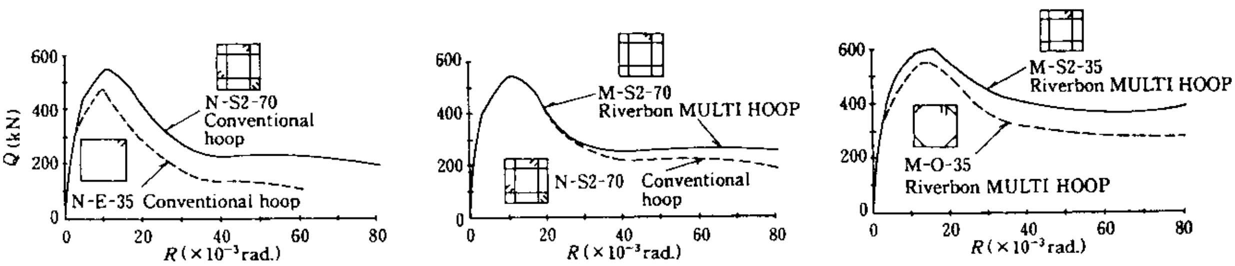
Photo 1 Appearance of specimens

ken due to repeated fatigue and failed. Compared with the specimens subjected to the shear test, the hysteresis loops were stable.

2.3 Comparison of the Effect of Reinforcement

2.3.1 Effect of hoop configuration

In the specimens subjected to the shear test, a comparison of the ductility curves was made between specimen N-E-35 with only a peripheral hoop and specimen N-S2-70 with a peripheral hoop and internal hoops with the same amount of reinforcement as specimen N-E-35 (**Fig. 6** (a)). This reveals that the maximum proof stress of specimen N-S2-70 with internal hoops was higher than that of specimen N-E-35, and that the decrease in proof stress, after the maximum proof stress had been reached, was more controlled. In other words, the use of internal hoops in combination with a peripheral hoop was more effective than the dense arrangement with only a peripheral hoop in increasing the proof stress and ductility when the amount of reinforcement was the same. Although bond cracks were formed along the main reinforcement in both specimens after



(a)Effects of hoop configuration　　(b)Comparison of conventional hoop and Riverbon MULTI HOOP　　(c)Effects of inner hoop configuration

Fig. 6 Comparison of ductility curves (shear test)

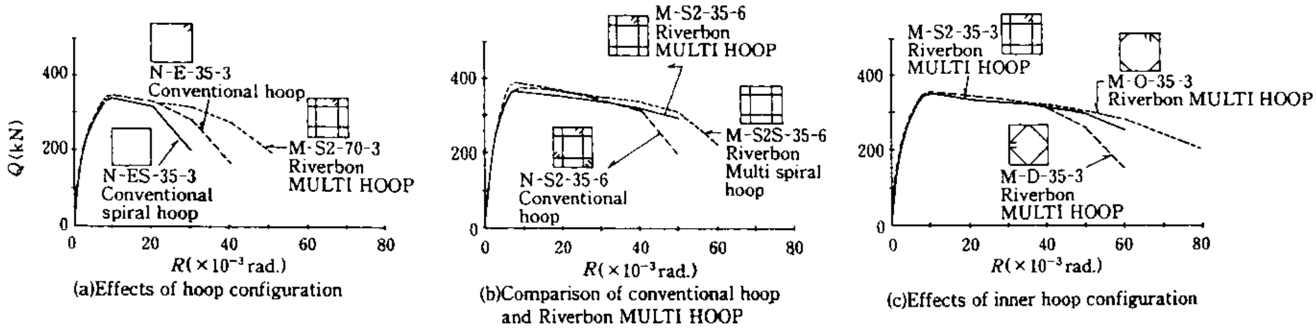


Fig. 7 Comparison of ductility curves (flexure test)

the maximum stress had been reached, the propagation width of the bond cracks along the main reinforcement was smaller in specimen N-S2-70 than in specimen N-E-35. It is apparent from this that the propagation of bond cracks can be suppressed by using internal hoops in combination with a peripheral hoop.

A comparison of the ductility curves for specimens with the same amount of reinforcement ($p_w = 0.38\%$) when subjected to the flexure test (**Fig. 7** (a)) shows that conventional spiral hoop specimen N-ES-35-3 with hoop configuration □ and the conventional hoop with a 135° hook anchor were broken due to the propagation of bond cracks at the center of the member after flexural yield. Although specimen M-S2-70-3, in which Riverbon MULTI HOOP with hoop configuration ⊞ was used, developed bond cracks at the center of the member after the maximum proof stress had been reached, the cracks did not propagate much, thus showing greater ductility compared with hoop configuration □. Thus, the propagation of bond cracks can be suppressed by using internal hoops in combination with a peripheral hoop.

2.3.2 Comparison between conventional and Riverbon MULTI TYPE hoop reinforcement

In the specimens subjected to the shear test, a comparison of the ductility curves between the conventional hoop and specimens S1 and S2 with Riverbon MULTI TYPE reinforcement (Fig. 6 (b)) does not show any difference because the conventional hoop and Riverbon MULTI HOOP have almost the same maximum proof stress. After the maximum proof stress had been reached, however, bond cracks were formed along the main reinforcement and the concrete peeled off. In connection with this, the hook anchor of the peripheral hoop began to slip in the specimen with the conventional hoop, and this hook anchor finally slipped out of the core concrete at a deflection angle $R = 65 \times 10^{-3}$ rad. In contrast to this, none of the hook anchors slipped out in the specimens reinforced with Riverbon MULTI HOOP, which shows its better ductility than the conventional hoop. Only one hook anchor is needed with Riverbon MULTI HOOP reinforcement due to the use of a onepiece steel bar without breaks or welded joints, and the position of this hook anchor is designed to be away from the corners of the section, resulting in less likelihood of the hook anchor slipping out.

Figure 7 (b) shows a comparison of the ductility curves for Riverbon MULTI TYPE, conventional hoop and Riverbon MULTI SPIRAL TYPE reinforcement in specimens subjected to the flexure test. In the high axial force test at an axial force ratio $n = 0.6$, the specimen with Riverbon MULTI SPIRAL HOOP shows the best ductility characteristics, the specimen with Riverbon MULTI HOOP being next best and that with the conventional hoop being worst. From these results, it seems that when an RC column, in which the amount of shear reinforcement is relatively large and flexural yielding occurs preferentially, is subjected to a high axial stress, the ductility characteristics are influenced by the degree of confinement of the core concrete in the plastic hinge region at the ends of the member. Furthermore, this degree of confinement of the core concrete seems to have increased in the order of conventional hoop, Riverbon MULTI HOOP, and Riverbon MULTI SPIRAL HOOP reinforcement.

2.3.3 Effect of internal hoop configuration

In the specimens subjected to the shear test, a comparison of the ductility curves for types S1, S2, D and O of Riverbon MULTI HOOP (Fig. 6 (c)) reveals that the maximum proof stress and the degree of decrease in proof stress depended on the ratio of shear reinforcement defined in 2.1.1, although the pitch of the reinforcement was the same.

When the ratio of shear reinforcement with the same reinforcement configuration was compared, it was found that the maximum proof stress increased with increasing ratio of shear reinforcement with all types S1, S2, D and O. After the maximum proof stress had been reached, the propagation of bond cracks was suppressed in those specimens with a high ratio of shear reinforcement. The theoretical flexural yield was reached only in specimen M-O-35 with a large amount of shear reinforcement.

In the specimens subjected to the flexure test, Fig. 7 (c) shows a comparison of Riverbon MULTI HOOP reinforcement in the ⊞, ◇ and octagonal configurations. In all of the specimens, buckling of the main reinforcement at the ends of the member and peeling off and damage to parts other than the core concrete enclosed with an internal hoop are severe, leading to reputure. The best ductility is observed in the specimen with an octagonal internal hoop, the specimen with hoop ⊞ having the next best ductility, and the specimen with hoop ◇ having the least. This variation in ductility is because the specimen with hoop ◇ had a lower ratio of shear reinforcement and a smaller number of main reinforcing bars subjected to buckling confinement than the other two types. In the case of specimens with the octagonal and ⊞-shaped internal hoops, in which the same number of reinforcing bars were confined, the octagonal Riverbon MULTI HOOP reinforcement had the best ductility in spite of the lower ratio of shear reinforcement. This is because the area of core concrete enclosed with an octagonal internal hoop was about $\sqrt{2}$ times that of the specimen with a ⊞-shaped internal hoop. It seems that, because the octagonal internal hoop used in this experiment had a shape approaching a circle, it had a confining effect similar to that of a circular hoop.

2.4 Strain Characteristics of the Shear Reinforcement

Figure 8 shows average strain changes and hysteresis loops for the specimens subjected to the shear test (N-S2-70, M-S2-70 and M-S2-35) and those subjected to the flexure test (N-S2-35-6, M-S2-35-6 and M-S2S-35-6). The thick solid lines shows the hysteresis loops, and the thin solid lines and dotted lines show the strain changes in the peripheral hoop and internal hoop, respectively, in the working direction. The left ordinate is load Q (kN), the right ordinate is strain ε_i ($\times 10^{-3}$), and the abscissa is deflection angle R ($\times 10^{-3}$ rad).

Shear specimen N-S2-70 (a in Fig. 8) with a conventional hoop shows a decrease in strain after the maximum proof stress has been reached, while the strain does not decrease much in specimens M-S2-70 and M-S2-35 (b and c in Fig. 8) with Riverbon MULTI HOOP reinforcement after the maximum proof stress has been reached. This is due to the ductility being increased by using Riverbon MULTI HOOP. Furthermore, it suggests that, because the strains in the internal hoops are larger than those in the peripheral hoops, the combined use of internal hoops is effective for improving the proof stress and ducility.

In the specimens subjected to the flexure test, increased deformation of the member tends to increase the strain in the internal hoop more than that in the peripheral hoop after the maximum proof stress has been reached. This tendency is most marked with

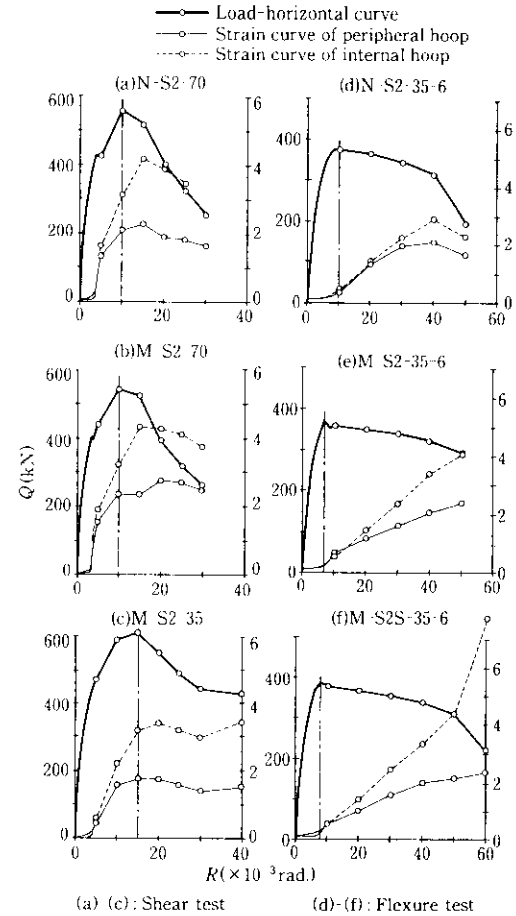


Fig. 8 Behavior of strains on the transverse reinforcement

Riverbon MULTI SPIRAL HOOP reinforcement, with Rivebron MULTI HOOP next, and the conventional hoop showing this least. From these observations, it is considered that the more continuous the reinforcement and the smaller the number of hook anchors, the more the reinforcing effect will increase and the more the ductility will be improved.

2.5 Examination of Shear Proof Stress

Figure 9 shows the relationship between Q_{su} and shear reinforcement ratio p_w calculated with various equations for shear proof stress. Superimposed on these corves are the experimental values for conventional hoop reinforcement (open symbols), and those for Riverbon MULTI HOOP reinforcement (closed symbols). The experimental values tend to increase with increasing shear reinforcement ratio p_w and the same tendency is also apparent in the experimental values for types D and O, so it seems that the calculation method for shear reinforcement ratio p_w can be evaluated by the concept described in 2.1.1. The experimental value (Q_{max}) divided by the calculated value (Q_{su}) in Ara-

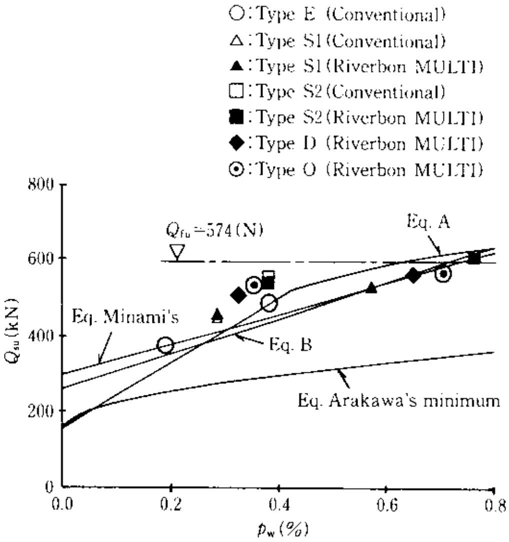


Fig. 9 Effect of reinforcement ratio on experimental strength

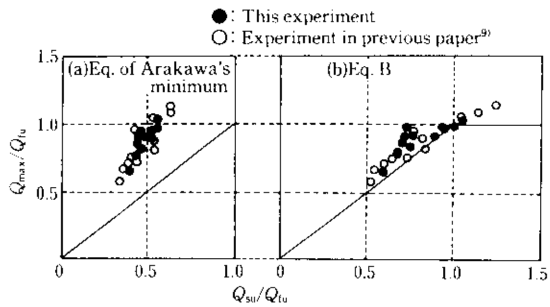


Fig. 10 Comparison of experimental ultimate strength and calculated strength

kawa's minimum equation[6] ranges from 1.64 to 2.01, which are conservative values. Q_{max}/Q_{su} in Minami's modified equations,[7] Eq. A and Eq. B,[8] ranges from 0.97 to 1.23, from 0.91 to 1.16, and from 0.96 to 1.27, respectively; the three equations shows little variation and high accuracy compared with the experimental results, except for the type S2 specimens. However, the value for Q_{max}/Q_{su} obtained for the type S2 specimens obviously exceeds that obtained for the type E specimens with the same amount of reinforcement and is the highest value. In this figure, Q_{fu} represents the calculated value for flexural proof stress.[7] The relationship Q_{max}/Q_{fu}-Q_{su}/Q_{fu} in Arakawa's minimum equation and in Eq. B is shown in **Fig. 10** (a) and (b), respectively. In this figure, Q_{max} represents the experimental value for the maximum proof stress, and Q_{su} the calculated value for the shear proof stress. Symbol ● in this figure represents the values obtained in this experiment, and symbol ○ represents the experimental values for RC columns with shear reinforcement of 1 275 N/mm² yield strength which have already been reported.[9] From this figure, it can be seen that the values obtained in this experiment represent safety factors equal to or higher than the experimental values previously reported.

3 Development of Manufacturing Equipment

3.1 Background

In parallel with the development of Riverbon MULTI SPIRAL HOOP reinforcement, it was necessary to develop equipment capable of efficiently and accurately forming this complex shape. The problem with existing equipment was that only one arbitrarily set angle could be used and that the length of two sides could not be set. An even greater problem with the manufacture of MULTI SPIRAL HOOP was to develop a mechanism for consistantly handling the finished products without damaging the shape. If present computer numerical control (CNC) technology is used, it is possible to input angles and side lengths that differ from one motion to another, and there is a spring forming machine that works in a similar way. However, this spring forming machine cannot handle finished products and allows free movement during forming. This would damage the formed shape of the hoops which exceed 50 kg in weight. After investigating other possible techniques at home and abroad, it was decided to develop equipment in cooperation with another company which was keen to do this and had advanced techniques. The specifications of the equipment are shown in **Table 3**.

The developed equipment is a CNC machine that comprises feed rollers, bender, a carrier (product handling device), six AC servo motors, and a hydraulic cutter.

3.2 Features of the Manufacturing Equipment

This equipment is characterized by the high length accuracy and bending angle accuracy that can be obtained by AC servo motors and a computer. In addi-

Table 3 Specifications of equipment

Steel rod diameter range	6-13 mm for PC bar 10-16 mm for normal strength bar
Steel rod	
Tensile strength	Up to 1 600 N/mm²
Yield strength	Up to 1 550 N/mm²
Max bending angle	+/−180 deg.
Max side length	≦1 200 mm
Spiral layers	Up to 50
Length cutting accuracy	+/−2 mm
Angle bending accuracy	+/−1 deg. (ajustable)
Max feed speed*	80 m/min
Max bending rate*	800 deg/s

* Auto changeable

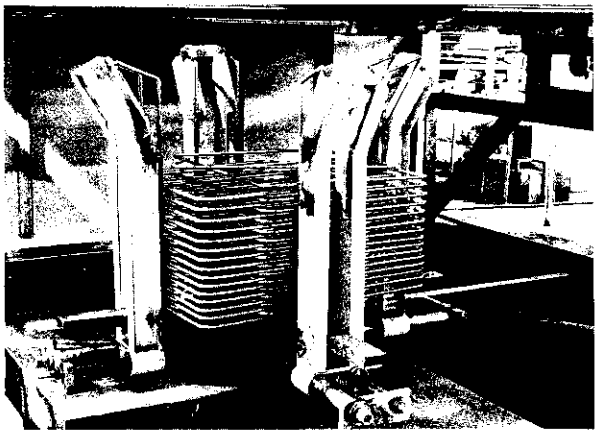


Photo 2 Manufacturing of MULTI SPIRAL HOOP

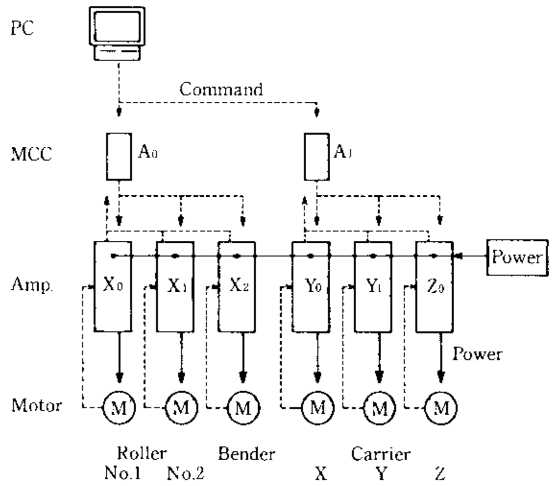


Fig. 11 Control System

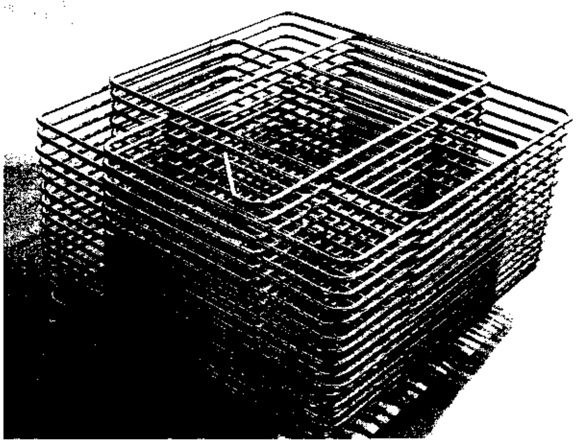


Photo 3 Riverbon MULTI SPIRAL HOOP (Type S2S)

tion, settings, changes and fine adjustment of the length and bending angle can be easily done by unskilled operators only by inputting numerical values from a keyboard. The product handling device (carrier) can follow all the movement of a product, and perform forward, backward, lateral, vertical and rotational motions so that it can handle products without damaging the shape after forming. After being formed in the bender, the finished product moves downward into this carrier, which is shown in **Photo 2**. A typical product of Riverbon MULTI SPIRAL HOOP reinforcement is shown in **Photo 3**.

3.3 Control System

Instructions input from a 16-bit personal computer are sent as signals by a micro-processor, called the motion control card (MCC), to amplifiers linked to the six motors. Each motor rotates by the required amount according to the magnitude and timing of the current fed from the amplifier, the position then being fed back to the amplifier by a resolver attached to the motor shaft to make any necessary corrections. High accuracy is ensured by this system, which is shown in **Fig. 11**.

4 Assembly Efficiency at the Construction Site

In 1991, Riverbon MULTI HOOP reinforcement was adopted in four high-rise buildings, and its high assembly efficiency won a high reputation.

Table 4 shows a comparison of the assembly procedure between conventional hoop and Rivebon MULTI TYPE reinforcement. With conventional reinforcement, three packages of hoops need to be stored and

Table 4 Comparison of the assembly procedure for a column

Operation	Conventional hoop	Riverbon MULTI HOOP
Procurment and storage	3 packages	1 package
Pre assembling the internal hoops	30 min/column	Not necessary
Assembling to longitudinal bars	30 min/column	30 min/column
Total	1 h/column	30 min/column

assembled into one package, before this can finally be assembled with the main reinforcement. In the case of Riverbon MULTI TYPE reinforcement, which is all-in-one, only one package needs to be stored, before being directly assembled with the main reinforcement. Therefore, when the work for assembling the hoops to the main reinforcement is considered, one process can be completely omitted, and the time needed for the work is reduced to one half. Furthermore, the floor area for storage is reduced to about one third. Another of the features of Riverbon MULTI TYPE reinforcement is the small number of hook anchors, and this saves about 10% of material when using Riverbon MULTI SPIRAL. This small number of hook anchors also results in easier concrete placing work and an overall improvement in quality.

5 Conclusions

Riverbon with 1 275 N/mm^2 yield strength was used as shear reinforcement in an RC column, and the reinforcing effects of the conventional hoop and Riverbon MULTI TYPE were examined and compared.

(1) The use of internal hoops in combination with a peripheral hoop was more effective than dense arrangement of peripheral hoops in increasing the proof stress and ductility for the same amount of reinforcement.

(2) Riverbon MULTI TYPE provided a proof stress equal to that given by conventional hoop reinforcement, and can ensure ductility equal to or higher than that of the conventional type.

(3) For shear reinforcement by Riverbon MULTI TYPE, an octagonal shape provided the best ductility. Next to the octagon, the ⊞-shaped hoop offerred the highest ductility, with the ◇-shaped hoop third.

(4) Riverbon MULTI TYPE allows one assembly process to be completely omitted at the construction site, so that the steel-fixing time can be reduced to one half.

(5) Riverbon MULTI TYPE reinforcement uses a small number of hook anchors, so that about 10% of material can be saved compared with conventional hoops. Furthermore, the floor area for storage can be reduced to about one third.

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