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Shear strength of Steel-Hoop-Concrete composite column

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ABSTRACT: Steel-Hoop-Concrete(SHC)composite is a new structural system without longitudinal reinforcing bars. In this study, the shearing behavior of SHC column was examined, when shearing force was applied to it in the direction of minor axis of the column. The purpose of this paper is to make clear the shear-resisting-mechanism of the concrete that is almost divided into two pieces by the web plate of the steel. The shear strength can be well estimated by a mechanical model of the concrete newly proposed.

1 INTRODUCTION

Steel-Hoop-Concrete(SHC)composite is a new composite consist of steel and concrete without longitudinal reinforcing bars. By removing the main reinforcements, a diagonal crack due to the bond between concrete and reinforcement can be avoided, and the shearing behavior of the member is greatly improved under large deflection. These knowledges were obtained from the previous studies, in which the behavior of a column with H-shaped steel was investigated, in case the shearing force was loaded in the direction of major axis of the column.(Fig.-1(a)) They were published in the previous papers, e.g., Proc. of the 12th congress of IABSE, Proc. of the 9th WCEE and so on.

In SHC composite, a member encased the steel with greater depth can resist against greater bending moment. When the steel of great depth is used, a new problem arises. It is that how the concrete resist against a shearing force in the member, in case that it is loaded in the direction of minor axis of the column.(Fig.-1(b)) The concrete is almost divided into two pieces by the web plate of the steel. This issue also occurs, when cross-H-shaped steel is encased in the column. (Fig.-1(c))

This paper deals with this issue, i.e., the shear resisting mechanism of the concrete in SHC column with cross-H-shaped steel and H-shaped steel when a shearing force is applied in the direction of minor axis. They are examined experimentally, and finally, a mechanical model, which can estimate the maximum strength well, is proposed.

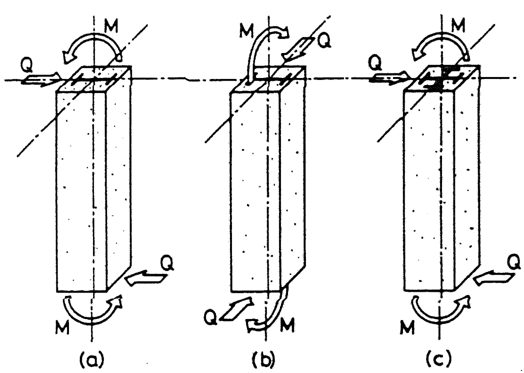

Fig.-1 Type of steel section and direction of loading

2 OUTLINE OF THE EXPERIMENT

Fourteen SHC column specimens listed in Table -1 were made and tested. Two of them encased cross-H-shaped steel and the others encased H-shaped steel. The dimension of a typical specimen is shown in Fig.-2. The clear length was 72.8cm long, and the depth of the section was 20cm wide, for all specimens. The concrete(c=438kg/cm^3, w/c≈0.4) was placed from the upper end through the holes bored at the end plate as shown in Fig.-2. The compressive strength of the concrete(σ_B), described in Table-1 for each specimen, was ranged from 480kg/cm^2 to 550kg/cm^2. The standard classification of the steel was SS41, and the actual yield strength(σ_y) was 31kg/mm^2. The experimental variables were the width of the section, the interval of the hoop reinforcements(30mm,60mm) and the strength of them

($59.0 kg/cm^2$ for N-hoop, $98.6 kg/cm^2$ for P-hoop). The diameter of the hoop is 4mm.

Cyclic shear-bending tests were carried out under a constant axial load. The constant axial force was 20% of the ultimate compressive strength of the section(N_u), which was calculated by sum of resistance of the concrete and the steel. The loading apparatus is illustrated in Fig.-3. In this figure, the measuring method of the deflection is also drawn. The axial displacement and the rotations of the both ends were measured. The moment was applied through the loading beams by the two hydraulic jacks set at the both ends, controlling the rotations at the both ends to be equal.

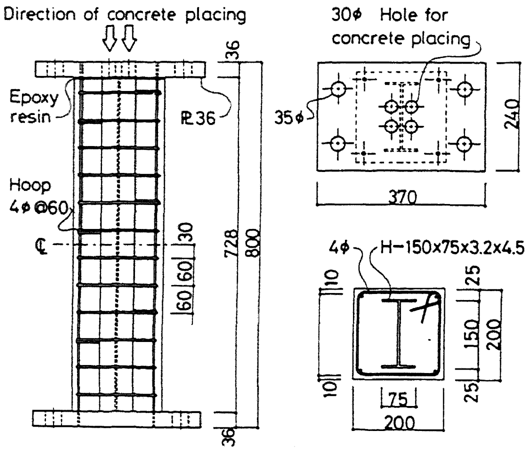

Fig.-2 A typical specimen

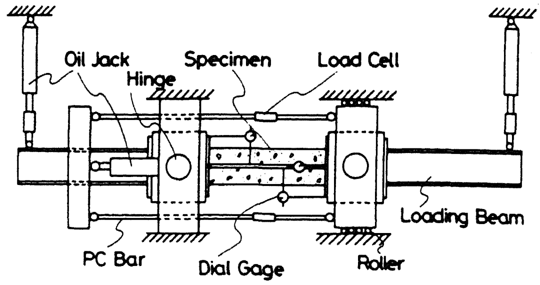

Fig.-3 Loading setup

Table-1 List of specimens

Name of specimen	Section B×D (mm)	Shape* of steel	Strength of concrete (kg/cm^2)	Shear reinforcement d (mm)	Shear reinforcement Interval (mm)	Shear reinforcement Strength (kg/mm^2)
H-180-P-30	180×200	H	517	4ϕ	30	98.6
H-180-P-60			527		60	
H-180-N-30			517		30	59.0
H-180-N-60			527		60	
H-200-P-30	200×200		493		30	98.6
H-200-P-60			533		60	
H-200-N-30			493		30	59.0
H-200-N-60			533		60	
H-230-P-30	230×200		552		30	98.6
H-230-P-60			505		60	
H-230-N-30			552		30	59.0
H-230-N-60			505		60	
CrH-200-P-30	200×200	cross H	523		30	98.6
CrH-200-P-60			523		60	

* H-150×75×3.2×4.5(mm); $\sigma y = 31 kg/mm^2$

3 THE EXPERIMENTAL RESULTS

For an example, the relationship between the shearing force(Q) and the lateral displacement of top of the column specimen relative to the base(δ) is shown in Fig.-4. In the figure, ΔQ is the additional shear force due to N-δ effect, and Q_u is the ideal ultimate shear strength calculated from the ultimate end moment(M_u). The ultimate end moment(M_u) is calculated based on the additional theorem and the following assumptions;

Concrete is rigid-plastic material, whose yield strength is σ_B for compression, and 0 for tension.

Steel is rigid-plastic material, whose yield strength is σ_y.

Q_M/Q_u versus δ skeleton curves for all the specimens are described in Figs.-5,6,7 and 8, where Q_M is the actual shear force, considering the N-δ effect (Q_M=Q+ΔQ). All specimens resisted the axial force($0.2N_u$) until they deformed grossly; rotation is about 1/10 rad, although the restoring force decreased according to the increase of the deflection.

The following knowledges were obtained from the experimental results.

(1) The maximum restoring force is obviously influenced by the thickness of the cover concrete.

(2) In case the cover concrete is relatively thin, the maximum restoring force becomes smaller than the ideal ultimate shearing force(Q_u).

(3) The amount and the strength of the hoop reinforcements affect the restoring force at large deflection, but almost never the maximum restoring force.

(4) The failure made is shear failure, but rapid degradation of the restoring force never occur.

(5) The restoring characteristic of SHC column encased cross-H-shaped steel is more stable than that encased H-shaped steel.

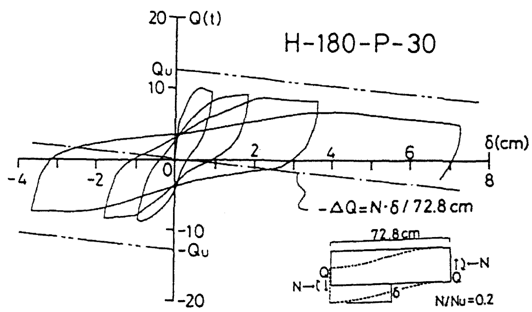

Fig.-4 Shear force(Q) vs. deflection(δ) curve of H-180-P-30

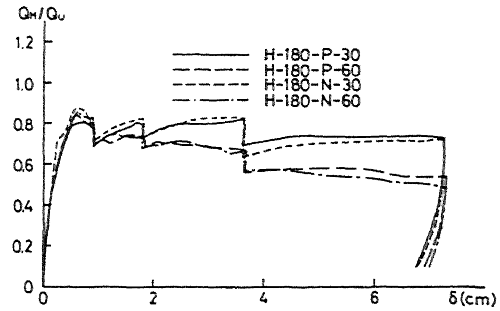

Fig.-5 Q_M/Q_u-δ skeleton curves of H-180 series

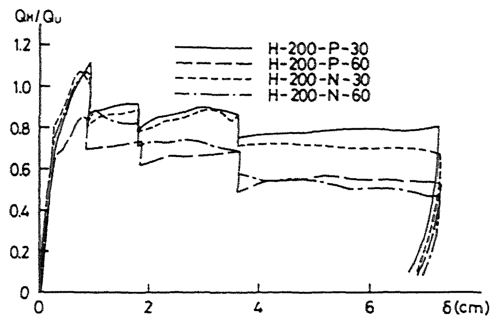

Fig.-6 Q_M/Q_u-δ skeleton curves of H-200 series

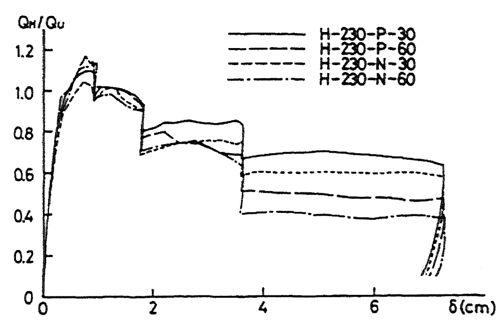

Fig.-7 Q_M/Q_u-δ skeleton curves of H-230 series

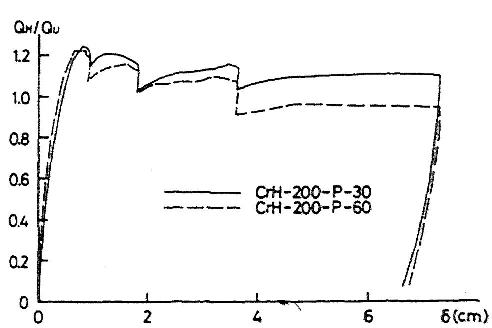

Fig.-8 Q_M/Q_u-δ skeleton curves of CrH-200 series

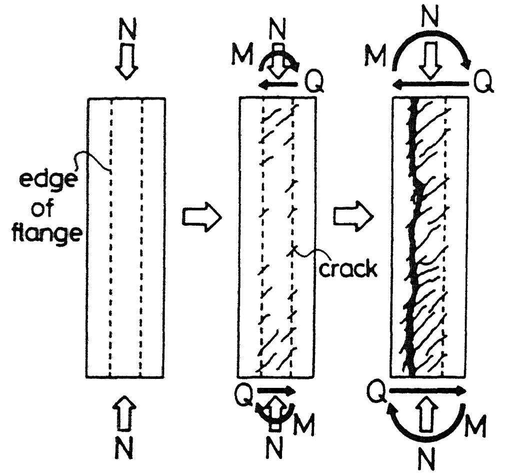

Fig.-9 Crack pattern and failure mode of cover concrete

The evolution of the shear cracks and the failure mode of the specimen is shown in Fig. -9. In case of the specimen with thick cover concrete, many fine diagonal cracks arose along the edge of the steel flange, and they grew according as the shear force increased. Finally, they were connected with one another and the concrete failed slipping along the surface of those cracks. At that time, the restoring force also degraded. In case that the cover concrete is relatively thin, the cracks grew similarly, but the specimen had not resisted the maximum restoring force yet at the time they connected, and the restoring force increased still more.

4 ESTIMATION OF THE MAXIMUM RESTORING FORCE

A mechanical model concerned with diagonal compression transfer mechanism of concrete is proposed in this section. Under the compression and shear-bending, the role of the concrete is to transmit the compressive load from the top to the base of the member diagonally. The direct transmission is disturbed by the web of the steel when a shear force is loaded in a direction of the minor axis of the member.

If the friction between the steel and the concrete is few, the compressive force will be transferred through the cover concrete. The region which resists the greatest shear stress, i.e. the area =b'/2×L, or =d'/2×L as shown in Fig.-10 will be critical at that time. In this experiment, as the covering width(b') is smaller than the covering depth (d'), the area consist of the covering width (b') and the length of the column(L) will be a critical region. The shear failure occured concentrately in this region actually in the experiment. The maximum shearing force resisted in this section can be decided by the shear strength of the concrete(Fs) as follows:

$$N = b' \cdot L \cdot F_s. \qquad (1)$$

The shear strength of the concrete(Fs) is assumed to be decided by the Mohr's circle as shown in Fig.-11 in consideration of the hoop restraining the concrete. The formula is as follows:

$$F_s + (\sigma_B/2)^2 = (\sigma_B/2 + \sigma_t)^2, \qquad (2)$$

where is the tensile strength of the concrete (assumed $0.1\sigma_B$). Hence, concrete can resist the normal stress equal to the compressive strength(σ_B), while it resists the shear stress equal to the shear strength(Fs). When the concrete resists the compressive force same as that given by eq.(1) in the region B×x, where x is given by

$$N = B \cdot x \cdot \sigma_B, \qquad (3)$$

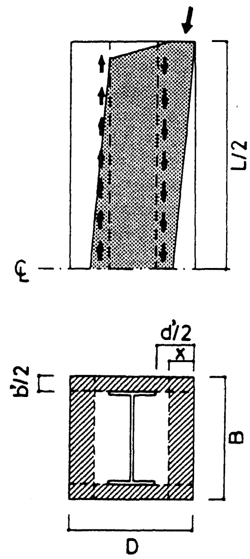

Fig.-10 Diagonal compression transfer mechanism of concrete(1)

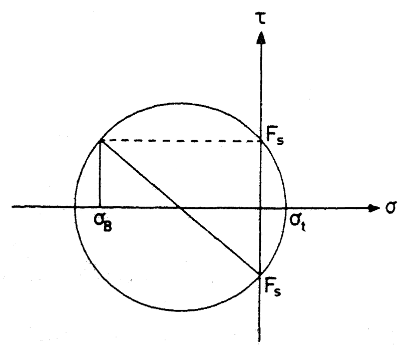

Fig.-11 Mohr's circle for defining Fs

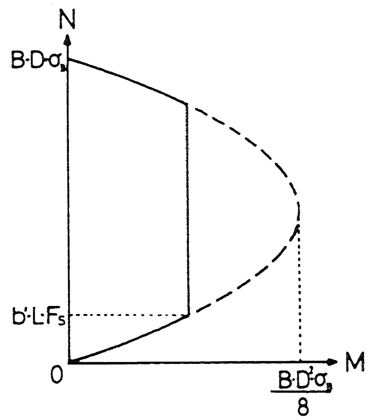

Fig.-12 M-N interaction curve of concrete(1)

the end moment resisted by the concrete(M_c) becomes greatest, and it is given by the next equation:

$$M_c = \frac{1}{2}N\cdot(D - \frac{N}{B\cdot\sigma_B}). \quad (4)$$

Substituting eq.(1) into eq.(4) yields

$$M_c = \frac{1}{2}b\cdot L\cdot F_s\cdot(D - \frac{b\cdot L\cdot F_s}{B\cdot\sigma_B}). \quad (5)$$

In case that more compressive force than the one given by eq.(1) is loaded to the concrete, the difference between them can be transferred from the top to the base of the column in parallel with the axis of the column because of the definition of the shear strength(Fs). Therefore the interaction curve of the moment and the axial force for the concrete can be given as a solid line illustrated in Fig.-12 when the compressive force is transmitted through the cover concrete.

As for the specimens with thin cover concrete, the increase to the restoring force was observed after the failure of the cover concrete. Therefore another mechanism resisting shear force should exist. As the cover concrete has already failed, two pieces of the concrete divided by the web plate will behave separately. A couple of struts are substituted for the concrete as shown in Fig.-13(a). It is assumed that compressive force resisted by the area of B×x at one end can be withstood by the region inside both flange plates at another end, because the concrete at this region is restrained by the steel. Moreover, the center of the force resisted by the region inside the flange is assumed to be equal to the center of the column. This assumption is available if confining of the steel makes the strength of the concrete at that region much greater than σ_B, even though there is no friction between the steel and the concrete. On the above suppositions, the interaction of the moment and the axial force is given as follows:

$$M = \frac{1}{4}N\cdot(D - \frac{N}{2B\cdot\sigma_B}). \quad (6)$$

In case $N>2BD\sigma_B/3$, two struts overlap each other, and inadequately heavy confinement by the steel has to be allowed under high axial force. Therefore, the upper limit of the axial force is defined as $BD\sigma_B/2$, and it is supposed that the above assumption is available in that range of the axial force. Hence, the upper limit of the depth represented as the character 'a' in Fig.-13(b) is D/8, and the end of the strut slides from the center to the edge of the column section according to the increase of the axial force as shown in the figure, in case $N>BD\sigma_B/2$. The interaction on the moment and the axial force can be given by the following equation:

$$M = \frac{3}{8}N\cdot(D - \frac{N}{B\cdot\sigma_B}). \quad (7)$$

The interaction curve given by eq.(6) and eq.(7) is illustrated as a solid line in Fig.-14.

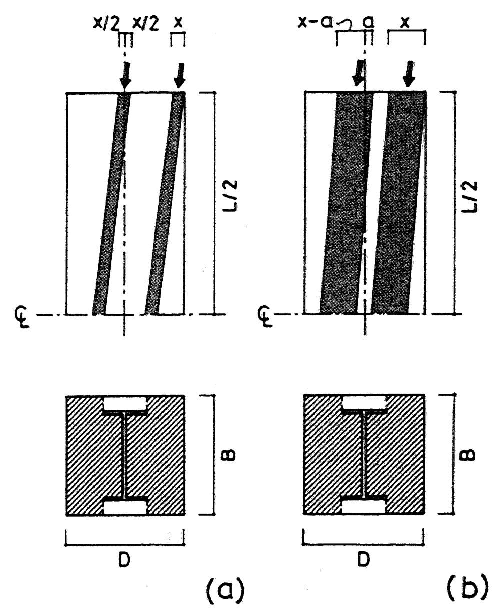

Fig.-13 Diagonal compression transfer mechanism of concrete(2)

The maximum restoring force is determined by the addition of the strength of the steel and the concrete element. The strength of the concrete element is decided by M-N interaction as described in Fig.-12 or Fig.-14. In Fig.-15, the calculated results of all specimens are compared with the experimentally observed maximum restoring forces. Except for the results of the specimens with the cross-H-shaped steel, the calculated results are sufficiently in conformity with experimental results.

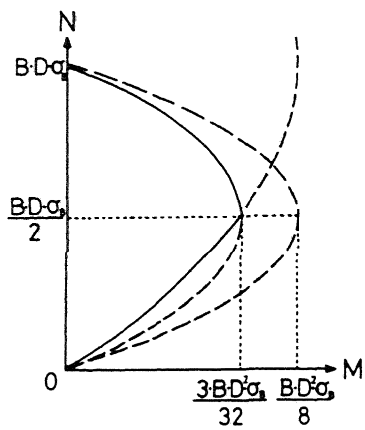

Fig.-14 M-N interaction curve of concrete(2)

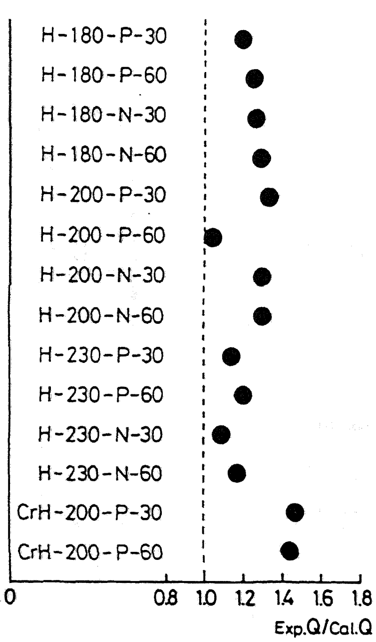

Fig.-15 Comparison of observed maximum restoring force with calculated results

5 CONCLUSIONS

In this study, the shearing behaviors of SHC column with H-shaped steel were mainly investigated experimentally, in case the shearing force was applied in the direction of the minor axis of the column. A mechanical model of concrete was produced so as to explain the following knowledges obtained from the experiment:

Hoop reinforcement do not affect the maximum restoring force. The maximum restoring force is influenced by the thickness of cover concrete.

Although the axial force, the detail of the steel section and the shear-span ratio were not varied and thier influences were not examined in the experiment, they are considered in the proposed model. Needless to say, it is neccessary for proving the propriety of the proposed model to investigate them hereafter, but in the common SHC member under the common range of the axial force, the maximum restoring force can be explained well by the proposed mechanical model. The following knowledges were also obtained from the experiment.

The failure mode is shear failure, but rapid degradation of the restoring force does not occur.

The restoring force characteristic of SHC column with cross-H-shaped steel is much more stable than that with H-shaped steel.

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