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High Strength Steel, Concrete, Hoop Composite Structure

Structure composite béton — acier à haute résistance

Verbundsystem aus Beton und hochfestem Stahl

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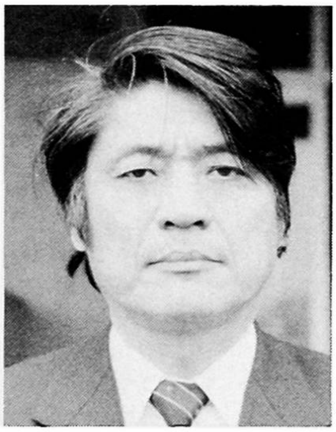

Toshiro Suzuki, born 1936, received his doctor's degree from the University of Tokyo in 1963. He was awarded the Prize from the Architectural Institute of Japan for his study on steel structure in 1981.

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SUMMARY
A new steel and reinforced concrete structural system is proposed. It consists of high strength steel, concrete and hoop reinforcement. Longitudial reinforcement is not used. Experiments are carried out to study the restoring force characteristics of the proposed system. The proposed system showed a large energy dissipating capacity as well as a large deformation capacity.

RESUME
Un nouveau système structural béton-acier à haute résistance est proposé. Il est constitué d'un profilé H en acier à haute résistance et du béton renforcé d'étriers fermés. Il ne présente pas d'armature longitudinale. Les expériences ont montré que le système a de grandes capacités de dissipation d'énergie et de déformation.

ZUSAMMENFASSUNG
Eine neue Verbundbauweise für Rahmentragwerke wird vorgestellt. Die Stützen bestehen aus hochfesten H-förmigen Stahlprofilen, die mit Betón ummantelt sind, der keine Längsbewehrung enthält. Er ist nur mit einer geschlossenen Bügelbewehrung umschnürt. Die experientellen Untersuchungen zeigen, dass das System viel Energie zu dissipieren vermag und ein grosses Deformationsvermögen besitzt.

1. INTRODUCTION

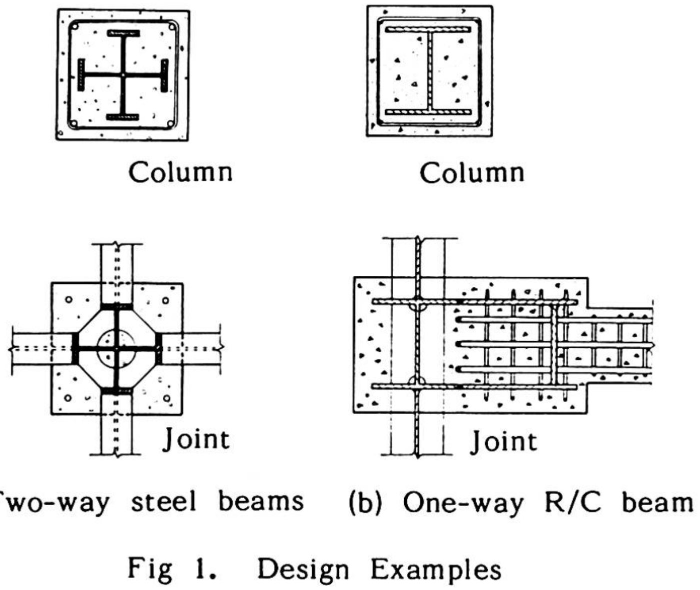
The steel and reinforced concrete composite (SRC) is one of the commonly used structural systems in Japan, especially for tall buildings. About 92% of the buildings taller than 9 stories were built by SRC system during the past five years in Japan.

The objective of this study is to develop a new SRC, 'H or cross-H shaped 784MPa (80kgf/mm²) strength steel' - 'concrete' - 'hoop reinforcement' composite. Illustrative examples of the proposed structural system are shown in Fig 1. The beams are made of the H-shaped steel or the ordinary reinforced concrete. The columns and the beam-column joints are made of the proposed SRC. Unlike the customary SRC, longitudinal reinforcement is not used in the column. Experiments are carried out to study the restoring force characteristics of the proposed SRC system. Effects of the hoop reinforcement and the steel strength are discussed.

2. THE FEATURES OF THE PROPOSED 'SRC' AND THE PROBLEMS LIABLE

One feature of the proposed SRC system is the non usage of longitudinal reinforcement. When the deformed bar is used as the longitudinal reinforcement, the bond between the deformed bar and the concrete induces the inclined flexural shear cracks, which consitute the truss action together with the web reinforcement. The authors intend that the concrete should be liberated from the truss action in the proposed SRC system. The role of the longitudinal bar is replaced by the larger section of H-shaped steel. The role of the concrete is limited to the arch action to sustain the diagonal compressive force and the axial force. This would make the concrete more ductile for the compressive straining. The non-usage of the longitudinal reinforcement brings about another merit; it shall reduce the congestion of reinforcement, which leads to the better concrete placing.

Another feature of the proposed SRC structural system is the usage of high tensile strength (784MPa or 80kgf/mm²) H or cross-H shaped steel instead of normal strength steel. This might cause the following problems concerning to the deformation capacity of the column.
(a) The concrete might not be able to sustain the compressive stress enough at small ductility factor, because the yield strain of the high strength steel is large.
(b) The local buckling of compressive steel flange might occur, because the



(a) Two-way steel beams (b) One-way R/C beam

Fig 1. Design Examples

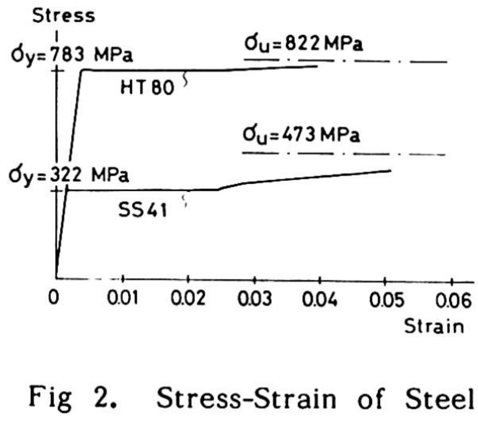


Fig 2. Stress-Strain of Steel

thickness of the steel plate should be designed thinner than that of the normal strength steel.
These problems shall be surmounted by the confinement [3] of the concrete by the hoop reinforcement within the column. On the other hand, the authors recommend that the hoop reinforcement within the beam-column joint should be curtailed as shown in Fig 1, in order to save the constructors' labor. The effect of the hoop reinforcement upon the restoring force characteristics of the columns and the beam-column joint is investigated within this paper.

The usage of high strength steel might cause another problem. The welding of high strength steel is more difficult than that of normal strength steel. The inelastic strain is apt to concentrate near the critical section, because the strain hardening of high strength steel is small and the yield zone length should be smaller. (Examples of stress strain relationships of high and normal strength steels are shown in Fig 2.) Therefore, the tensile fracture of steel flange at the critical section might be induced by the inperfection of the welding and by the inelastic strain concentration. In this paper, such effects are also to be discussed comparing the experimental results of the SRC members of various strength steels.

3. RESTORING FORCE CHARACTERISTICS OF THE COLUMN

Fifty-four SRC member specimens were tested. The variables were,
(1) amount of hoop reinforcement,
(2) the tensile strength of the H-shaped steel, and
(3) loading conditions, which include
C : monotonic Compression, B : cyclic Bending without axial force,
CB : constant Compressive force and cyclic Bending, and
CBS: constant Compressive force and cyclic Bending Shear.
The yield strength of the hoop reinforcement was not the variable; the normal strength steel was used. In this paper, only the results of the CB and CBS series testings with HT80 steel are reported. The detailed informations of the experiments is reported in the reference [4].

An example of the CB and CBS test specimens is shown in Fig 3. The compressive strength of concrete was 29.7 to 30.6 MPa. The loading and measuring system of the CB and CBS tests is shown in Fig 4. Axial force was maintained as N=500kN, which was about 20% of the calculated concentric compressive strength.

Test results of the HT80-CB series specimens are plotted in Fig 5. The second part of the specimens name '020' or '000' indicates that the spacing of the hoop reinforcement was 20mm or no hoop was used, respectively. The specimen with 20mm pitched hoop showed a stable spindle shaped hysteresis loop. Although

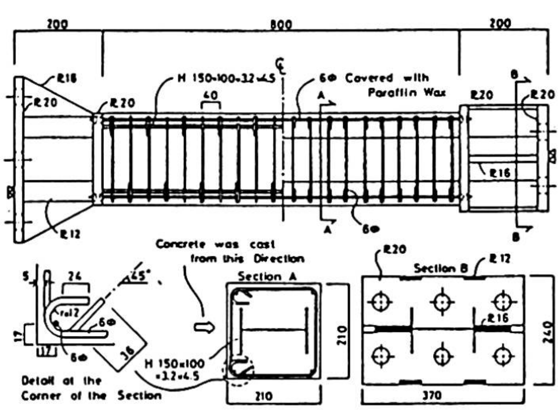


Fig 3. Specimen HT80-040-CBS-20

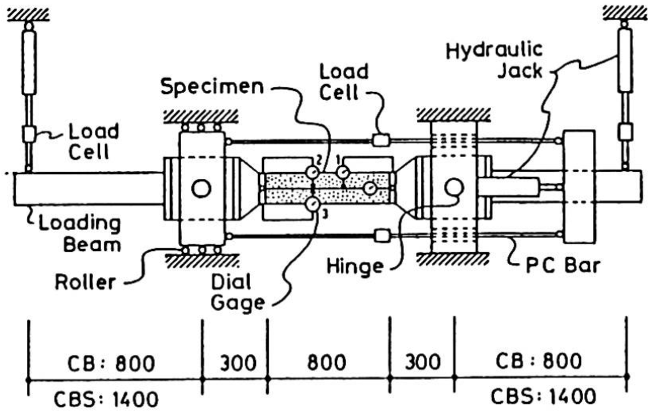


Fig 4. CB and CBS Test Setup

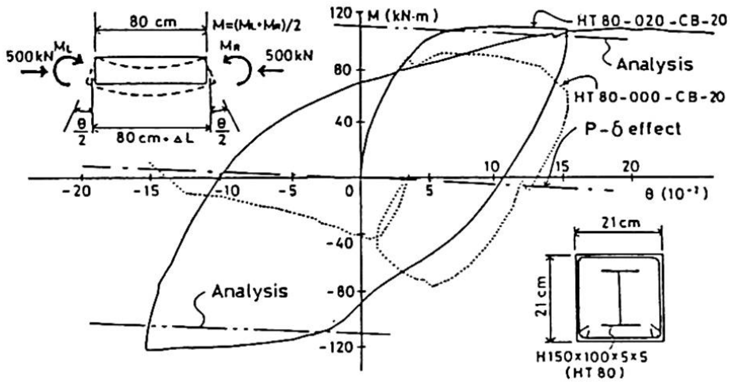


Fig 5. Moment - Rotation Angle Relations of CB Specimens

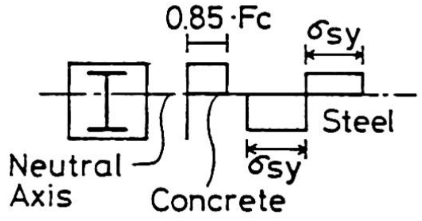
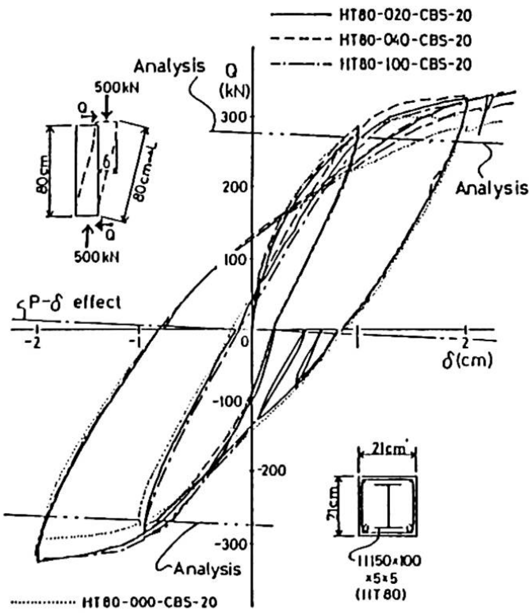
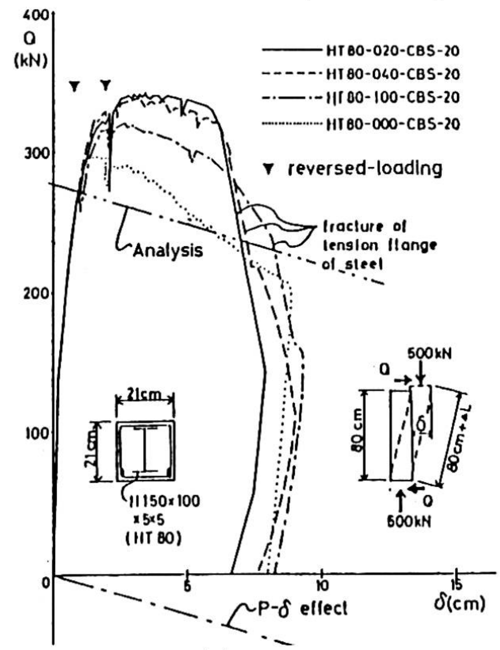


Fig 7. Assumed Stress Distribution



(a) Cyclic loops –



(b) Skeleton curves

Fig 6. Shear Force - Deflection Relations of CBS Specimens

the shell concrete spalled almost completely, the core concrete did not spall. The strength of the unhooped specimen was 73% of that of the hooped specimen. The concrete started to crush and spall at theta=0.04 rad. Local buckling of the steel flange was observed at theta=0.10rad. At theta = -0.15rad, the moment resistance of the specimen was completely lost.

Test results of HT80-CBS series are plotted in Fig 6. The strength of the unhooped specimen was 84% of that of the 20mm-pitched specimen. The ductility was also affected by the hoop. Local buckling of steel and diagonal cracks of concrete were observed in the specimens without hoop, but not in the hooped specimens. The flexural cracks concentrated at the critical sections in all the specimens. Flexural shear crack was not observed.

The resistance of all the HT80-CBS series specimens degraded largely by the fracture of the tension flange of steel at delta=6cm to 8cm (deflection angle=1/13 rad). Such fracture was not observed in the specimens of normal strength steel.

The ultimate strength was calculated assuming the stress distribution shown in Fig 7 and was indicated in Figs 5 and 6. The calculated strength agreed roughly with the observed strengths.

4. RESTORING FORCE CHARACTERISTICS OF THE BEAM-COLUMN JOINT

Twelve specimens were tested. An example of test specimen is shown in Fig 8. The beams are bare H-shaped steel. The variables were,
(a) the type of the H-shaped steel (SS41 or HT80),

(b) the amount of the hoop reinforcement, and
(c) the amount of the axial force on the column (0% or 25% of the calculated compressive concentric strength of the column)

The H-shaped steel of the column was continued through the joint; the beams and the stiffners were welded to the column. The hoop reinforcement was assembled through the slender holes of the beam webs. The joint panel was designed as the weakest; the column was designed stronger than the joint panel but weaker than the beam. (In the design of the actual structures, the order of the strengths shall be the opposite.) The compressive strength of the concrete was from 22.3 MPa to 24.4 MPa.

Loading and measuring system is shown in Fig 9. Forces were applied to the joint panel as Fig 10. The joint panel distortional moment PM was defined by the following equation.

$$PM = (Q_B+Q_B') \quad [H\ (L+J_c) - J_c\ (H+J_b)]\ /\ (H+J_b) \quad \text{.........(a)}$$

The panel moment PM corresponds to the shear deformation angle of the panel, 'gamma', according to Takizawa [2].

Test results of the specimens with HT80 steel and 25% axial force are shown in Fig 11. The joint panel strengths were affected by hoop reinforcement but not much by axial force. The strengths of hooped specimens were 14% to 17% higher than those of unhooped specimens, irrespective to the amount of the axial force. The ductility, however, was not affected by hoop reinforcement. The situation of the specimens with normal strength steel was very similar to those with high strength steel.

Failure patterns of the specimens were affected by the hoop reinforcement, but not much by the tensile strength of the H-shaped steel, nor by the amount of axial force. In the unhooped specimens, the joint panel concrete outside the stiffners and flanges of the column spalled almost completely. Only the concrete enclosed within the stiffners and flanges remained in the joint panel. Spalling occured in the connecting columns as well. On the other hand, the concrete of hooped specimens were well confined. A lot of inclined narrow cracks were observed in the joint panel but they did not penetrate the column.

The strength of the joint panel was calculated by the addition theorem [1] assuming as Fig 12. The shear force was assumed to be carried by the web of the H-shaped steel, the concrete, and the hoop reinforcement. The cracks of concrete were assumed to occur along the direction of the diagonal compressive force. The concrete was assumed to carry the compressive stress of 0.85 times of the compressive strength. The steel was assumed to carry the tensile or compressive yield stress. Calculated and observed strengths are shown in Fig 13. The theory explained the observed fact that axial force did not affect the strength within the tested range. However, it did not explain the observed effect of hoop reinforcement on the joint shear strength well.

5. INTERACTION BETWEEN THE COLUMN AND THE BEAM-COLUMN JOINT

Four specimens were tested. An example of the specimens is shown in Fig 14. The specimens were named as 'HT80-C-30','HT80-C-20','HT80-B-30', and 'HT80-B-20'. The variables in the specimens were,
(a) the thickness of the steel web in the joint, (This parameter was indicated by the second part of the specimens' name, C or B. The H-shaped steel of the Column or that of the Beam was continued through the joint; the web thickness of the column steel, 5mm, was thinner than that of the beam steel, 8mm.) , and
(b) the amount of the axial force on the column. (This parameter was indicated by the third part of the specimens' name. The axial force was 20% or 30% of BDFc, where B=D=350mm and Fc=22MPa.)

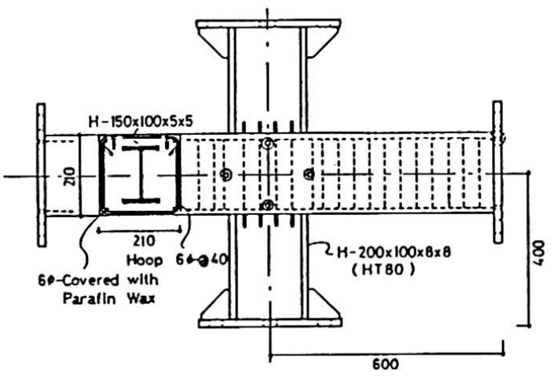


Fig 8. HT80-040-JPS-** Specimens

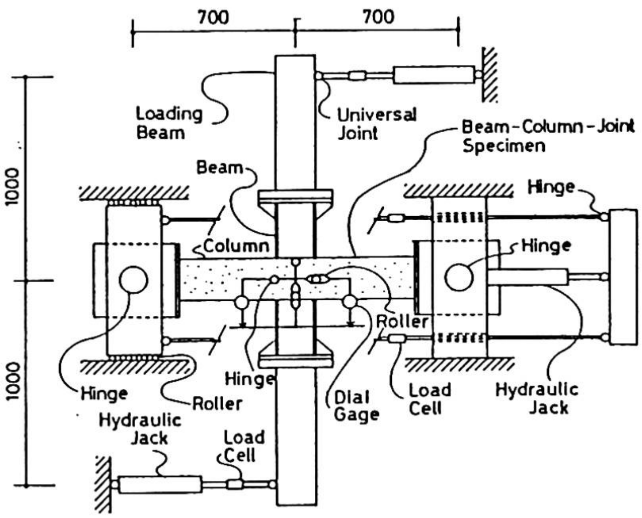


Fig 9. JPS Test Setup

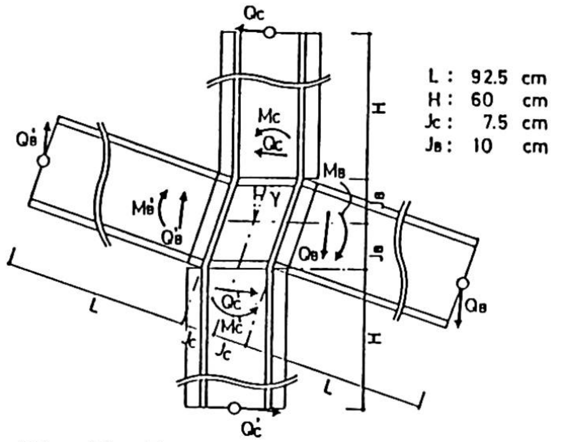
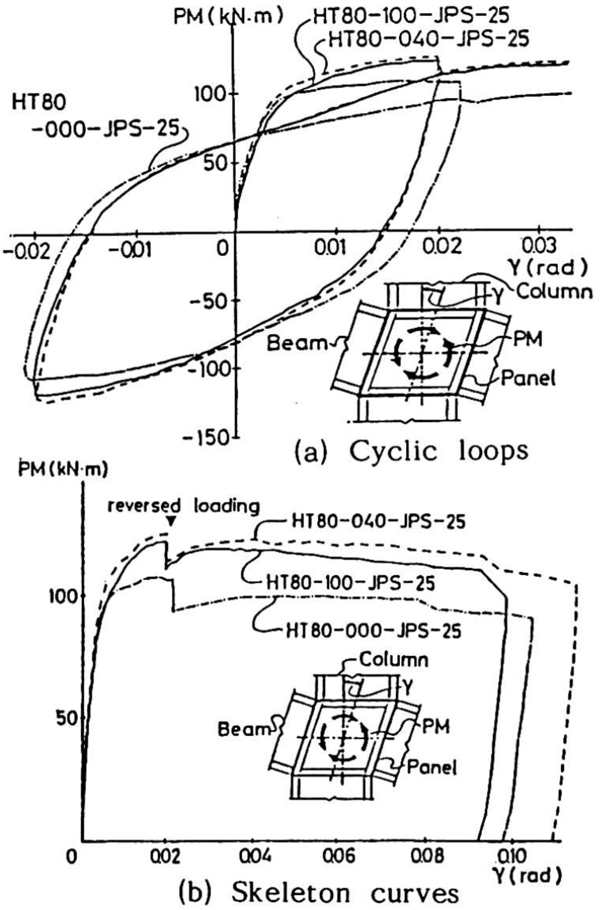


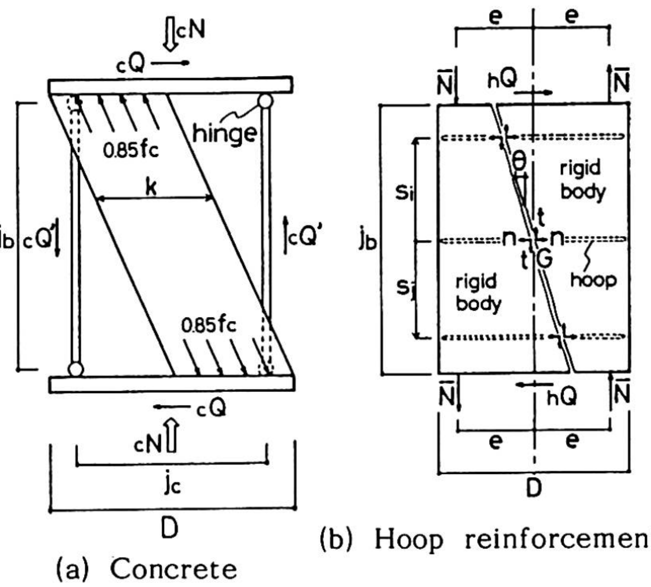
Fig 10. Forces around Joint Panel



(a) Cyclic loops

(b) Skeleton curves

Fig 11. Panel Moment-Shear Deformation Angle Relation of JPS Specimens



(a) Concrete

(b) Hoop reinforcement

Fig 12. Assumed Shear Resistant Mechanism

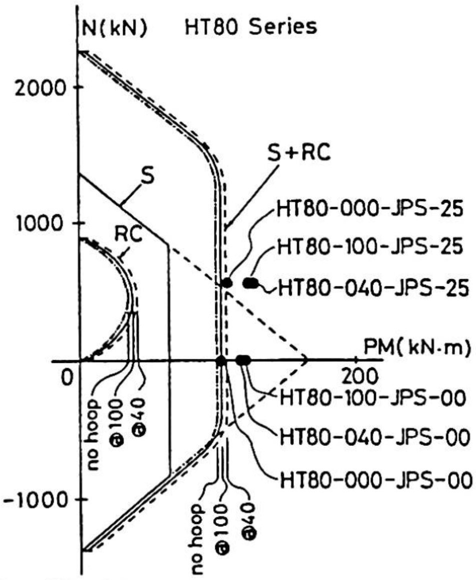


Fig 13. N-PM Interaction Curves

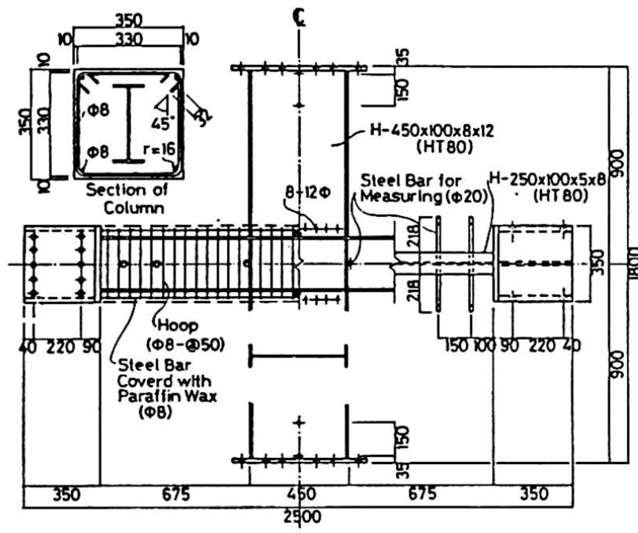


Fig 14. Dimensions of Interaction Specimens

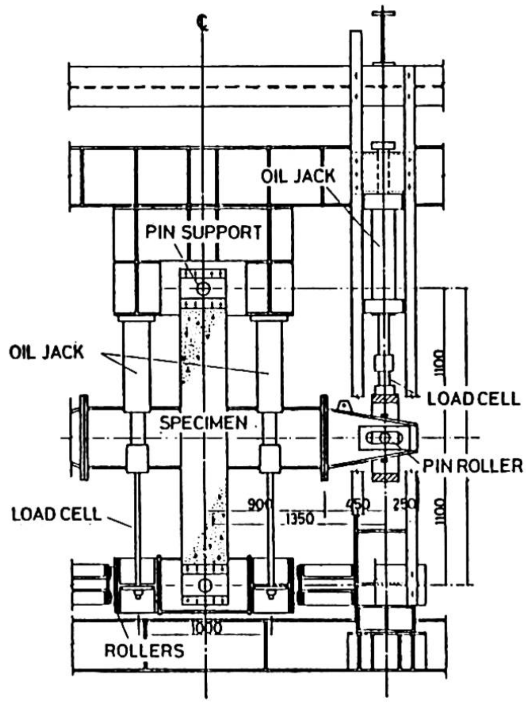
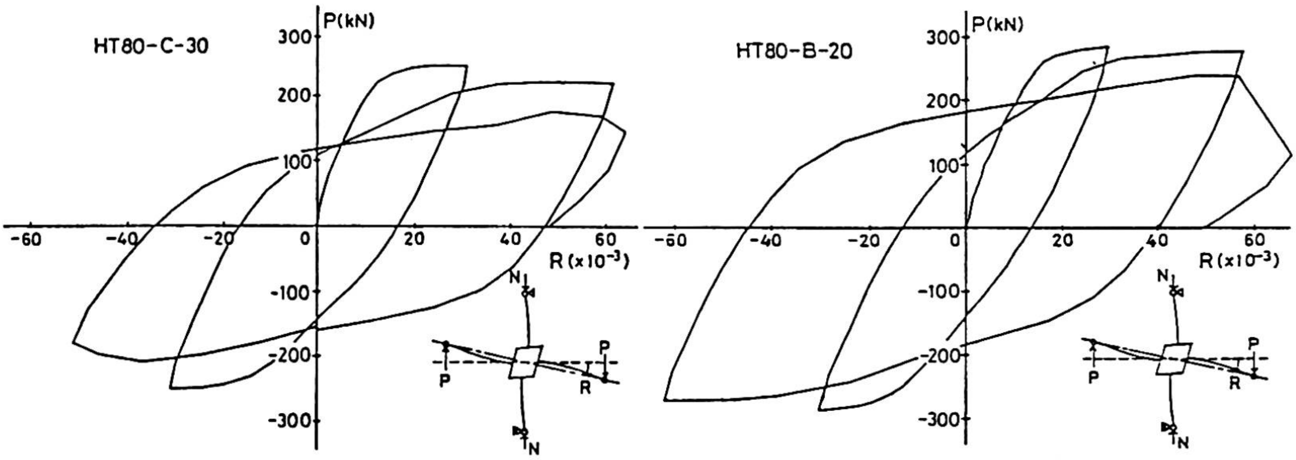


Fig 15. Interaction Test Setup



(a) HT80-C-30

(b) HT80-B-20

Fig 16. Beam End Force - Deflection Angle Relations

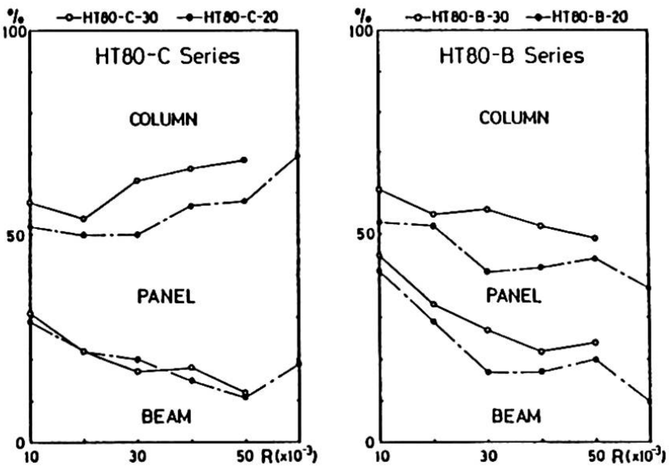


Fig 17. Component of Delection Angle

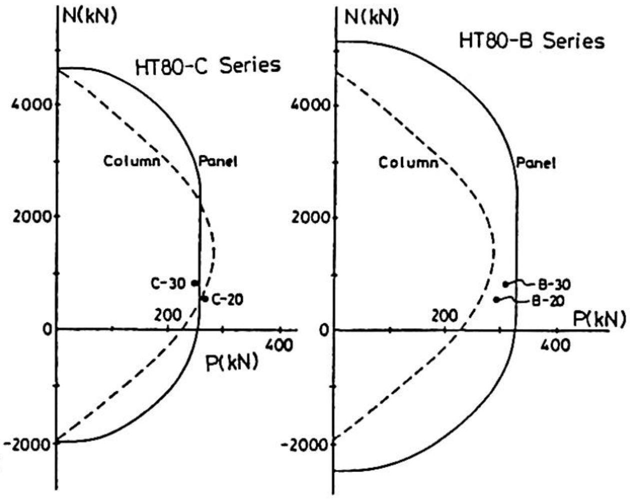


Fig 18. N-P Interaction Curves

The 'HT80' steel was used both in the column and in the beam. The web reinforcement ratio in the column and in the joint of all the specimen was uniformly 0.57%. The compressive strength of the concrete was from 25.5 to 26.8MPa. Loading and measuring system is shown in Fig 15.

Test results of the specimens HT80-C-30 and HT80-B-20 are shown in Fig 16. The P-R curves of all the specimens were spindle-shaped. The tensile fracture of the flange was observed at the critical section of the column of all the specimens at R=50-60x10^{-3}rad of the final loading cycle. The column axial force N vs. the beam end force P interaction curves to be carried by the column or the joint were calculated by the addition theorem, and were shown in Fig 17, together with the observed strength. The observed strengths agreed with the calculated values. The contribution ratios to the beam-end deflection by the deformation of the columns, the joint panel, and the beams are shown in Fig 18. The HT80-C series and the HT80-B series specimens may be regarded as the joint collapse and the column collapse type, respectively. However, there existed an interaction between the collapse of the column and the joint; the yielding of the steel web and the hoop reinforcement was observed in the joint of all the specimens, including the HT80-B series.

6. CONCLUSIONS

(a) The proposed SRC system, [H-shaped high strength (784MPa or 80kgf/mm^2) steel] - [concrete] - [hoop reinforcement] composite has a large energy dissipating capacity as well as a large deformation capacity.
(b) Flexural cracks concentrate at the critical sections in the proposed SRC members subjected to bending-shear. Flexural-shear cracks do not occur. Concrete is liberated from the truss action in the proposed SRC.
(c) One defect of the proposed SRC member subjected to bending-shear is that the tensile fracture of the steel flange is more liable to occur than that of normal strength steel. This is attributable to the inelastic strain concentration, and shall be surmounted by some devices such as tapering of the steel flange.
(d) Hoop reinforcement improves the compressive behavior of concrete and protects the H-shaped steel from the local buckling.
(e) Hoop reinforcement contributes to the ductility as well as the strengths of the proposed SRC members and beam-column joint with high strength steel.
(f) The flexural strength of the column and the shear strength of the beam-column joint can be roughly estimated by the addition theorem.

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