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STRENGTH AND DUCTILITY OF STEEL BEAM-RC COLUMN JOINT

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SUMMARY

A new type of frame structure composed of steel beams and reinforced concrete columns is proposed. The concrete in the beam-column joint is confined by thin steel plates named "cover plates". Strength and ductility of the frame, in particular the behavior of the beam-column joint, are investigated experimentally. It is proved that the proposed frame and its joints are safe against seismic loads. It is also proved that the cover plates increase the strength and stiffness of the frame. A simple design method for the beam-column joint is presented.

INTRODUCTION

This new structural system differs from conventional reinforced concrete and steel structures. It is unique in its combination of different materials (i.e. reinforced concrete columns and steel beams) and its rigid beam-column connections. Reinforced concrete columns have excellent axial capacity and steel beams have excellent strength and ductility against bending and shear loads. Therefore it is reasonable to construct a building using reinforced concrete columns and steel beams. However, it has been considered rather difficult to perform a rigid connection between members of different materials. We have developed a simple way to perform the rigid connection of a steel beam and a reinforced concrete column. (Refs. 1,2) Some buildings were constructed economically and in a short construction period with this new structural system.

Outline of Structural System Fig.1 illustrates the details of the joint. The reinforcing bars with screws, except the bars located at the corner of the column,run through both the upper and lower flanges of the steel beam and are tightened using nuts. Shear key bars are also tightened to the steel beam in the center of the joint. The reinforcing bars of the column are surrounded by spiral hoops, and they are assembled in factory together with the beam brackets. This assemblage is carried to the construction site and erected by crane. (See Photo 1) This assembly procedure shortens the construction period, because no reinforcing work is required at the site. The concrete in the beam-column joint is surrounded and tightly confined by thin steel plates named "cover plates". Due to the confinement of the concrete in the joint, the strength and stiffness of the frame increase substantially. In addition, the cover plates also act as concrete forms, thus reducing the manpower for forming columns at the site.

Test

Buildings in which the new proposed frames are to be used are assumed to be 3 to 6 stories with bays of about 8m span. The beam-column assemblages were tested for strength and ductility of the frames under seismic loading. The effects of the cover plates on the behavior of the joint was also studied.

Test Specimens Three test specimens of the interior column-beam assemblage, all in actual size, were prepared. Fig.2 shows one of the specimens. The cover plate is made by back-bending of checker-plates. The thickness of the cover plates is 3mm for the specimen No.2 and 6mm for the specimen No.3. Specimen No.1 has no cover plates. The cross section of the column is 650mm×650mm. Reinforcement of the column consists of twelve D32 (32mm diameter) bars with screws. The spiral hoops are D13 (13mm diameter) bars at 100mm spacing. Four shear key bars, D32, run through the upper and lower flanges of the beam and extend 300mm on each side. The section of the beam is H-594×302×14×23. The concrete slab is cast onto the beam, producing a composite beam system with stud connectors. Material properties are given in Table 1.

Test Setup and Instrumentation The test specimen was mounted on a special testing machine. The inflection points of the column were fixed with pins and rollers. An axial load of 285 tons was applied at the top of the column. Alternating loads were applied to the inflection points of the beam in order to deform the left and right beam portions asymmetrically. The rotation (R) is defined as the relative change in angle between a straight line connecting the beam inflection points and a straight line connecting the column inflection points, as shown in the sketch in Fig.3. Strain gages were mounted on the beam web within the connection (joint web) and the cover plates. The shear forces in the joint web and cover plates were calculated based on the values of strain provided by these strain gages.

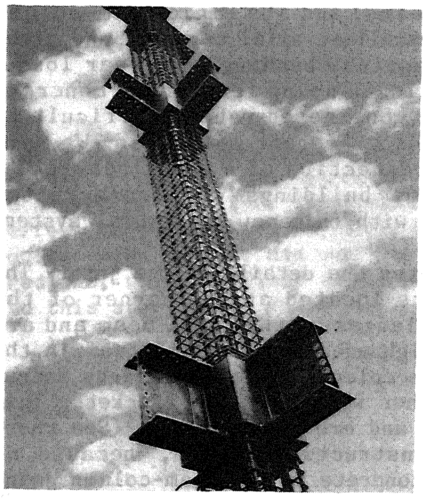


Photo 1 Bars of the Column with Beam Brackets

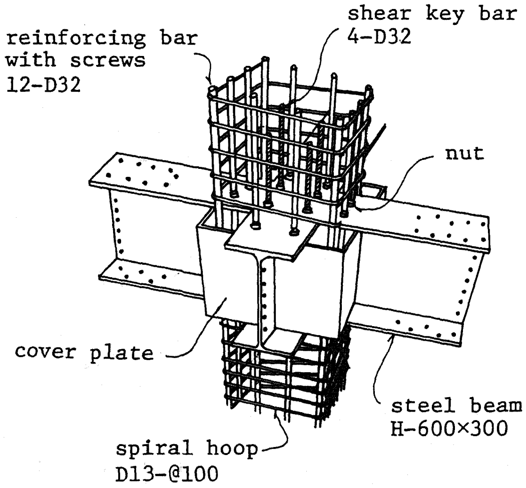


Fig. 1 Details of Joint

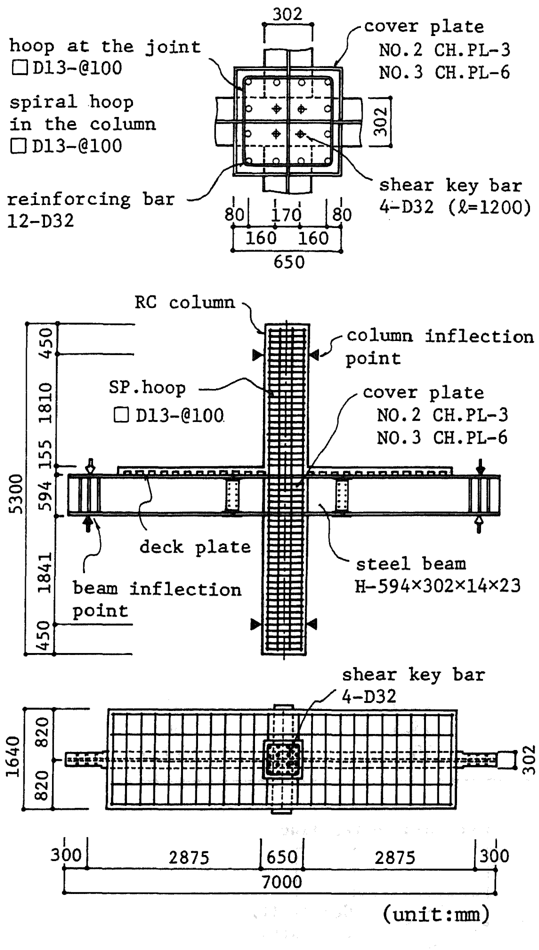


Fig. 2 Test Specimen

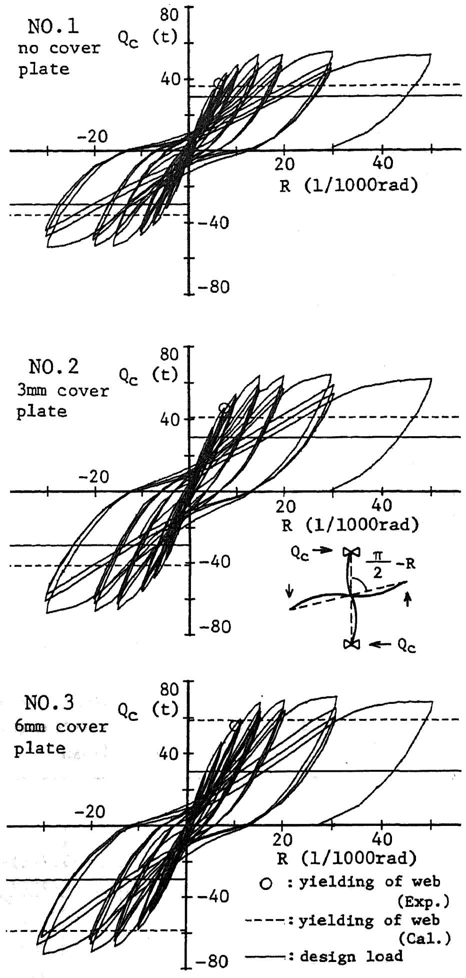


Fig. 3 Column Shear Force versus Rotation

Table 1 Material Properties of Specimen

Member		Thickness or Diameter mm	Yield Strength kgf/mm^2	Young's Modulus $\times 10^3$kgf/mm^2
Beam Flange	No.1,2	22.2	38.7	21.6
	No.3	23.1	39.8	20.6
Beam Web	No.1,2	13.8	42.5	21.3
	No.3	14.1	44.8	20.0
Reinforcement	No.1,2	32	40.4	19.6
	No.3	32	39.4	19.3
Cover Plate	No.2	3.0	16.5	20.6
	No.3	6.1	26.2	18.9
Member		**Compressive Strength kgf/cm^2**	**Tensle Strength kgf/cm^2**	**Young's Modulus $\times 10^5$kgf/cm^2**
Concrete	No.1,2	244	23.7	1.91
	No.3	259	22.0	2.34

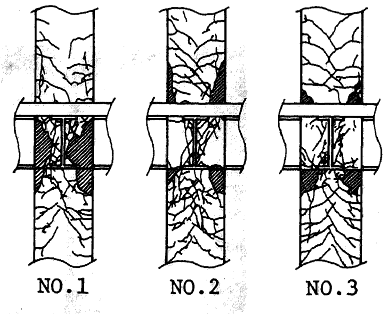


Fig. 4 Crack Pattern at Final Stage

Test Results The test results are listed in Table 2. The relations between the column shear force (Qc) and the rotation (R) are shown in Fig.3. The design load of the structure in which this new system will be used is also shown in this figure. The crack patterns at the final stage, are shown in Fig.4. From these figures and the table the following points can be deduced:

(1) In all specimens, the yielding of the joint web occurred first. The column shear force at which the joint web yielded exceeded the design load. The ultimate load occurred after the yielding of the column reinforcement.

(2) Hysteresis loops are of an inverse S-shape peculiar to the bending fracture of the reinforced concrete columns, but enough toughness remains even after yielding. At the final deformation, R≒1/20 radians, the strength exceeded the yield load.

(3) The stiffness and capacity of the assemblage increase as the thickness of the cover plates is increased. This indicates that the cover plates are effective in increasing the stiffness and capacity of the frame built with this system.

(4) In the specimens No.2 and No.3, there were few cracks in the concrete of the joint, because the joint concrete was confined by the cover plates. On the other hand, in case of the specimen No.1 which had no cover plates, the concrete cover of the joint spalled off and the damage to the joint was considerable. (See Photo 2)

Table 2 Test Results (Column Shear Force: tons)

Test Specimen	No.1	No.2	No.3
Yielding of Joint Web	37.4	46.2	55.4
Yielding of Reinforcement	53.5	64.5	66.1
Ultimate load	55.1	64.8	71.4

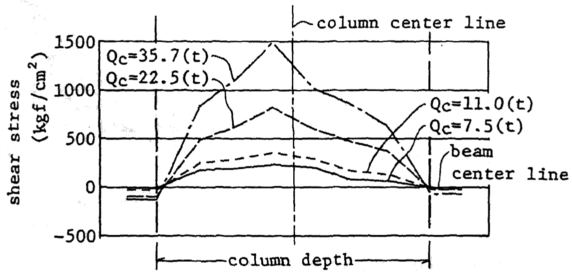
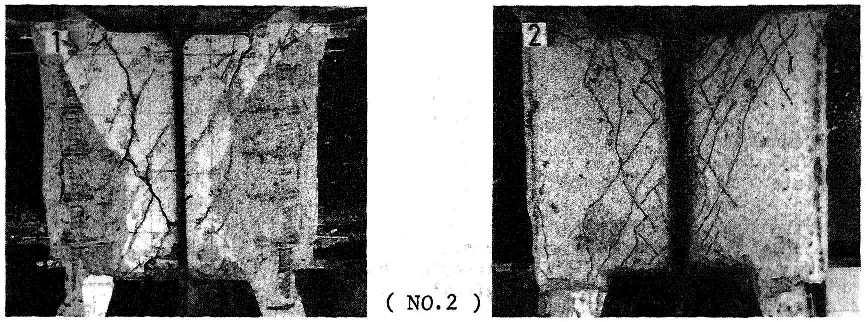


Fig. 5 Shear Stress Distribution in Joint Web



(NO.1) (NO.2)

Photo 2 Damage to Joint at Final Stage

DESIGN PROCEDURE

Fig.5 shows an example of shear stress distributions in the joint web obtained by measurements with rosette strain gages. This figure indicates that the shear stress in the joint web is not distributed uniformly. The maximum stress occurs at the point near the center of the joint. Therefore, yielding of the joint web occurs first at its center and spreads to the region near the column face. In designing the frame of this system, it is important to evaluate the shear load when the joint web will yield, because the yielding of the connection begins with that of the joint web. The joint web should be designed to be prevented from yielding under the seismic loads. A simple method to calculate the yield strength of the joint is proposed in this section.

The shear force acting on the column side of the joint can be modeled as shown in Fig.6 and expressed as (Refs.3,4):

$$ {}_{p}Q_c = \frac{M_{bl} + M_{br}}{j_b} - Q_c \qquad (1)$$

where M_{bl} and M_{br} are beam moments, Q_c is column shear force and j_b is the distance between beam flange centroids. The shear force ${}_{p}Q_c$ can be resolved into three shear forces, namely, the shear force in the joint web (${}_{w}Q_c$), the shear force in the cover plate (${}_{f}Q_c$), and the shear force in the joint concrete (${}_{c}Q_c$). The shear force ${}_{p}Q_c$ can be expressed as:

$$ {}_{p}Q_c = {}_{w}Q_c + 2\,{}_{f}Q_c + {}_{c}Q_c \qquad (2)$$

Accordingly, the yield strength of the joint can be found by summing the yield shear force of the joint web with the additional shear forces carried by the cover plates and the joint concrete. The yield shear force of the joint web can be calculated as:

$$ {}_{w}Q_c = \frac{\sigma_y}{\kappa\sqrt{3}}\, j_c \cdot t_w \qquad (3)$$

where σ_y is the yield strength of the joint web, j_c is the length of the joint on the side of the column, and t_w is the thickness of the joint web. Here, j_c is taken as the distance between the reinforcing bars of the column. κ is the ratio of the maximum stress to the average stress in the joint web, as shown in Fig.7. From test results κ can be assumed to be 1.6. The additional shear force carried by one cover plate and the joint concrete are expressed as:

$$ {}_{f}Q_c = k_f \frac{G_f \cdot t_f}{G_w \cdot t_w}\, {}_{w}Q_c \quad , \qquad {}_{c}Q_c = k_c \frac{G_c \cdot b_c}{G_w \cdot t_w}\, {}_{w}Q_c \qquad (4)$$

where G_w, G_f and G_c are the elastic shear moduli of the joint web, cover plate and the joint concrete respectively, and t_f is the thickness of the cover plate, and b_c is the width of the joint concrete. The coefficients k_f and k_c determine the effective thickness of the cover plate and the effective width of the joint concrete, respectively. The values of the coefficients k_f and k_c depend on the details of the joint. The variations of these coefficients are shown in Fig.8. It can be seen that the coefficient k_f is constant at about 0.8 for the specimen No.2 and 0.7 for the specimen No.3. The coefficient k_c decreases as the joint shear force increases. The value of k_c, when the joint web is yielded, is assumed to be 0.25 for all specimens.

The values of the shear forces at yielding of the joint web are calculated by the above equations and coefficients. The results are 35.9 tons for No.1, 41.2 tons for No.2 and 58.4 tons for No.3. These calculated values are close to the test results shown in table 2.

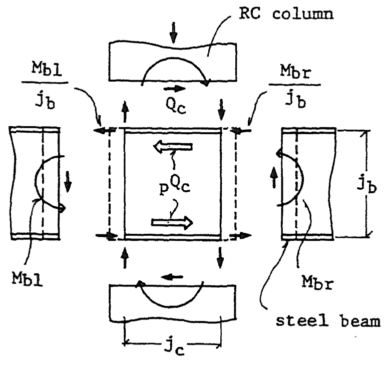


Fig. 6 Shear Force Acting on Column Side of Joint

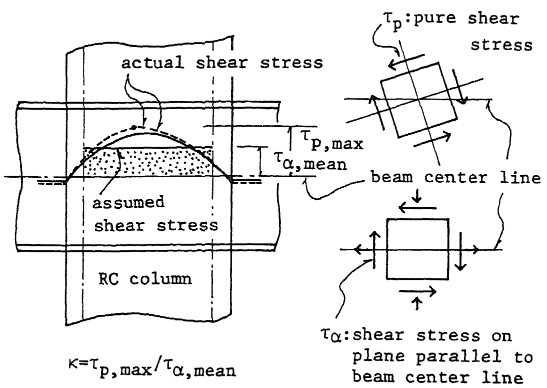


Fig. 7 Definition of Coefficient κ

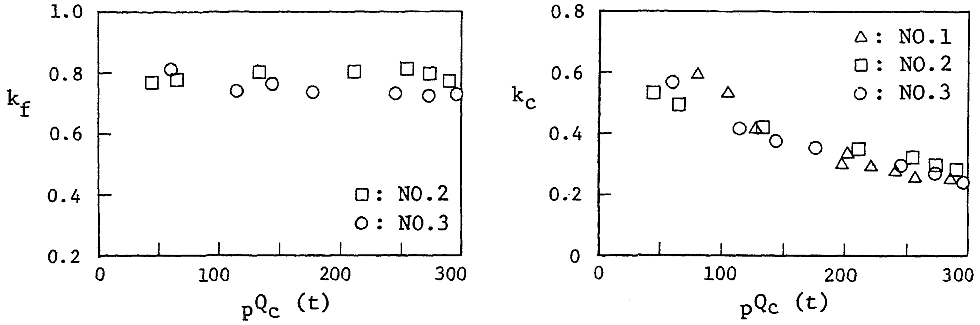


Fig. 8 Coefficient k_f,k_c versus Joint Shear Force ${}_pQ_c$

CONCLUSIONS

This new structural system is composed of members made of different materials, i.e. reinforced concrete columns and steel beams. The conclusions obtained from this study are as follows:

(1) Structures built with this new system are sufficiently safe against seismic loads.

(2) The cover plates increase the stiffness, strength and ductility of the beam-column joint.

(3) The yield strength of the joint can be calculated by assuming that the cover plates and some portions of the concrete effectively carry a fraction of the total shear force.

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