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Seismic Behavior of Steel Beam-to-Column Connection

Comportement sismique d'assemblages poutres-colonnes

Seismisches Verhalten von Stützen-Träger Anschlüssen

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SUMMARY

Tests on the seismic behavior of beam-to-column connections composed of H-shaped column and composite beams are reported. Methods to evaluate strength, ductility and energy absorption are presented, which utilize an enlargement model of the panel region due to the reinforcing effect of concrete slab and empirical formulas derived from test results of beam-to-column connections composed of normal steel beams. A model to evaluate restoring force characteristics of beam-to-column connections under repeated loading is also proposed.

RÉSUMÉ

Des essais du comportement sismique d'assemblages poutres-colonnes composés d'une poutre mixte et d'une colonne en H sont rapportées. Des méthodes d'évaluation de la résistance, de la ductilité et de la capacité d'absorption d'énergie en sont tirés; ces méthodes utilisent un modèle de panneaux – renforcés par l'effet de la dalle de béton – dérivé de celui utilisé pour ces mêmes assemblages, mais pour des structures métalliques pures. Un modèle de comportement de ces assemblages sous charges répétitives est donné.

ZUSAMMENFASSUNG

Tests über das seismische Verhalten von Stützen-Träger Anschlüssen, bestehend aus H-Profil Stütze und Verbundträger werden dargestellt. Methoden zur Bewertung der Festigkeit, der Dehnbarkeit und des Energieaufnahmevermögens werden vorgestellt, die sich im Plattenbereich ein Modell zunutze machen, welches aus der armierenden Wirkung der Betonplatte und aus empirischen Formeln, hergeleitet aus Testresultaten von Stützen-Träger Anschlüssen mit reinen Stahlträgern, basiert. Ein Modell zur Ermittlung der Umlagerungskräftecharakteristiken von Stützen-Träger Anschlüssen unter zyklischer Belastung wird ebenfalls vorgeschlagen.

1. INTRODUCTION

In the present design of steel buildings, reinforced concrete slabs with steel deck-plate are commonly used and usually connected to steel beams using shear-connectors to combine parallel frames under seismic loading. Hence, it is necessary to treat the beams as composite beams in the evaluation process of restoring force characteristics of beam-to-column connections as well as beams themselves. However, recent researches on the beam-to-column connections deal with those composed of bare steel beams and no paper has reported on the influence of the reinforced concrete slab of composite beams on the strength and the deformation capacity of steel beam-to-column connections subjected to seismic loading.

As this problem is very important in the seismic design of steel buildings, study on the behavior of steel beam-to-column connections was executed through experiments of 11 specimens of frame subassemblage composed of H-shaped column subjected to strong axis bending and composite beams.

2. OUTLINE OF EXPERIMENTS

2.1 Frame Subassemblage

Specimens designed represent a model of frame subassemblage around inner column subjected to strong axis bending. Configuration of specimens is shown in figure 1. Cross-sections of beams and columns are listed in table 1. The values of relative yield strength of panel-zone to those of adjoining members,"cRpy" and "sRpy", are also shown in table 1. Those are considered to be the key parameter on the evaluations of strength, deformation capacity and energy absorption of beam-to-column connections and are named as "panel yield ratio". Series of specimens are named as (ZO, AO, BO, B'O, CO, DO) in descending order of panel yield ratio. Mechanical properties of steel plates are shown in table 2.

Table 1 Test Specimens

Specimen	Column	Beam	Slab type	Material group	$_cR_{py}$	$_sR_{py}$	
ZO-I	H-300x300x22x22	H-350x175x9x12	I	2	1.13	0.80	m
AO-I	H-300x300x16x16	H-350x175x9x12	I	1	0.63	0.62	m
BO-I	H-300x305x16x16	H-450x200x9x16	I	3	0.52	0.47	m
BO-IV	ditto	ditto	IV	3	0.57	0.47	m
B'O-I	H-250x250x12x16	H-350x175x9x12	I	2	0.56	0.40	c
B'O-III	ditto	ditto	III	2	0.56	0.40	c
B'1-I	ditto	ditto	I	2	0.49	0.80	m
CO-I	H-250x250x 9x16	H-350x175x9x12	I	1	0.33	0.33	c
CO-IIW	ditto	ditto	IIW	1	0.51	0.33	c
CO-IIS	ditto	ditto	IIS	1	0.28	0.33	c
DO-I	H-234x234x 6x12	H-339x170x6x12	I	3	0.25	0.25	c

2.2 Reinforced Concrete Slab with Steel Deck-plate

Five types of reinforced concrete slab with steel deck-plate are planned as shown in figures 2a-e. In the cases of type-I, type-III and type-IV, deformed

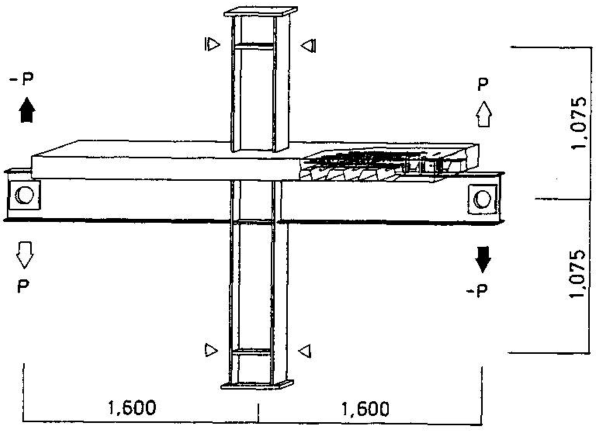


Fig.1 Configuration of Specimen

Table 2 Mechanical Properties of Materials

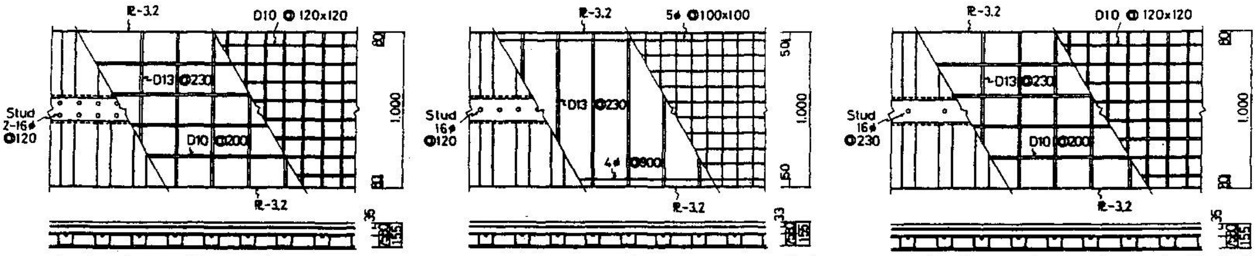
Group	thickness	σ_y MPa	σ_B MPa	ε_{st} (%)	elong. (%)	E_{st} MPa
1	9	401.	547.	1.95	22.1	3730.
	12	366.	524.	1.81	20.4	4350.
	16	348.	505.	1.99	23.0	4350.
2	9	366.	528.	2.28	22.7	4220.
	12	351.	529.	2.03	23.8	4890.
	16	329.	518.	1.56	26.0	4290.
	22	321.	517.	1.38	28.1	4970.
3	6	433.	528.	2.34	19.6	3460.
	9	434.	554.	2.59	22.2	3980.
	12	379.	513.	2.27	26.4	3580.
	16	354.	503.	2.07	28.4	4080.

bars (D10) are arranged at intervals of 200 millimeters in parallel with steel beam and deformed bars (D13) are arranged at intervals of 230 millimeters in each groove of deck-plate in the perpendicular direction to beam. Welded wire fabrics (D10) are arranged at 35 millimeters below surface to prevent surface cracks of concrete. In the case of type-II, reinforcing bars (ϕ4) are arranged at intervals of 900 millimeters in the perpendicular direction to grooves of deck-plate and deformed bars (D13) are arranged in each groove of deck-plate. Welded wire fabrics (ϕ5) are arranged at 35 millimeters below surface. Type-IIS has the same reinforcement with type-II, however, grooves of deck-plate were set in parallel with steel beam. In the case of type-I and type-IV, stud-connectors are disposed in double rows to beam flange at intervals of 120 millimeters to satisfy the condition of "fully composite beam". In the case of type-II, stud-connectors are disposed in a row to beam flange at intervals of 120 millimeters to make "partially composite beam". In the case of type-III, stud-connectors are disposed in a row to beam flange at intervals of 230 millimeters.

Width of slab, 100 millimeters except for the case of type-IV, is nearly equal to the calculated effective width according to the "Design Standard for Concrete Structures" of the Architectural Institute of Japan.

The hollows surrounded by web and flanges of column are filled up with concrete and no diaphragm is set at the surface level of concrete slab. The influence of the reinforced concrete slab of composite beams on the local deformation of column flanges is to be observed.

Designed type of concrete is normal weight concrete of required strength 20.6 MPa and required slump 18 cm. Measured compressive strength were 23.0 MPa (used for A0-I, C0-I, C0-II and C0-IIS) , 24.5 MPa (used for Z0-I, B'0-I, B'0-III and B'1-I) and 27.6 MPa (used for B0-I, B0-IV and D0-I).

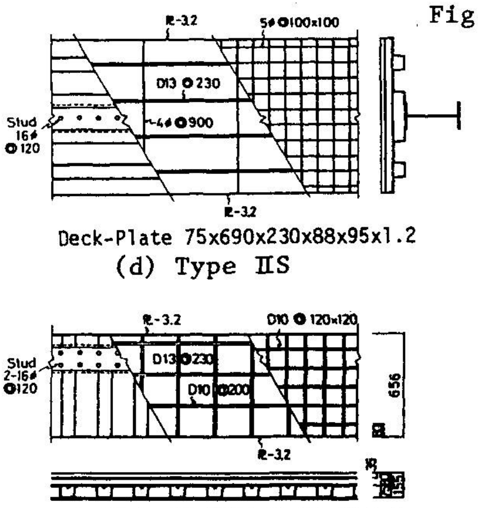


Deck-Plate 75x690x230x88x95x1.2
(a) Type I

Deck-Plate 75x690x230x88x95x1.2
(b) Type IIW

Deck-Plate 75x690x230x88x95x1.2
(c) Type III

Fig.2 Details of Concrete Slab



Deck-Plate 75x690x230x88x95x1.2
(d) Type IIS

Deck-Plate 75x690x230x88x95x1.2
(e) Type IV

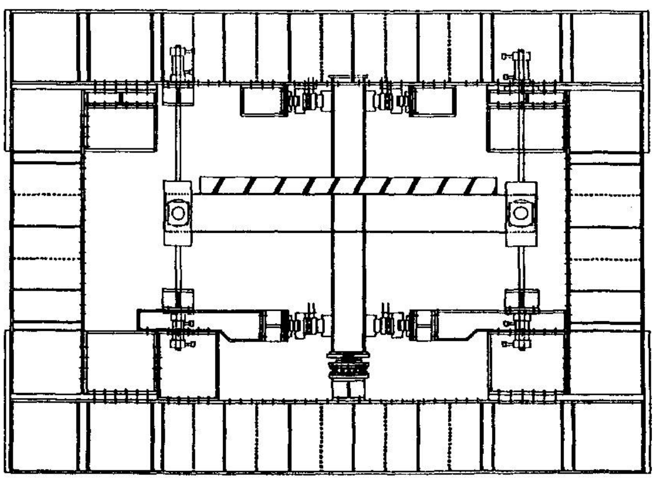


Fig.3 Loading Apparatus

2.3 Loading

Loads to simulate horizontal loading on frame are applied to beam ends in the opposite directions as shown in figure 1 in a loading apparatus shown in figure 3. Applied loads are monotonic for some specimens (marked "m" in table 1) and cyclic for the others (marked "c" in table 1).

3. RESTORING FORCE CHARACTERISTICS

3.1 Frame Subassemblage

Figure 4 illustrates relations between load and deflection of standard specimens. Vertical axis represents the ratio of load to calculated yield strength of column or steel beam whichever is smaller, while horizontal axis represents the ratio of deformation to calculated yield deformation at the yielding of column or steel beam whichever is smaller. Ultimate strength of frame subassemblage is larger than Ppm when sRpy is larger than 0.62.

Relations between deformation capacity of frame subassemblage and panel yield ratio of bare steel beam-to-column connection (sRpy) when shear deformation of panel-zone became twenty times the yield shear deformation are shown in figure 5 with test results of beam-to-column connections composed of bare steel beams [1]. The empirical formula in figure 5 is one derived from regression analysis on the test results of beam-to-column connections composed of bare steel beams. The results of beam-to-column connections with composite beams have resemblance to those of beam-to-column connections composed of bare steel beams. The deformation capacity of frame subassemblage can be estimated by the empirical formula in figure 5.

3.2 Beam-to-Column Connections

Monotonized restoring force characteristics of beam-to-column connections are shown in figures 6a-c. Vertical axis represents the ratio of load to calculated yield strength of beam-to-column connections composed of bare steel beams, while horizontal axis represents the ratio of shear deformation of panel-zone to calculated yield shear deformation. Dotted lines in figures 6a-e show the test results of beam-to-column connections of the same configuration with bare steel beams. The reinforcing effect of steel beam-to-column connections by the reinforced concrete slab of composite beam is illustrated.

A model to take the effect of concrete slab into consideration is proposed in figure 7. In this model, the strength of panel-zone is considered to increase by the enlargement of nominal volume of panel-zone ($V_{pc} \rightarrow V_{pc}'$) as shown in figure 7. Volumes of panel-zone are defined as

$$V_{pc} = d_b \cdot d_c \cdot t_p \qquad V_{pc}' = d_b' \cdot d_c \cdot t_p$$

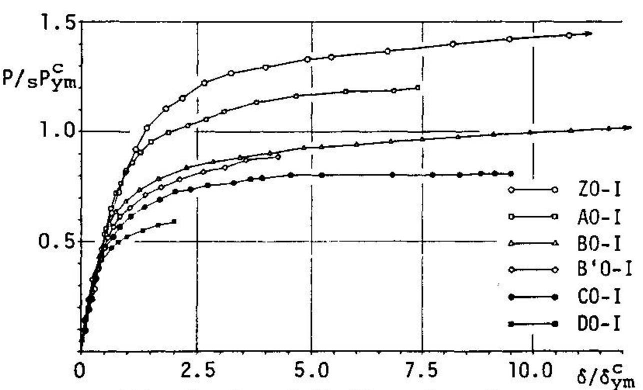


Fig.4 Load-Deflection Curves

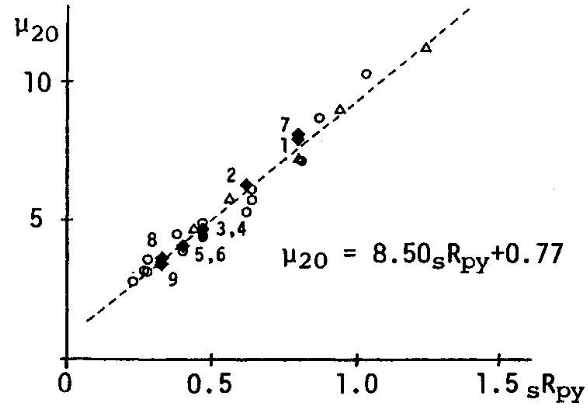
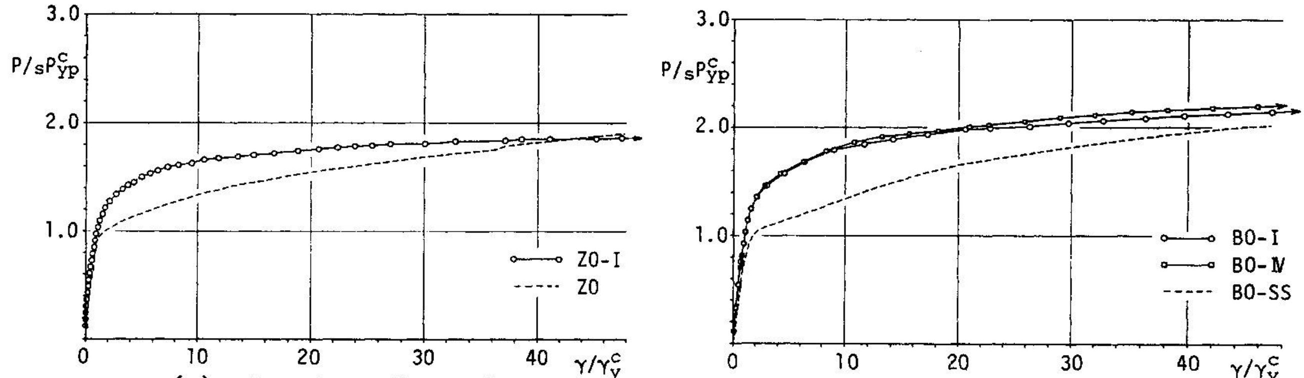


Fig.5 μ_{20} - sRpy Relation

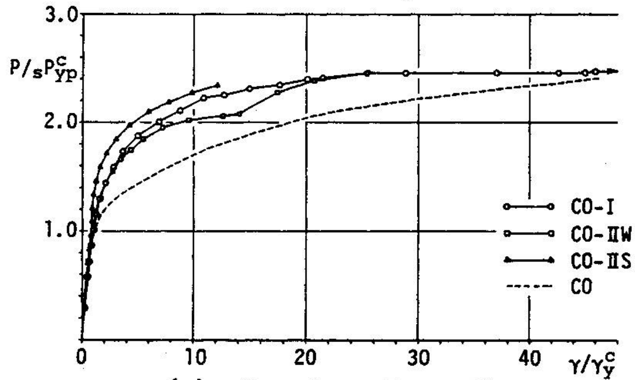
in which, d_b=beam depth, d_c= column depth, t_p = thickness of panel-zone, d_b' = distance between center of the distributed compressive stress and center of thickness of lower flange in composite beam.

Relations between ultimate strength of panel and panel yield ratio of bare steel beam-to-column connection (sRpy) are shown in figure 8. Relations between strength of panel-zone and panel yield ratio (sRpy) when shear deformation of panel-zone became twenty times the yield shear deformation are shown in figure 9. The other data shown in figures 8 and 9 are test results of beam-to-column connections composed of bare steel beams. The empirical formulas in figures 8 and 9 are those derived from regression analyses on the test results of beam-to-column connections composed of bare steel beams. Shiftings to the estimated



(a) Specimen Type ZO (b) Specimen Type BO

Fig.6 Monotonized Restoring Force Characteristics of Panel Compared with those of Steel Specimens



(c) Specimen Type CO

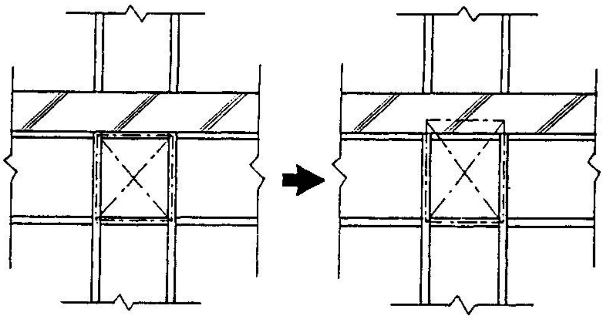


Fig.7 Enlargement of Panel Region

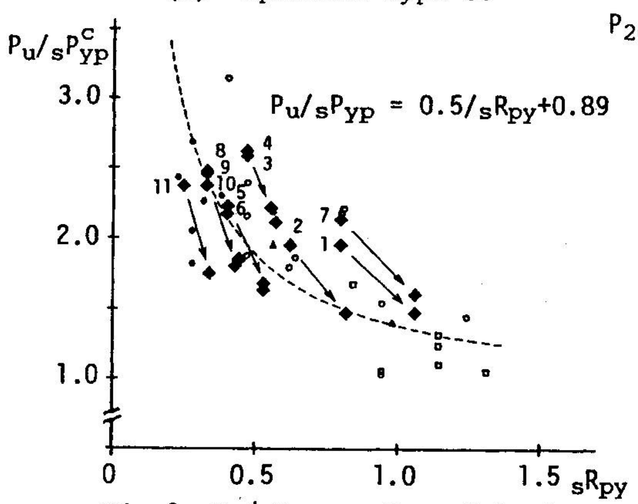


Fig.8 Pu/sPyp - sRpy Relation

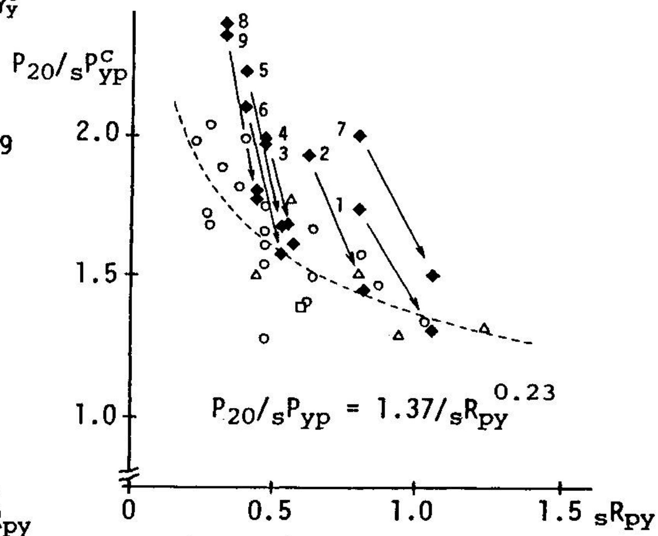


Fig.9 P20/sPyp - sRpy Relation

results of yield strength of enlarged panel-zone are indicated by arrows. The strength of panel-zone can be evaluated by making use of the enlargement model of panel-zone (figure 7) and empirical formula in figure 8 or 9.

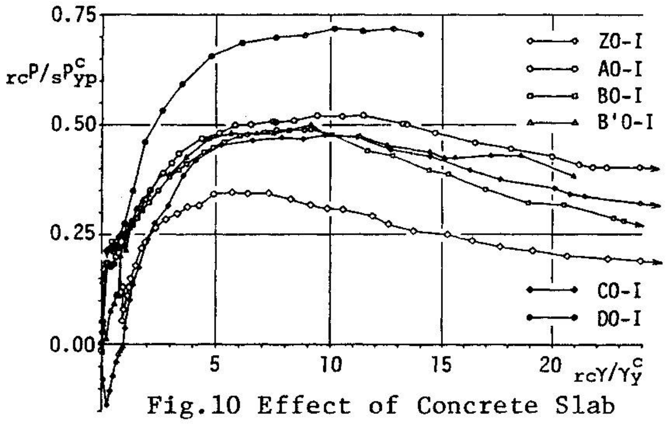


Fig.10 Effect of Concrete Slab

The differences between restoring force of beam-to-column connections with composite beams and that of beam-to-column connections composed of bare steel beams are plotted in figure 10, which can be regarded as the reinforcing effect of concrete slab of composite beam. Restoring force characteristics of each specimen due to the reinforcing effect by concrete slab has the same feature except for the following two cases: when the ultimate strength is larger than 1.3Pmy; when panel yield ratio is smaller than 0.25.

Restoring force characteristics of reinforcing effect by concrete slab tend as follows: rcP/sPyp is nearly equal 0.25 when shear deformation of panel-zone arrives at the yield value; rcP/sPyp is nearly equal 0.48 when shear deformation of panel-zone is between four times and eleven times the yield shear deformation; rcP/sPyp decreases after shear deformation of panel-zone exceeds eleven times the yield shear deformation.

A model to evaluate restoring force characteristics of beam-to-column connections with composite beams under repeated loading is proposed as follows.

1) Restoring force of beam-to-column connections with composite beams comprises two components: restoring force of beam-to-column connections composed of bare steel beams and column (steel part); reinforcing effect of beam-to-column connections by concrete slab (R.C. part).

2) Restoring force characteristics of steel part can be evaluated by the model proposed by NAKAO [2].

3) Skeleton restoring force model of R.C. part is shown in figure 11b. Parameters in figure 11b were determined from test results in figure 10 as follows.

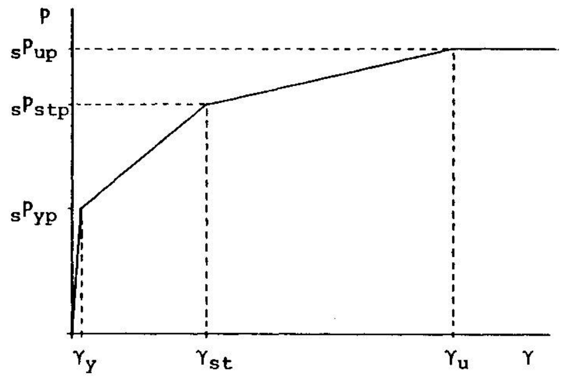
rcPy = 0.25sPyp , rcPu = minimum (0.48sPyp , 0.80 (Ppm-sPpy))

$_{rc}\gamma_1 = \gamma_{yp}$, $_{rc}\gamma_2 = 5\gamma_{yp}$, $_{rc}\gamma_3 = 11\gamma_{yp}$, $_{rc}\gamma_4 = 48.2\gamma_{yp}$

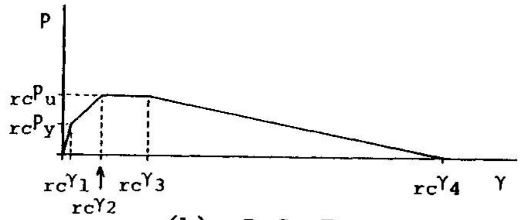
4) Restoring force of steel part under negative or positive loading is influenced by the preceding restoring force of R.C. part positive or negative respectively as illustrated in figure 11c. In this figure, a_i = maximum restoring force of R.C. part at loop i, b_i = the difference between skeleton restoring force shown in figure 11a and restoring force of steel part when shear deformation of panel-zone becomes maximum in loop i, Δ_i = drop of restoring force of steel part at loop i, i = number of loop odd for positive loading and even for negative loading.

5) Restoring force characteristics model of R.C. part under repeated loading is shown in figure 11d. In this figure, rc cr = shear deformation of panel-zone when crack due to bending moment appears at surface of concrete slab.

Samples of restoring force characteristics of beam-to-column connections with composite beams under repeated loading evaluated by the model mentioned above are illustrated and compared with test results in figures 12a,b. Estimated curves and test curves are in considerable coincidence.



(a) Steel Part



(b) R.C. Part

Fig.11 Restoring Force Characteristics Model

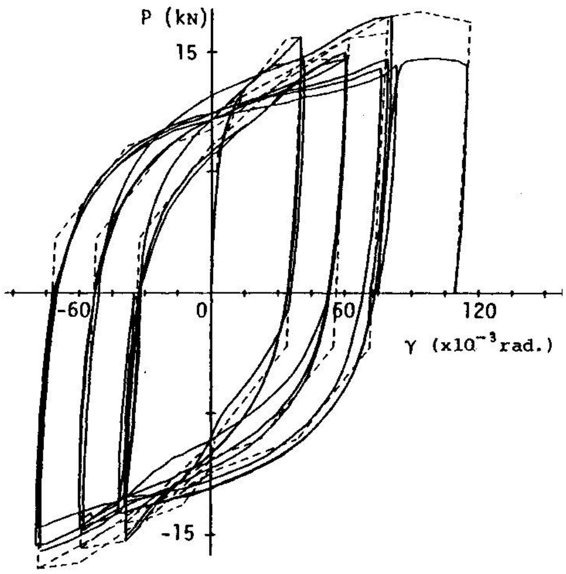
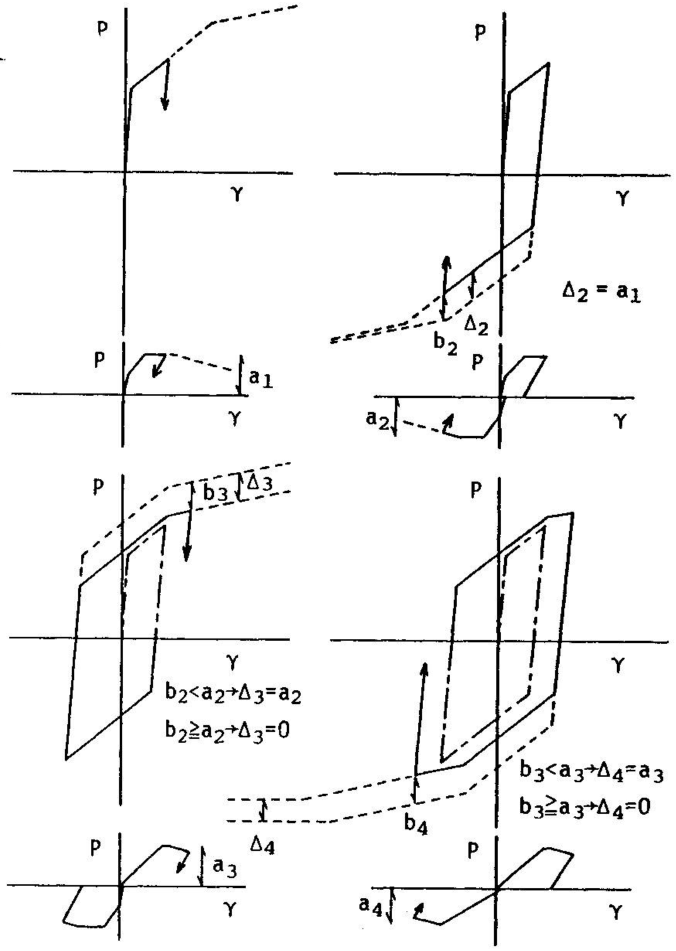
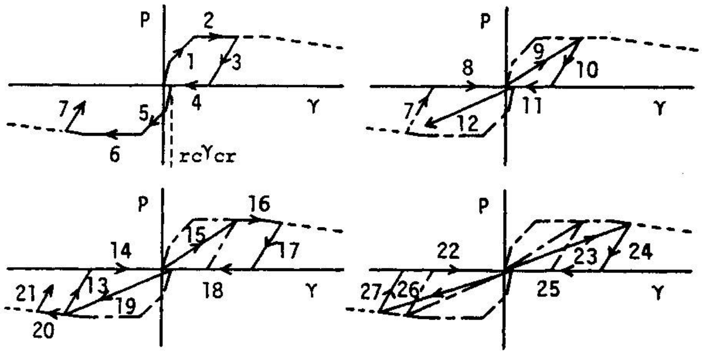


Fig.12a Evaluation of Hysteretic Loops Compared with Test Results (type C0)



(c) Steel Part in Negative or Positive Loading influenced by the Restoring Force of R.C. Part Positive or Negative respectively



(d) Slip Modeling of R.C. Part due to Crack

4. ENERGY ABSORPTION

Relation between energy absorption of frame subassemblage and panel yield ratio (sRpy) are plotted in figure 13 with test results of beam-to-column connections composed of bare steel beams. The empirical formula in figure 13 is one derived from regression analysis on the test results of beam-to-column connections composed of bare steel beams. Shiftings to the estimated results of panel yield

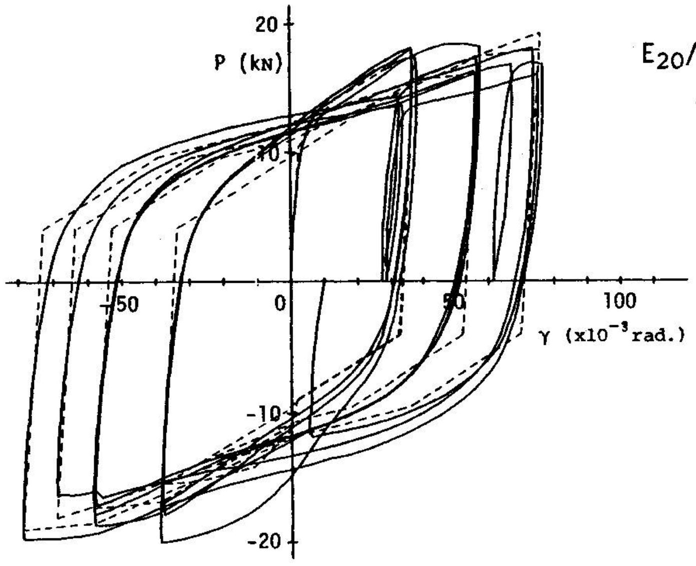


Fig.12b Evaluation of Hysteretic Loops Compared with Test Results (type B'0)

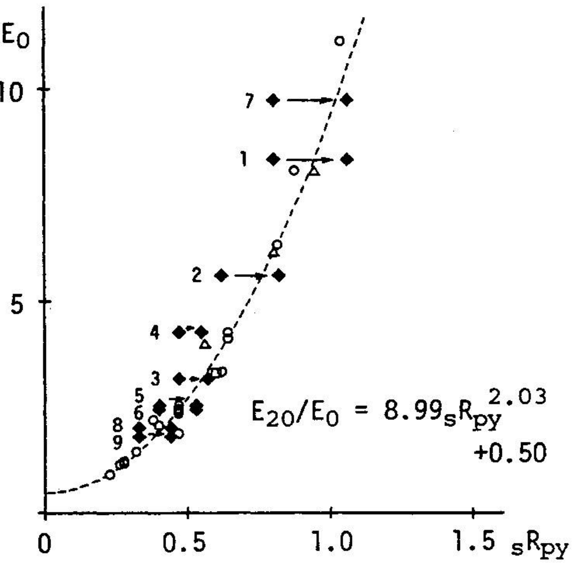


Fig.13 E_{20}/E_0 - sRpy Relation

ratio of enlarged panel-zone are indicated by arrows. The energy absorption of frame subassemblage can also be evaluated by the enlargement model of panel-zone and empirical formula in figure 13.

5. CONCLUSION

Through experiments of frame subassemblage composed of H-shaped column and composite beams, the followings are clarified on the seismic behavior of steel beam-to-column connections with composite beams.

1) Reinforcing effect by concrete slab of composite beams improve the restoring force of beam-to-column connections within the maximum practical shear deformation (i.e. twenty times the yield shear deformation).

2) Strength, deformation capacity and energy absorption can be estimated by making use of the model in figure 7 and empirical formulas in the figures 5,8 and 9.

3) Restoring force characteristics of beam-to-column connections under repeated loading can be evaluated by the model proposed through figures 11a-d.

4) No diaphragm will be required to prevent local deformation of column flange if the hollows surrounded by column web and flanges are filled with concrete.

SYMBOLS

cRpy = sPyp / Pym   sRpy = sPyp / sPym $\mu_{20} = \delta_{20} / \delta_{ym}$ E_0 = sPym·δ_{ym}

sPyp = Yield strength of panel-zone.

sPym = Yield strength of column or steel beam, whichever is smaller.

Pym = Yield strength of column or composite beam, whichever is smaller.

sPpm = Full plastic strength of column or steel beam, whichever is smaller.

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