STRENGTH AND HYSTERESIS CHARACTERISTICS OF STEEL-REINFORCED CONCRETE BEAM-COLUMNS WITH BASE

by

Takeo Naka[I)], Koji Morita[II)], Masahiko Tachibana[III)]

SUMMARY

This paper discusses the stress distribution of Steel-Reinforced Concrete (SRC) beam-columns and the mechanism of stress transmission from SRC beam-column to Reinforced Concrete (RC) foundation when the steel skeleton composing SRC beam-column is connected with RC foundation by anchor bolts at base. The flexural cracking strength, the shear cracking strength, and the maximum flexural strength at the base connection are discussed considering the flexural rigidity and strength of the connection of the steel skeleton and those of the added reinforcements.

I TEST SPECIMENS

The grade and mechanical properties of the used material are listed in Table 1. The details of the test specimens are shown in Fig.1 and Table 2. The types of the base connection of the steel skeleton (wide flange section) are classified as follows by the arrangement and material properties of the anchor bolts. [Type A]: Two anchor bolts of 19 mm ϕ (SS41) are arranged at the center of base plate (Fig.1 (a)). [Type B]: Four anchor bolts of 16 mm ϕ (F10T) are arranged inside the flanges of the steel skeleton (Fig.1 (b)). [Type C]: Four anchor bolts of 14 mm ϕ (F8T) are arranged outside of the flanges of steel skeleton (Fig.1 (c)).

In case of [Type A], seven specimens are schemed as follows by the methods of reinforcing the base connection, A1) Not reinforced (A R4 H100 N0, A R4 H100 N441), A2) Reinforced by two added reinforcements at base side which are extended at the mid-span of the beam-columns (A R6 H100 N441), A3) Reinforced by two added reinforcements and hoops at base side (A R6 H50 N100), A4) Reinforced by four added reinforcements at base side (A R8 H100 N0, A R8 H100 N441), and A5) Reinforced by four added reinforcements and hoops at base side (A R8 H50 N0, A R8 H50 N441)[1)]. Constant axial force N = 0 or 441 kN is introduced to the beam-column and reversal asymmetric bending moment and shearing force are loaded (Fig.1). The specimens are named as follows, for example, A R6 H50 N441 means the specimen whose type of the base connection is Type A (A), total numbers of main and added reinforcements at base side is six (R6), hoop pitch is 50 mm (H50), and whose constant axial force is 441 kN (N441).

II TEST RESULTS

The initial flexural cracking strength (eMcr) and shear cracking strength (eQcr) at both capital and base sides, and the maximum strength (eQm, eMm) are shown in Table 3. The typical hysteresis loops are shown in Fig.2 (a), and envelops of the hysteresis loops for Type A specimens are shown in Fig.2 (b). Their ordinate shows the working shearing force and abscissa shows the amount of deflection δ_B or δ_C and drift angle

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I) Professor Emeritus, University of Tokyo, Tokyo, Japan
II) Associate Professor, Chiba University, Chiba, Japan
III) Research Associate, Tokyo Denki University, Tokyo, Japan

$R_B = 2\cdot\delta_B/h$ or $Rc = 2\cdot\delta c/h$, where h means the inside height of beam-columns. The marks ▽ indicate the points when covering concrete at compression side was crushed, and ▼ express the points when the reinforcements were buckled. The initial rigidity at both capital and base sides is shown in Fig.3 for each specimen. And the typical examples of over-all view of the specimens after testing are shown in Fig.4.

III DISCUSSIONS

Treating anchor bolts beneath base plate, and added reinforcements as steel skeleton, their flexural rigidity (EI) and strength Mp are considered as follows.

[For Anchor Bolts]

Type A : $b(EI) = sE \cdot bA^2/8\pi$, $bMp = 2\sqrt{2}\, bA^{3/2} \cdot b\sigma y/3\sqrt{\pi}$

Type B, Type C : $b(EI) = sE \cdot bA \cdot bj^2/4$, $bMp = bA \cdot bj \cdot b\sigma y/2$

[For Added Reinforcements]

Type A : $a(EI) = sE \cdot aA \cdot aj^2/4$ $aMp = aA \cdot aj \cdot a\sigma y/2$

Where, prefix "b" is for anchor bolts, "a" is for added reinforcements, and "s" is for steel materials. And "A" means the total sectional area, "j" means distance between centers of tension and compression, and σy means yield strength of steel materials.

The ratios of b(EI) to s(EI),(b(EI) + a(EI))to s(EI), bMp to sMp, and(bMp + aMp)to sMp are listed in Table 2 for each specimen, where s(EI) and sMp mean flexural rigidity and full plastic moment of wide flange section (steel skeleton) respectively.

As shown in Fig.3, when BR = (b(EI) + a(EI))/s(EI) of the specimen is more than 1.0, the initial rigidity at base side coincides with that at capital side of beam-columns. And as shown in Fig.4, the specimens whose BM =(bMp + aMp)/sMp is less than 1.0 had been fractured at base side, but those whose BM is more than 1.0 had been fractured at both capital and base sides.

III-1 BENDING MOMENT VERSUS CURVATURE RELATIONSHIP AT EACH SECTION

The relations between bending moment (M) and the curvature of the wide flange section ($s\phi$) and reinforced concrete element ($r\phi$) at each section are shown in Fig.5. And Fig.6 shows the curvature distributions of the beam-columns. These curvatures are calculated from the strains measured by wire strain gauges at sections Ⓐ, Ⓑ, Ⓒ, Ⓓ, and Ⓔ shown in Fig.1. As strain values of the added reinforcements are almost the same with those of the main reinforcements, the average values of them are used to obtain the curvature $r\phi$.

Before the initiation of flexural cracking, $s\phi$ coincides with $r\phi$ irrespective of the b(EI)/s(EI)value. Thereafter they diverge at section Ⓐ remarkably for the specimens of Type A and Type B whose b(EI)/s(EI) are from 0.0 to 0.34, but they coincide comparatively well even at section Ⓐ for the specimen of Type C whose b(EI)/s(EI) is 1.04. The inflection points of $s\phi$ and $r\phi$ coincide approximately as shown in Fig.6. After the yielding of beam-columns, the curvature distribution of $s\phi$ has steep inclination only at capital side for the specimens of Type A whose bMp/sMp are 0.03, but it has steep inclination at both capital and base sides for the specimens of Type B and Type C whose bMp/sMp are from 1.37 to 1.81.

III-2 THE INITIAL FLEXURAL CRACKING STRENGTH

As the Navier's assumption consists before the initiation of flexural cracking, the initial flexural cracking strength at base side (cMcr) can be estimated from Eq.(1). As for the tensile strength of concrete material $0.75\sqrt{Fc}$ (N/mm^2) may be adopted from the statistical analysis on SRC beam-columns[2].

$$cMcr = (0.75\sqrt{Fc} + \sigma_0)Ze \qquad (N\text{-}mm) \cdots\cdots\cdots\cdots(1)$$

σ_0 means the average longitudinal compressive stress of SRC section above base plate. And as shown in Fig.7, Ze is smaller value of Ze(B) and Ze(b), where Ze(B) means effective section modulus of RC section beneath base plate considering the effect of reinforcements and anchor bolts (mm^2) (Fig.1(d)), and Ze(b) means that of SRC section above base plate. The estimated values coincide well with the experimental values as shown in Table 3.

III-3 THE INITIAL SHEAR CRACKING STRENGTH

The initial shear cracking strength at both capital and base sides (cQcr) can be estimated from Eq.(2). [2),4)]

$$cQcr = \frac{7}{8}\, b\cdot rd(1+\beta)\left(\frac{C_1 \cdot kc(49+Fc)}{M/Q\cdot rd + 1.7} + 0.1\sigma_0\right) \qquad (N) \cdots\cdots(2)$$

Where, b means width of beam-column (mm), rd means distance between centers of tension reinforcements and compressive edge of concrete (mm), kc means corrective coefficient from the sizes of RC sections (0.80), M/Q·rd means shear span ratio, and the values of C_1 and β are shown in Table 4. The estimated values coincide with the experimental values as shown in Table 3.

III-4 THE FLEXURAL MAXIMUM STRENGTH

The flexural maximum strength at base side of beam-column can be estimated as the smaller value of cMm(B) and cMm(b) as shown in Fig.8, and the estimated values coincide with the experimental values as shown in Table 3. Where cMm(B) and cMm(b) are calculated values by computing the moment-curvature relations of the RC sections beneath base plate and those of the SRC sections above base plate respectively as shown in Fig.9 based on the Navier's assumption. The stress-strain relationships used are elastic-perfectly plastic relation for steel material, and non-linear relation as shown in Fig.10 for concrete material.

The moment - curvature relations of RC sections and SRC sections are indicated in Fig.5 by the dot-dash-lines and the dotted lines respectively. M - rϕ relations at base side section Ⓐ for the specimens whose BM are less than 1.0 coincide with the dot-dash-lines, but M-rϕ and M-sϕ relations at both capital and base side sections Ⓐ, Ⓔ for the specimens whose BM are more than 1.0 coincide with the dotted line close to the maximum strength.

For designing the flexural maximum strength of the base side of SRC beam-columns to be the same with that of the capital side, it is sufficient to design BM of beam-columns to be more than 1.0 as shown in Fig.11.

III-5 THE SUPERPOSED STRENGTH METHOD ADOPTED IN AIJ STANDARD[3)]

The combined stress states of axial force and bending moment worked on the wide flange section computed from the measured strains at steel flanges are shown in Fig.12. The interaction curve between axial force and ultimate bending moment of the RC section whose size is that of base plate and whose main reinforcements are anchor bolts as shown in Fig.13 (a) is indicated by the dot-dash-line in Fig.12. And the interaction curve of the wide flange section is also indicated by the broken line. The dotted lines show the behaviour of the wide flange section at capital side of beam-columns which are obtained from the M-sϕ relationships based on the Navier's assumption.

The stress states of the wide flange sections at base side behave within the interaction curve of the RC section for the specimens whose bMp/sMp are less than 1.0, but they behave within that of the wide flange section for the specimens whose bMp/sMp are more than 1.0.

Therefore, the superposed flexural strength (cMsup.) at base side can be calculated from the summation of the flexural maximum strength of the RC section of base plate size (rM_B) and that of the RC section (rM) for the specimens whose aMp/sMp are less than 1.0 as shown in Fig.13(a), but for the specimens whose aMp/sMp are more than 1.0 it can be calculated from the summation of that of the wide flange section (sM) and that of the RC section (rM) as shown in Fig.13(b). cMsup. can estimates the flexural maximum strength (eMm) as shown in Table 3 and Fig.14.

REFERENCES

1) T.Naka, K.Morita, and M.Tachibana, "Strength and Hysteretic Characteristics of Steel-Reinforced Concrete Columns with Base" Transactions of the Architectural Institute of Japan, No.276, Feb. 1979

2) T.Naka, K.Morita, and M.Tachibana, "Strength and Hysteretic Characteristics of Steel-Reinforced Concrete Columns (Part II)" Transactions of the Architectural Institute of Japan, No.260, Oct. 1977

3) AIJ Standard for Structural Calculation of Steel-Reinforced Concrete Structures, Architectural Institute of Japan, 1975.

4) T.Arakawa, "Experimental Studies on Shear Strength of Reinforced Concrete Beams·Conclusions" Transactions of the Architectural Institute of Japan, No.66, Oct. 1960

5) K.Masuda, "Connections in Steel Reinforced Concrete Structures-Column Bases (Part 1) Tests on Column Bases under Combined Axial Compression, Bending and Shear" Transactions of the Architectural Institute of Japan, No.260, Oct. 1977

Table 1. Mechanical Properties of Materials

	Grade of steel	Yield Point (N/mm²)	Tensile Strength (N/mm²)	ε_{st} (%)	Elongation (%)	Specimen	Remarks
PL 18	SM50A	393 364	559 528	1.53 -	23.7 26.5	A B,C	Base Plate
PL 6	SM50A	361 338	523 485	1.55 1.90	22.3 22.2	A B,C	Wide Flange
PL 4.5	SM50A	397	513	1.75	20.9	A	Section
D 13	SD35	464 399	688 588	1.50 -	13.1 16.9	A B,C	Reinforcements (Defoumed Bar)
9 φ	SR30	332 346	463 468	2.29 -	26.3 22.1	A B,C	Hoop (Round Bar)
M 19	SS41	299	433	2.03	26.7	A	Anchor Bolts (Round Bar)
M 14	F8T	892	1,023	-	-	B	
M 16	F10T	1,039	1,094	-	-	C	

Concrete (Grade)	Mixing Propotion by Weight			Water-Cement ratio (%)	Slump (cm)	Maximum strength (Fc) (N/mm²)	Maximum Compressive Strain(ε_m) (%)	Young's modulus (Ec) (N/mm²)	Specimens
	Cement	Fine Aggregate	Course Aggregate						
Light-Weight (First Class)	1 1	2.28 2.59	1.27 1.33	54.0 53.0	19.0 15.6	33.7 27.3	0.265 0.337	17400 13200	A B , C

ε_{st}: strain at beginning of strain hardening
A, B, C represent the types of the base-connection

Table 2. List of the Test Specimens

Specimen	N (kN)	N / bDFc	Reinforcement Main	Reinforcement Added	Hoop Pitch(mm) Capital Side	Hoop Pitch(mm) Base Side	bMp / sMp	b(EI) / s(EI)	BR	BM
AR4H100N0	0	0.0	4-D13	0	100	100	0.025	0.003	0.003	0.025
AR4H100N441	441	0.242	4-D13	0	100	100	0.025	0.003	0.003	0.025
AR6H100N441	441	0.242	4-D13	2-D13	100	100	0.025	0.003	0.480	0.406
AR6H50N441	441	0.242	4-D13	2-D13	100	50	0.025	0.003	0.480	0.406
AR8H50N0	0	0.0	4-D13	4-D13	100	50	0.025	0.003	1.010	0.837
AR8H100N441	441	0.242	4-D13	4-D13	100	100	0.025	0.003	1.010	0.837
AR8H50N441	441	0.242	4-D13	4-D13	50	50	0.025	0.003	1.010	0.837
BR4H100N441	441	0.300	4-D13	0	100	100	1.373	0.338	0.338	1.373
CR4H100N441	441	0.300	4-D13	0	100	100	1.810	1.035	1.035	1.810

BR=(b(EI)+a(EI))/s(EI), BM =(bMp+aMp)/sMp

Table 4

	β	C_1
$_b(EI) < {}_s(EI)$	$n \cdot \frac{b(EI)}{s(EI)} \cdot \frac{tw \cdot sj}{b \cdot rj}$	0.085
$_b(EI) \geq {}_s(EI)$	$n \cdot \frac{tw \cdot sj}{b \cdot rj}$	0.140

rj: distance between centers of tension snd compression of RC element
sj: distance between centers of tension and compression flange of the wide flange section
n : ratio of modulus of elasticity of steel to that of concrete
tw: web thickness of the wide flange section

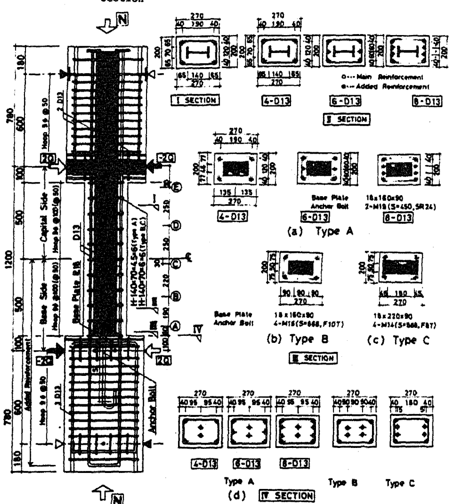
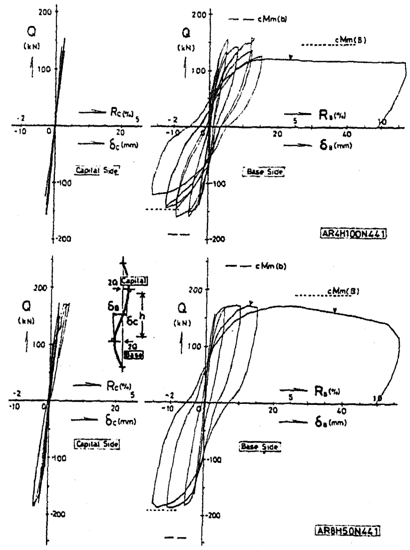


Fig. 1 Test Specimen

Table 3. Test Results

Specimen		eMcr (kN-m)	eMcr / cMcr	eQcr (kN)	eQcr / cQcr	eQm(kN) eMm(kN-m)	eMm / cMm(B)	eMm / cMsup.
AR4H100N0	(C) (B)	15.8 10.4	1.08 0.82	72.1 66.6	0.61 1.14	102.9 51.5	1.17	1.46
AR4H100N441	(C) (B)	34.3 27.0	1.04 0.99	161.7 98.0	1.12 1.25	-161.7 -80.9	1.09	1.11
AR6H100N441	(C) (B)	29.4 29.4	0.89 1.02	141.7 102.9	1.02 1.33	-166.6 -83.3	0.97	0.99
AR6H50N441	(C) (B)	36.8 33.1	1.11 1.15	132.3 88.2	0.91 1.14	-166.6 -83.3	0.97	0.99
AR8H50N0	(C) (B)	14.7 14.7	1.00 1.00	73.5 53.9	0.62 0.92	140.1 70.1	0.99	1.21
AR8H100N441	(C) (B)	34.3 29.4	1.04 0.97	160.1 117.6	1.11 1.15	-187.2 -93.6	0.97	0.98
AR8H50N441	(C) (B)	29.4 29.4	0.89 0.97	152.9 132.3	1.06 1.72	194.0 97.0	1.00	1.02
BR4H100N441	(C) (B)	29.4 29.4	0.96 1.04	132.3 117.6	0.98 1.49	-168.6 -84.3	1.07	0.99
CR4H100N441	(C) (B)	29.4 34.3	0.96 1.15	147.0 147.0	1.06 1.16	-178.2 -89.1	0.91	1.05

(B):Base Side (C):Capital Side



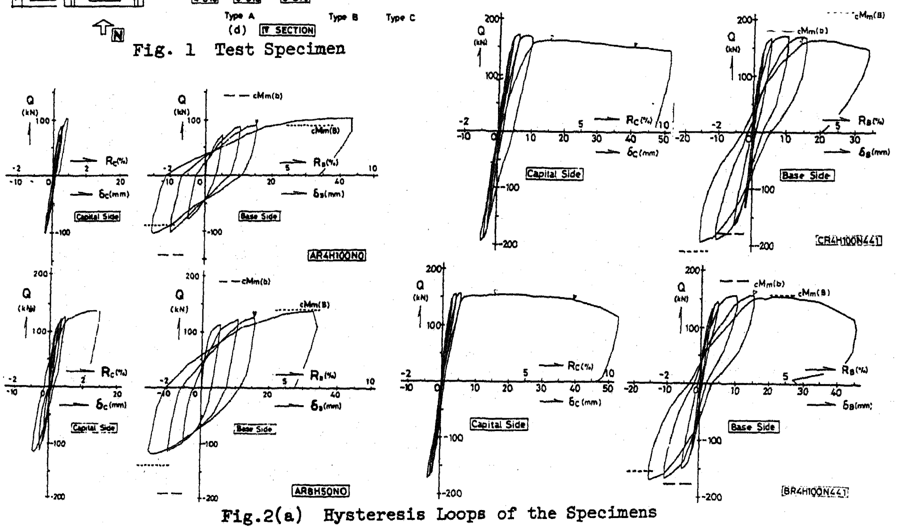


Fig.2(a) Hysteresis Loops of the Specimens

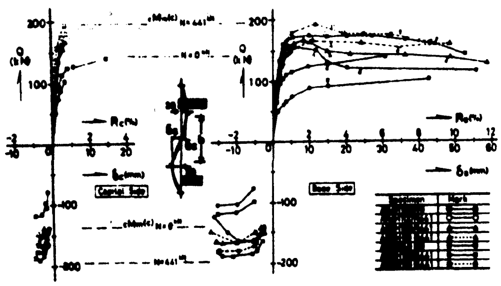


Fig.2(b) Enveloping Curves of the Hysteresis Loops

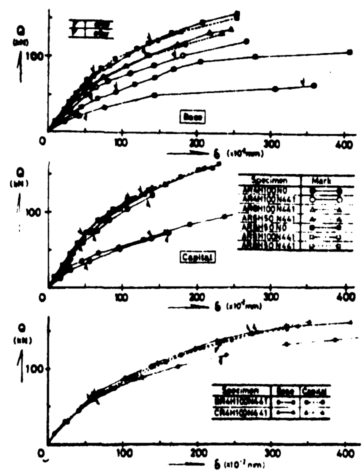
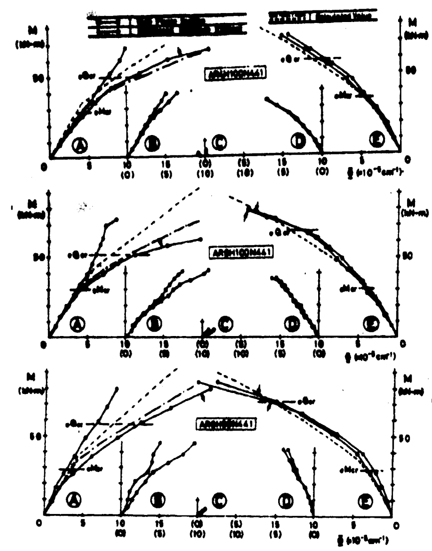


Fig.3 Load-Deflection Curve of the Beam Column Tests



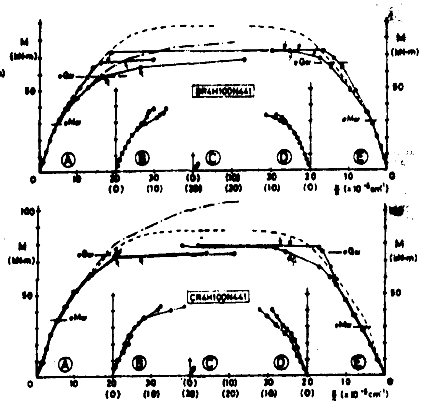
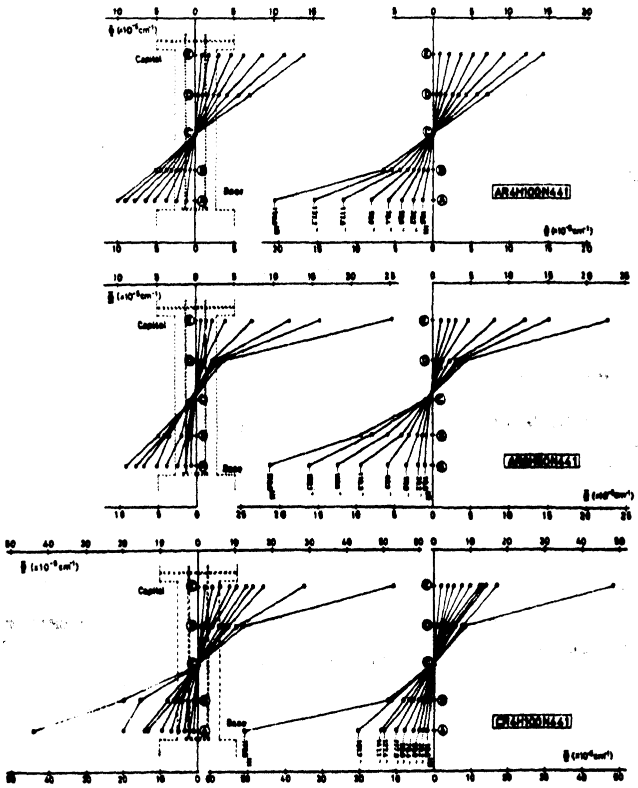


Fig.5 Moment (M) versus sϕ and rϕ at Each Section

Fig.4 Over-all View of Specimens after Testing



a). Wide Flange Section

b). Reinforced Concrete Element

Fig.6 Curvature Distribution of the Beam Column Tests

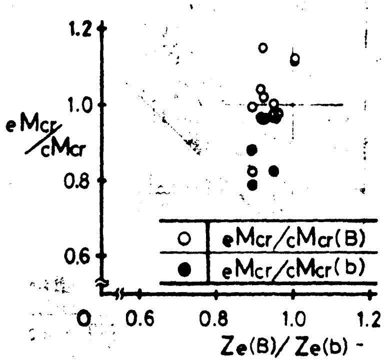


Fig.7 eMcr/cMcr versus Ze(B)/Ze(b)

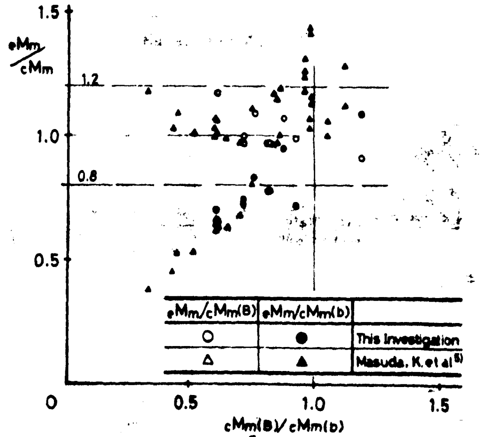


Fig.8 eMm/cMm versus cMm(B)/cMm(b)

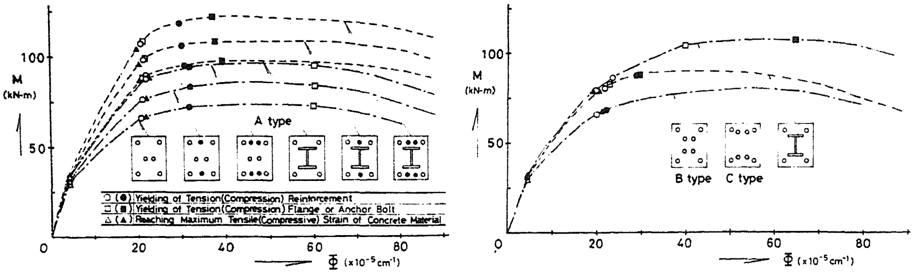


Fig.9 Moment (M) versus Curvature (ϕ) of Each Section

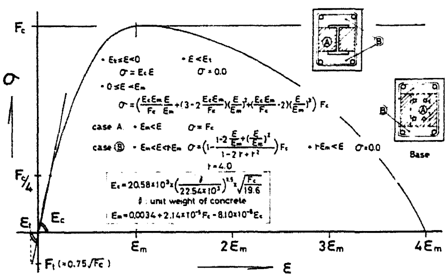


Fig.10 Stress (σ) versus Strain (ε) of Concrete Element

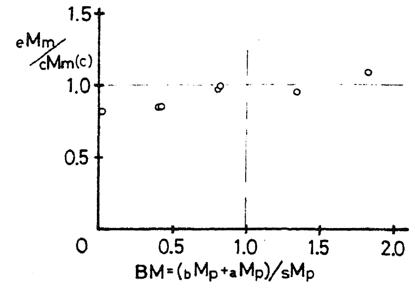


Fig.11 eMm/cMm(c) versus BM=(bMp+aMp)/sMp

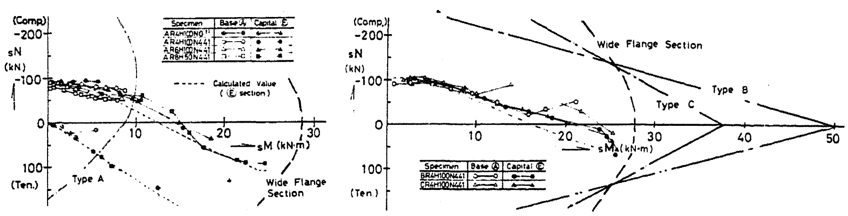


Fig.12 sN versus sM of Wide Flange Section (A Section)

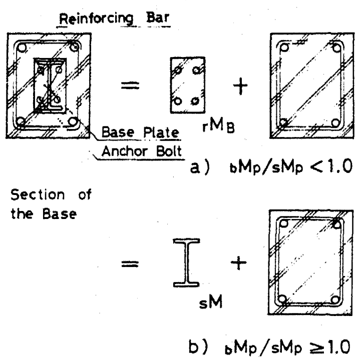


Fig.13 Superposed Method of the Base of Column

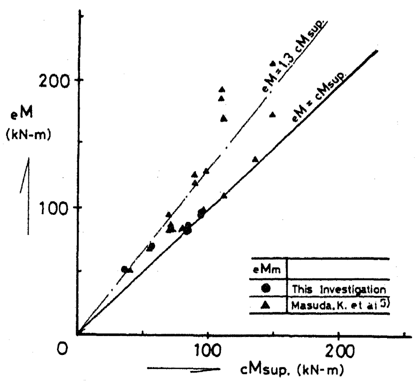


Fig.14 eM versus cMsup.