

Mechanical characteristics of steel column-base connections repaired by concrete encasement

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ABSTRACT: In Japan, not a few cases have been reported where a column base connection subjected to a large lateral load collapsed due to inadequate design and/or construction of such joint. In order to enable easy, economical and safe repair of such damaged column base, it is often encased in reinforced concrete. In such case it will be necessary to investigate the mechanical characteristics of the steel frame after the column base supporting condition has been changed, and for that purpose also the mechanical properties of the column base section thus encased should be clarified. Some experiments conducted for this purpose have clarified that the encasement with reinforced concrete is useful in reinforcing or repairing column bases damaged by application of lateral force.

1 INTRODUCTION

In Japan in the recent years the mechanical characteristics of steel column bases including their rigidity, ultimate strength and deformation performance have drawn strong attention. Such joints are where materials of different types, namely steel and concrete, meet and where their stress transmission mechanism changes abruptly. And also, such joints are very difficult to construct with high accuracy. This observation is endorsed by a number of cases where such column bases were damaged when subjected to lateral force or where the structural frame itself collapsed due to causes invited by damaged column base joints. Many of such damages involve column bases of the type wherein a base plate is welded to the bottom of the column and is then fixed to the concrete footing with anchor bolts (exposed type column base). In order to repair such damaged column bases, a method has been proposed whereby additional steel bars are welded to the vertical chord reinforcing steel bars embedded around the anchor bolts and a reinforced concrete stub having such bars is formed around the steel column base. However, the mechanical properties of the column bases after such repair/reinforcement greatly differ from those of the column bases before such repair/reinforcement. Especially in the case of a low height structural frame, such repair or reinforcement is presumed to greatly affect the mechanical behavior of the frame when subjected to horizontal force. Therefore, the hysteric performance, stress distribution, height of the column inflection point, etc. of a 1-story 1-span rigid frame

under lateral loading will be investigated as the supporting conditions of these column bases are changed, and further the mechanical properties of that part of the encased column base which is below the inflection point shall be studied in greater detail.

2 MECHANICAL PROPERTIES OF 1-STORY 1-SPAN FRAME WITH SUPPORTING STEEL COLUMN BASES IN CHANGING CONDITIONS

2.1 Experiment planning

Table 1 shows the experiment plan. As shown in Fig. 1, the supporting conditions of the column bases for 1-story 1-span rigid frame as reduced to an approximately 1/4 scale model were varied. The specimens used included 4 types namely the pinned type, the fixed type, the exposed type and the encased type. It was assumed that the moment resistance of the damaged steel column base itself could not be accounted for, and accordingly in the case of the encased type column base, the base plate was so shaped as to reduce the moment resistance as shown in Fig. 1. In all cases of

Table 1 Experiment plan

No.	Column base type	Specimen name	N/N ₀	Remark
1	Fixed type	K-11	0%	
2		K-12	15%	
3	Pinned type	P-11	0%	
4		P-12	15%	A. Bt: 4-M12
5	Exposed type	R-11	0%	BP: 190x190x16
6		R-12	15%	A. Bt: 6-M12
7	Encased type	N-21	0%	Height h=200 (2D)*
8		N-22	15%	Section bxd=300x300
9		N-31	0%	Height h=300 (3D)*
10		N-32	15%	Section bxd=300x300

* B: Outside dimension of tubular column

Table 2 Mechanical properties of materials
a)

Steel	Size	σ_s (N/mm ²)	σ_b (N/mm ²)	E x10 ⁴ (N/mm ²)	δ %
Beam	H-150-75	382	491	1.95	32.4
Column	□-150-150	407	482	1.80	24.7
Anchor bolt	12 ϕ	327	465	2.14	35.3
Base plate	E-12(16)	284(273)	448(416)	2.11	51.3
Chord bar	D13	347	592	1.90	18.2
Main bar	D16	382	556	1.92	23.1
Top hoop	D10	132	474	1.88	23.2
Hoop	D 6	292	425	1.81	22.9

b)

Concrete	σ_c (N/mm ²)	σ_t (N/mm ²)	σ_c (N/mm ²)	σ_t (N/mm ²)
Beam	23.2	3.04	Encasement	25.2
				3.94

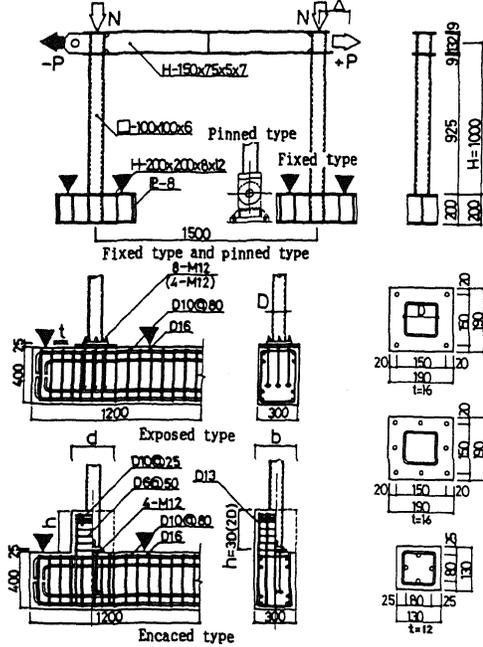


Fig. 1 Test specimens

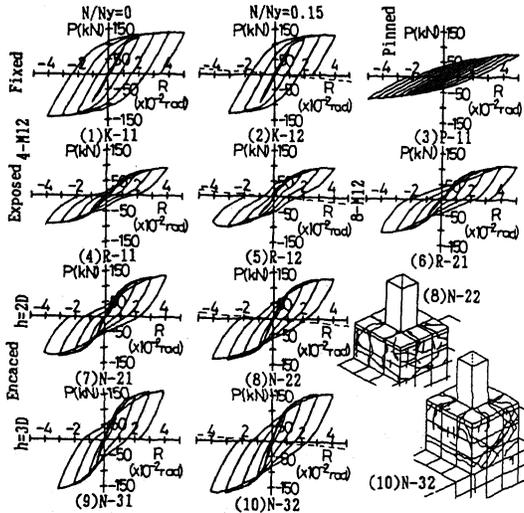


Fig. 2 H-R relations and crack after test

encased type column base, the length of each side of the section of the encasement was 3 times the outside dimension of the steel tube and the height of the encasement 2 to 3 times the outside dimension of the steel tube. As shown in Fig. 1, horizontal load was applied repeatedly to the column top under a constant axial pressure.

2.2 Results of the experiments and discussion

Fig. 2 shows the relations between the horizontal force (P) and the story deflection angle (R). The story deflection angle is the value obtained by dividing the displacement of the column top (Δ) by the height from the base plate lower surface to the beam center (H). In the case of a frame having exposed type column bases, the loop area is comparatively small but becomes large where there is an axial-force.

Further, the energy-absorbing capacity of the frame with this type column bases is larger than that of the frame with pinned column bases but is considerably smaller than that of the frame with fixed type column bases. However, when the column bases are encased in reinforced concrete, their hysteresis loops bulge and their strength and rigidity increase. Fig. 3 shows the bending moment distributions of the steel columns, and

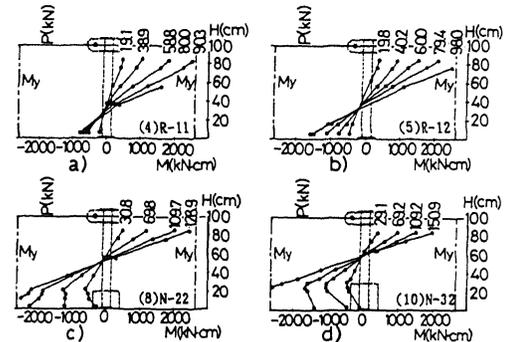


Fig. 3 Moment distributions of steel columns

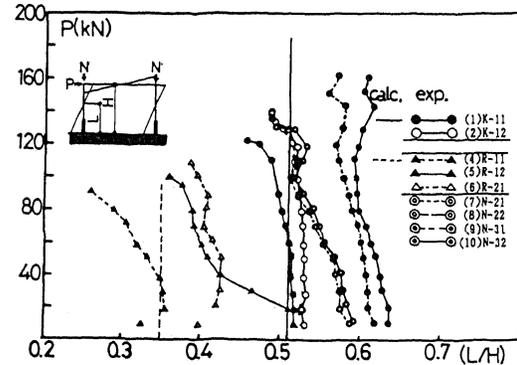


Fig. 4 Inflection point height ratios

Table 3 Experiment plan

No.	Specimen name	h	b×D (cm×cm)	N/Ny	Chord bar	Hoop	Top hoop	Anchor bolt
1)	A M Ⅲ5-13A-OR	3D	30×30	0.0	10-D13	D6 #25	3-D10#17.5	4-M16
2)	A M Ⅲ5-13O-OR	3D	30×30	0.0	10-D13	D6 #25	3-D10#17.5	-----
3)	A M Ⅲ5-33O-OR	3D	30×30	0.0	10-D13	D6 #25	2-D10#35.0	-----
4)	A M Ⅲ5-N3O-OR	3D	30×30	0.0	10-D13	D6 #25	-----	-----
5)	B M Ⅲ5-13A-OR	3D	30×30	0.0	10-D13	D6 #25	3-D10#20.0	4-M16
6)	B M Ⅲ5-17A-OR	3D	30×30	0.0	10-D13	D6 #70	3-D10#20.0	4-M16
7)	B M Ⅲ5-19A-OR	3D	30×30	0.0	10-D13	-----	3-D10#20.0	4-M16
8)	B M Ⅲ5-13A-OR*	3D	30×30	0.0	10-D13*	D6 #25	3-D10#20.0	4-M16
9)	C M Ⅲ5-25A-OR	2D	30×30	0.0	10-D13	D6 #50	3-D10#25.0	4-M16
10)	C L Ⅲ5-25A-OR	3D	40×40	0.0	10-D13	D6 #50	3-D10#25.0	4-M16
11)	C M Ⅲ5-25A-OR	3D	30×30	0.0	10-D13	D6 #50	3-D10#25.0	4-M16
12)	C M Ⅲ5-25A-1R	3D	30×30	1/6	10-D13	D6 #50	3-D10#25.0	4-M16
13)	C M Ⅲ5-25A-2R	3D	30×30	1/3	10-D13	D6 #50	3-D10#25.0	4-M16
14)	C M Ⅲ5-25A-5R	3D	30×30	2/3	10-D13	D6 #50	3-D10#25.0	4-M16

* No hook

Table 4 Mechanical properties of materials a)

Steel		σ_s (N/mm ²)	σ_t (N/mm ²)	E (x10 ⁴ N/mm ²)	ϵ (%)	
Column	AB □-150×150×6	STKR400	348	421	1.90	34.5
	C □-150×150×6	STKR400	388	433	2.10	42.0
Anchor bolt	AB M16	SR235	322	439	2.20	30.6
	C M16	SR235	290	433	2.00	27.0
Chord bar	AB D13	SD345	375	560	1.87	20.6
	C D13	SD345	356	531	1.90	18.5
Top hoop	AB D10	SD345	371	518	1.90	21.0
	C D10	SD345	385	555	1.90	18.4
Hoop	AB D 6	SD345	305	445	2.00	25.1
	C D 6	SD345	479	533	1.90	12.3

b)

Concrete	σ_c (N/mm ²)	σ_t (N/mm ²)	E _c (x10 ⁴ N/mm ²)	σ_c (N/mm ²)	σ_t (N/mm ²)	E _c (x10 ⁴ N/mm ²)	
Beam	A 21.8	1.80	2.01	21.8	1.90	2.01	
	B 23.9	1.80	2.01	Encasement	24.2	1.90	2.01
	C 25.8	1.95	2.54		26.0	1.91	2.53

Fig. 4 shows the heights of inflection points as the load is varied. It could be understood from these figures that the bending moments of the column head and the steel beam end in a frame with encased column bases are smaller than those in a frame with exposed type column bases indicating that the reinforcement/repair with column base encasement is effective on a frame to receive horizontal force. It could also be understood that the height of inflection point decreases, as the horizontal force increases, and that is affected depending on the height and the section of the encasement. In addition, it can be predicted that the mechanical properties of this portion differ depending on the method of reinforcement adopted. Then, the mechanical properties of the encased column base itself were investigated in greater detail.

3 MECHANICAL PROPERTIES OF ENCASED COLUMN BASES OF COLUMNS UNDER LATERAL FORCE

3.1 Experiment planning

Table 3 shows the experiment plan. The experiment elements included the presence/absence of anchor bolts, amount of steel bars for shear reinforcement, height and section of the encasement, presence/absence of main bar hooks and column axial force ratio. The height of inflection point varies depending on the details of the encasement stub, the magnitude of the load applied, etc., but for the purpose

Table 5 Experiment results

No.	Specimen name	scQu (kN)	Q _{su} (kN)	Q _{su} (kN)	cQu (kN)	Q _{max} (kN) + -	Q _{max} /cQu + -		
1)	M Ⅲ5-13A-OR	175.2	99.3	89.8	89.8	97.4	98.3	1.08	1.09
2)	M Ⅲ5-13O-OR	175.2	78.9	69.4	69.4	71.4	82.3	1.03	1.19
3)	M Ⅲ5-33O-OR	167.0	78.9	61.3	61.3	82.9	82.5	1.35	1.35
4)	M Ⅲ5-N3O-OR	167.0	78.9	55.7	55.7	75.5	68.9	1.36	1.24
5)	M Ⅲ5-13A-OR	169.3	99.9	86.2	86.2	106.6	96.4	1.24	1.12
6)	M Ⅲ5-17A-OR	169.3	99.9	80.1	80.1	99.0	94.3	1.24	1.18
7)	M Ⅲ5-19A-OR	169.3	99.9	72.1	72.1	74.5	72.8	1.03	1.01
8)	M Ⅲ5-13A-OR*	169.3	99.9	86.2	86.2	96.0	101.1	1.11	1.17
9)	M Ⅲ5-25A-OR	133.0	89.3	67.6	67.6	86.6	82.3	1.28	1.22
10)	L Ⅲ5-25A-OR	186.2	120.7	145.7	120.7	145.5	124.3	1.21	1.03
11)	M Ⅲ5-25A-OR	186.2	89.3	76.7	76.7	105.5	102.0	1.38	1.33
12)	M Ⅲ5-25A-1R	186.2	99.2	85.1	85.1	120.5	111.7	1.42	1.31
13)	M Ⅲ5-25A-2R	158.6	108.4	88.4	88.4	122.7	127.4	1.39	1.44
14)	M Ⅲ5-25A-5R	104.9	111.3	83.4	83.4	116.3	120.8	1.39	1.45

of the present experiments, a fixed value was assumed.

3.2 Specimens

Representative specimens out of the 30 specimens produced by concreting performed in 3 times will be shown in Table 3. The specimens are models scaled down to approximately 1/2.5 of the actual column base as shown in Fig. 5. Cold-formed square section steel tube of □-150 X 150 X 6.0 was used for columns. The encasement stub reinforcement was varied while the standard height and section of the encasement stub were assumed to be 3D (D: outside dimension of steel tube) and 2D X 2D, respectively.

3.3 Methods of loading and measurement

As shown in Fig. 5, a pin jig was installed at the position 75 cm above the lower surface of the base plate, and positive/negative alternating horizontal force by deflection controls was applied. Prior to the application of horizontal force, fixed axial pressures corresponding to 0, 1/6, 1/3 and 2/3 times as much as the yield load of the column were applied. The frame holding the measuring instrument was installed to the threaded steel bar which had been fixed to the foundation beam and was assumed to be a stationary point, and the deflection of each point was measured with the use of this setup as shown in Fig. 5.

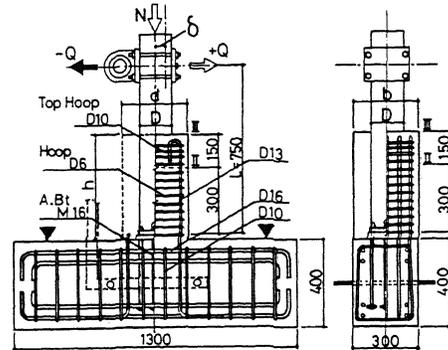


Fig. 5 Test specimen

3.4 Results of the experiments and discussion

3.4.1 Hysteretic characteristics

Fig. 6 shows the load (Q) - deflection (δ) curves at the loading points of the representative specimens. Their envelope curves are shown in Fig. 7 for each experiment element. The straight lines in the figure show the calculated value where the column bases are fixed perfectly. From these figures, the following facts were recognized:

- 1) When the repeated loading employed this time is given to the encased column base of the type adopted in the present experiments, inverted "S" shape hysteresis curves accompanied by slipping will be obtained.
- 2) Those with anchor bolts develop higher strength and deflection performance than those without anchor bolts (Fig. 7a)).
- 3) Encasement top reinforcement/shear reinforcement steel bar amount affects the maximum strength and the strength beyond maximum strength, but the initial rigidity will not be affected (Fig. 7b) and c)).
- 4) When the chord bars of the encasement stub do not have hooks, the strength beyond the maximum strength deteriorates fast. Therefore, it is necessary to secure a

sufficient amount of vertical chord bars and a sufficient bond length in order to secure necessary rigidity and strength (Fig. 7d)).

- 5) The elastic rigidity and ultimate strength of the encased type column base are greatly affected by the height and section area (cover thickness) of the encasement (Fig. 7e)).
- 6) In case an axial pressure exists, the hysteresis loop bulges more and the strength will be higher than in case no axial pressure exists, but the deterioration of the strength will be seen beyond the maximum strength (Fig. 7f)).

3.4.2 Rigidity

Fig. 8 a) shows examples of the envelop curves of the Q - δ relations in initial cycles on the positive force application side. The calculated value I in the figure represents the elastic rigidity of the encasement concrete before generation of initial bending cracks, and the calculated value II represents the rigidity after generation of cracks. The rigidity before and after crack generation was sought as follows:

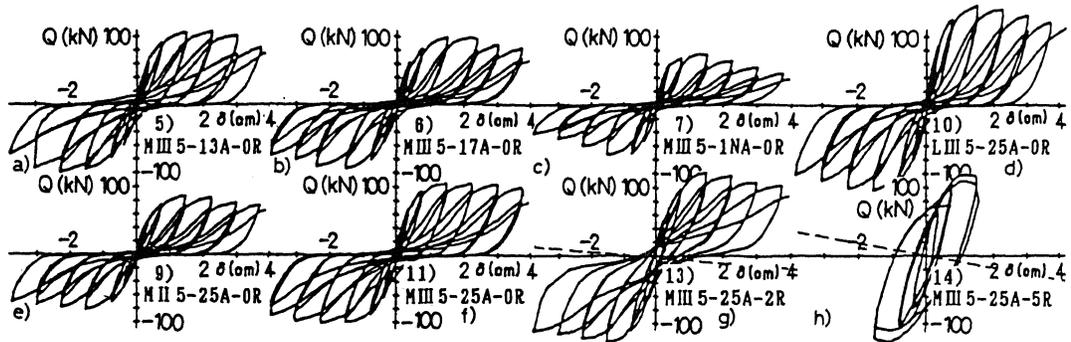


Fig. 6 Q - δ relations

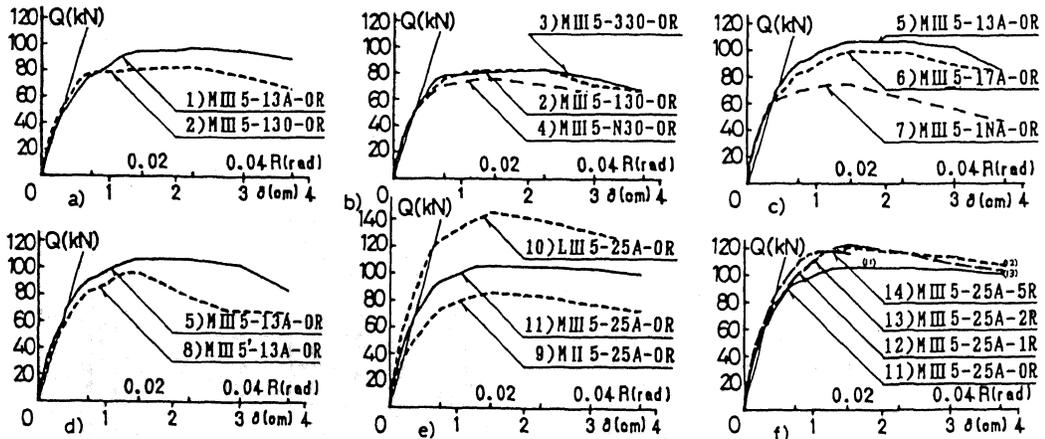


Fig. 7 Envelope curves of Q - δ relations

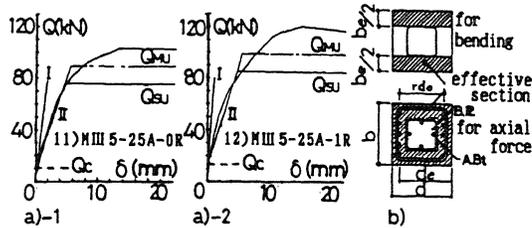


Fig. 8 Initial stiffnesses and effective area

- Rigidity before generation of bending cracks

The rigidity before generation of bending cracks was sought by adding the deformation of the structural steel element, that of the reinforcing bar element and that of the concrete element taking respective bending and shear deformation into consideration.

- Rigidity after generation of bending cracks

The rigidity after generation of bending cracks was obtained by adding the said deformation, assuming the bending rigidity of the concrete element to be zero, and the values of the chord bars drawn out. Further, the initial bending crack strength was sought assuming that the effective section of the reinforced concrete stub is as shown in Fig. 8 b) and using AIJ standard formula for reinforced concrete structure.

The rigidity values thus obtained tend to exceed their respective experimental values but are generally indicative of the values before and after crack generation.

3.4.3 Stress transmission mechanism and load bearing mechanism

Fig. 9 a) shows the representative examples of the relations between the lateral force (Q) and the strain (rε) of the chord bars at the base level of the encasement under lateral force. The typical examples of bending moment borne by the steel column and that borne by the encasement reinforced concrete obtained using these Q-rε relations are shown in Fig. 9 b). As is clear from the figure, the moment generated in the column is in part directly transmitted from the steel column base to the foundation and is in part transmitted by way of the encasement concrete. Fig. 10 shows the load bearing mechanism in a simplified form as clarified by the experiment.

3.4.4 Ultimate strength

The ultimate strength of the encasement stub is sought based on the load bearing mechanism as shown in Fig. 10 by adding the respective strengths of the encasement reinforced concrete element and the steel column base

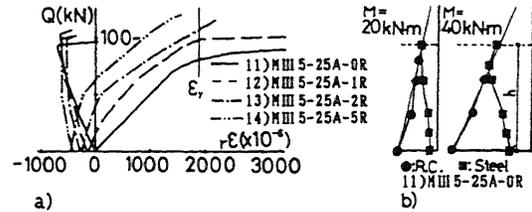


Fig. 9 Q-rε relations of chord bars and moment distributions of steel column & encased reinforced concrete

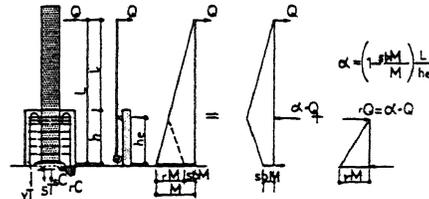


Fig. 10 Load bearing mechanism

element.

- Ultimate bending strength determined by the steel column:

$$sbMu = \{L/(L - he)\} \cdot Mp \dots\dots\dots (1)$$

where L is the height from the base plate lower surface to the loading point, he is the effective height of an encasement (=h-6 cm, h: encasement height) and Mp is the full plastic moment, taking axial force into consideration.

- Ultimate bending strength of the encased column base:

$$Mu = sbMu + rMu \dots\dots\dots (2)$$

where sbMu represents the ultimate bending moment of a steel column base element, and rMu represents the ultimate bending moment of a reinforced concrete portion of an encasement.

In each case, the calculation will be made applying the ultimate strength theory of the reinforced concrete structure calculation standard on the assumption that the base plate and the encasement stub section are sections of reinforced concrete respectively.

- Ultimate shear strength of an encased column base:

$$Qu = sQu + rQu \dots\dots\dots (3)$$

where sQu is the ultimate shear strength of a steel column element (= sbMu/L), and rQu is the ultimate shear strength of an encasement reinforced concrete element.

The application of the formula based on correspondingly the empirical formula of

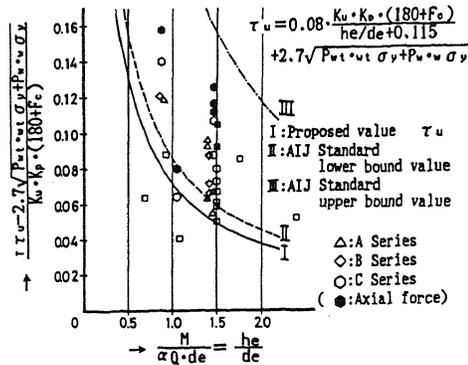


Fig. 11 Relations between shear span ratios and ultimate shear stresses

Ohno-Arakawa can be considered:

Using the load bearing mechanism as shown in Fig. 10, the shear force acting upon the encasement top was sought, and the relations of shear span ratios with ultimate shear stresses are shown in Fig. 11.

$$rQ_u = \left\{ \tau_c + 2.7 \sqrt{p_w t \cdot w_{t o y} + p_w \cdot w_{o y}} \right\} \cdot b_e \cdot r_j \cdot h_e / L \quad (4)$$

$$\tau_c = 0.080 \frac{k_u \cdot k_p \cdot (180 + F_c)}{h_e / d_e + 0.115} \quad (5)$$

where $p_w t$ is the top portion shear reinforcing bar ratio ($= \sum awt / b_e \cdot h$, awt : sectional area of a group of top hoops, b_e : effective width of encasement reinforced concrete portion) and p_w is the hoop ratio ($= aw / b_e \cdot X$, aw : sectional area of a group of hoops, X : hoop bar interval). $w_{t o y}$ and $w_{o y}$ are the yield stress of the top hoops and the hoops, respectively. r_j is the stress center to center distance in a section of encasement reinforced concrete. k_u is the compensation coefficient due to the encasement section size and k_p is that due to the tensile chord bar ratio p_t (%). d_e is the effective depth of the encasement and F_c is the compressive strength of the concrete.

The following conditions, however, must be satisfied:

$$2.7 \sqrt{p_w t \cdot w_{t o y} + p_w \cdot w_{o y}} \cdot b_e \cdot r_j \cdot h_e \leq r_{a t} \cdot r_{o y} \cdot r_{d o} \quad (6)$$

where $r_{a t}$ represents the total area of the tensile side chord reinforcement of the encasement, $r_{o y}$ represents the yield stress of the total area of the tensile side reinforcement and $r_{d o}$ is the chord bar interval on the tensile side and compressive side.

• Ultimate strength of encased column base

The ultimate strength of the encased column base can be sought by the following formula:

$$cQ_u = \min \{ s_c Q_u, Q_{Mu}, Q_{Su} \} \quad (7)$$

where $s_c Q_u = s_c M_u / L$, $Q_{Mu} = M_u / L$, $Q_{Su} = Q_u$

Table 5 shows the comparison between empirical values and calculated values. The ratio of the empirical value to the calculated value is approximately 1.2 on the average meaning that the empirical values are on the safe side.

4. CONCLUSIONS

The two experiments have proved that repairing and reinforcing partially damaged column bases for frames subject to lateral force by encasing such column bases with reinforced concrete is effective, and as the result of the investigation performed concerning the mechanical properties of such column bases as repaired and reinforced in said manner, the following facts were clarified:

- 1) Encased column bases such as those used in the present experiments show inverted "S" shape hysteretic behaviors accompanying the slip phenomenon.
- 2) The elastic rigidity of column base is governed by the height and section area of the encasement and can be sought by the method described in this paper.
- 3) If the height of the encasement is approximately 3 times the outside dimension of the steel tube, its rigidity will exceed that of the fixed column base.
- 4) Top reinforcing and shear reinforcing steel bars do not affect the initial rigidity but do affect the maximum strength and the strength beyond the maximum strength.
- 5) The ultimate strength of the encased column base can be sought by adding the strengths of the steel column base element and the encasement concrete element. However, the former should be ignored in the case of repair of the damaged column base.
- 6) The hysteretic behavior of the frame is alleviated compared with that of the specimen representing only that portion which is below the inflection point of the column.

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