Paper No. 1225. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

11 WCEE

RESPONSE OF STEEL COLUMN BASES EMBEDDED SHALLOWLY INTO FOUNDATION BEAMS

S. NAKASHIMA

Department of Architecture, Osaka Institute of Technology,
16-1, Ohmiya 5, Asahi-ku, Osaka, 535 Japan

ABSTRACT

Providing exposed type column bases with enough rigidity, strength and deformation capacity involves difficulties compared with other types of column bases. This paper describes the results of the experiments intended for developing the details of column bases which are only shallowly embedded in concrete footings thus facilitating column erection while satisfying required mechanical properties. The main experiment factors are baseplate sizes, anchor bolt layout and column base reinforcing method. In order to ascertain the effect of embedment, the specimens of exposed type column bases were also provided for testing. Influence of axial force was disregarded in these experiments. The author maintains in this paper that even if column bases are only shallowly embedded in concrete footing, they can still achieve enough rigidity, strength and ductility provided that due care is used in their joint detailing.

KEYWORDS

Anchor bolt, Anchor bar, Baseplate, Cold formed square steel tube, Embedded column base, Envelope curve, Hoop, Hysteretic loop, Slab bar

INTRODUCTION

Under horizontal loading, the stresses produced in structural elements should be transferred to the ground smoothly by way of column bases. These stresses are predominantly governed by the mechanical properties of column base joints and this is particularly so in the case of low-rise buildings. What is most important in any case is that these joints must be prevented from being ruptured. The reason why this is so important is because the rupture of column base joints is very likely to cause the structures as a whole to collapse. In this respect, it should be clearly noted that the rupture of column base joints much more seriously endangers the safety of the whole structures than the rupture of joints in upper structural elements (Nakashima et al., 1995).

In Japan, column bases of steel structures are generally designed to be fixed in accordance with the requirement restricting story drift angles as set out in the Building Standard Law Enforcement Order. In order to meet this requirement, if exposed type column bases are used, they must be provided with considerably thick baseplates which are held down by rather many anchor bolts that have substantial cross sectional areas. Thus, necessity to install many anchor bolts for each column base with positional accuracy makes column base placement a difficult task. It should also be remembered that the mechanical properties of this type of column bases are affected by the degree of contact between baseplates and footings as achieved by grouting.

In order to avoid these problems, it has become a common practice to embed the lowermost parts of steel columns in concrete footings or to encase them in concrete on footings. The mechanical properties of the aforesaid types of column bases have been reported by this author for cases wherein the embedment depth or the encasement height of columns was equal to two or three times the outer side dimensions of the steel tube columns (Nakashima et al., 1986, 1988, 1992). However, these types of column bases pose some problems because embedment of column bases in footings leads to difficulty in proper placement of reinforcing bars in footings and encasement of them on footings inevitably results in some restriction on usable floor space.

Thus, as solutions for such problems, an alternative method is proposed in which column bases are embedded in concrete footings to a depth equal to 1.0 ~ 1.5 times the side dimension of steel tube columns in such a way that stresses developed in column bases can be dealt with by the bearing strength produced between the column side faces and the concrete footing and by the resistive force of the baseplate portions inclusive of anchor bolts. It is expected that the use of the aforesaid column base arrangement will enable the design stresses to be considered for the lowermost ends of columns to be substantially reduced and thus their detailing to be simplified accordingly. The hysteretic properties of this type of column bases as subjected to lateral loads were investigated by assuming the baseplate size and anchor bolt layout as being invariable and by taking the magnitude of column axial force as a main experiment factor. In consequence, it was clarified that the mechanical properties of this type of column bases are greatly affected by the axial force on the columns (Nakashima, 1994).

In this report, baseplate sizes, anchor bolt layouts and methods of reinforcing the embedded portions of column bases are taken as experiment parameters, and consideration will be made how the mechanical properties of the column bases are influenced by these parameters.

For placement of this type of column bases, what is generally known as "box out method" may be considered. In this method, "boxes" are provided in footing beams for placement of column bases and they are filled up with concrete after columns have been erected. In this method, however, some problems still remain to be clarified in respect of the bonding properties of "boxes" in footing beams as well as assurance for integration of footing beam concrete and concrete fill around the column bases in the boxes.

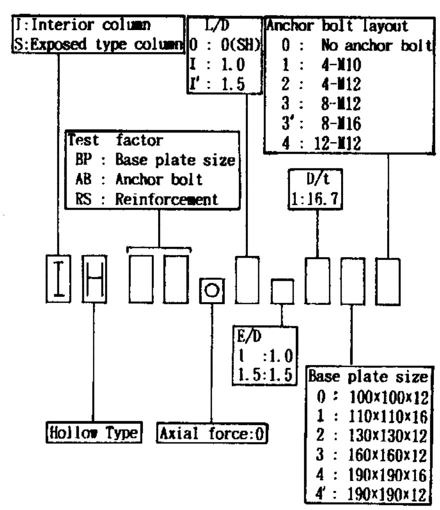
EXPERIMENT PLANNING

Table 1 indicates the experiment planning. The experiment parameters comprise the baseplate sizes and thicknesses, the sizes and number of anchor bolts, the reinforcing methods (slab bars, hoops and anchor bars) and the embedment or exposure of column bases. The method by which the specimens are identified is indicated on the right side of Table 1. The specimens, made to scales of 1/3 ~ 1/4 of actual sizes, represent the column portions below their points of inflection as shown in Fig. 1. All columns were made of cold-formed square steel tubing 100 × 100 × 6.0 in size.

Some baseplate and anchor bolt details as well as various reinforcement details are shown in Fig. 2.

Table 1 Experiment planning

	No.	Specimen No.	Embedment length L(mm)	L/D	Base plate size (mm)	Anchor bolt size	See Tables 2 and 3 Column	BPl.	Bar A.Bt	Concrete	Remark
	1)	IH-AF$_0$ I_1 142	100	1.00	190×190×16	4-M12	D	3	II	②	
	2)	IH-AF$_0$ I_1 143	100	1.00	190×190×16	8-M12	A	1	I	①	
	3)	IH-AF$_0$ I_1 143	100	1.00	190×190×16	8-M12	D	3	II	②	
	4)	IH-AF$_0$ I'_1 131	150	1.50	160×160×12	4-M10	B	2	I	①	
	5)	IH-BP I_1 100	100	1.00	100×100×12	—	E	4	I	③	
	6)	IH-BP I_1 120	100	1.00	130×130×12	—	E	4	I	③	
B. Pl.	7)	IH-BP I_1 14'0	100	1.00	190×190×12	—	E	4	I	③	
	8)	IH-BP I_1 140	100	1.00	190×190×16	—	E	5	I	③	
	9)	IH-BP I_1 14'3	100	1.00	190×190×12	8-M12	E	4	I	③	
	10)	IH-AB I_1 142	100	1.00	190×190×16	4-M12	F	5	I	③	
A. Bt.	11)	IH-AB I_1 143	100	1.00	190×190×16	8-M12	F	5	I	③	
	12)	IH-AB I_1 143'	100	1.00	190×190×16	8-M16	E	5	I	③	
	13)	IH-AB I_1 144	100	1.00	190×190×16	12-M12	F	5	I	③	
	14)	IH-RS$_0$ $I_{1.5}$140	100	1.00	190×190×16	—	E	5	I	③	
	15)	IH-RS$_{sl}$ $I_{1.5}$140	100	1.00	190×190×16	—	E	5	I	③	Slab bar
Rein-	16)	IH-RS$_{sl}$ $I_{1.5}$143	100	1.00	190×190×16	8-M12	F	5	I	③	Slab bar+A. Bt
force-	17)	IH-RS$_0$ I'_1 110	150	1.50	110×110×16	—	G	6	I	④	
ment	18)	IH-RS$_{ho}$ I'_1 110	150	1.50	110×110×16	—	G	6	I	④	Hoop
	19)	IH-RS$_{sl}$ I'_1 110	150	1.50	110×110×16	—	G	6	I	④	Slab bar
	20)	IH-RS$_{ar}$ I'_1 110	150	1.50	110×110×16	—	G	6	I	④	Anchor bar
Ex-	21)	SH-AF$_0$ 0_1 142	—	—	190×190×16	4-M12	D	3	II	② i ※	
posed	22)	SH-AF$_0$ 0_1 143	—	—	190×190×16	8-M12	D	3	II	② ii	
Column	23)	SH-00 0	—	—	—	—	—	—	—	—	



Naming procedure

In the specimens made to these reinforcement details, L/D (where L = embedment depth and D = peripheral length of tube) was taken as 1.0 and 1.5. For the specimens with L/D = 1.0, baseplates, 190 × 190 × 16 in size, were used and reinforcement was achieved by slab bars alone or by slab bars and anchor bolts. For those with L/D = 1.5, the protruding leg length of baseplates were reduced in consideration of the substantial embedment depth, and reinforcement was achieved by means of reinforcing hoop bars, slab bars and anchor bars. The footing width was taken as 4D for the reinforced specimens with L/D = 1.0 in which the baseplates had long protrusions and as 3D for all other specimens. A specimen without reinforcement was also provided to ascertain the effects of reinforcement. In addition, specimens of exposed type column bases and those intended for investigation of mechanical properties of steel columns themselves were also provided.

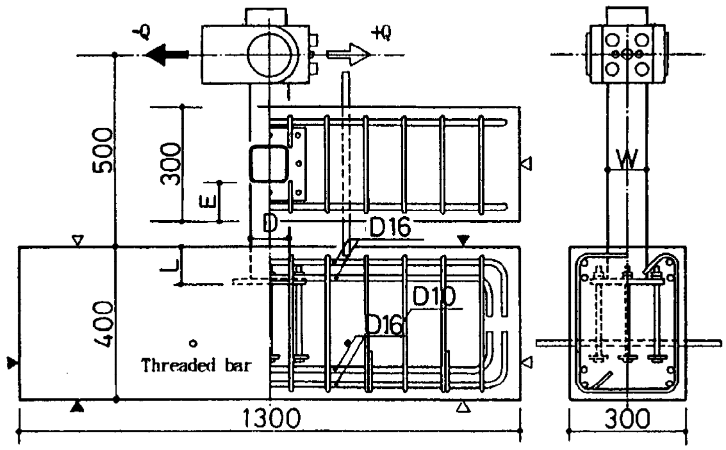


Fig. 1 Specimen and loading apparatus

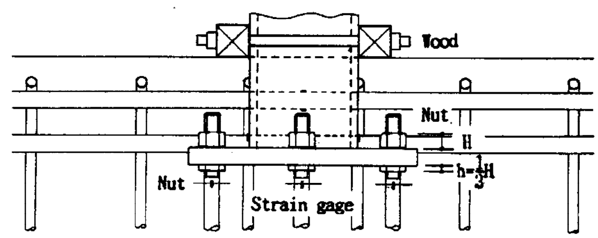


Fig. 3 Installation of steel column base

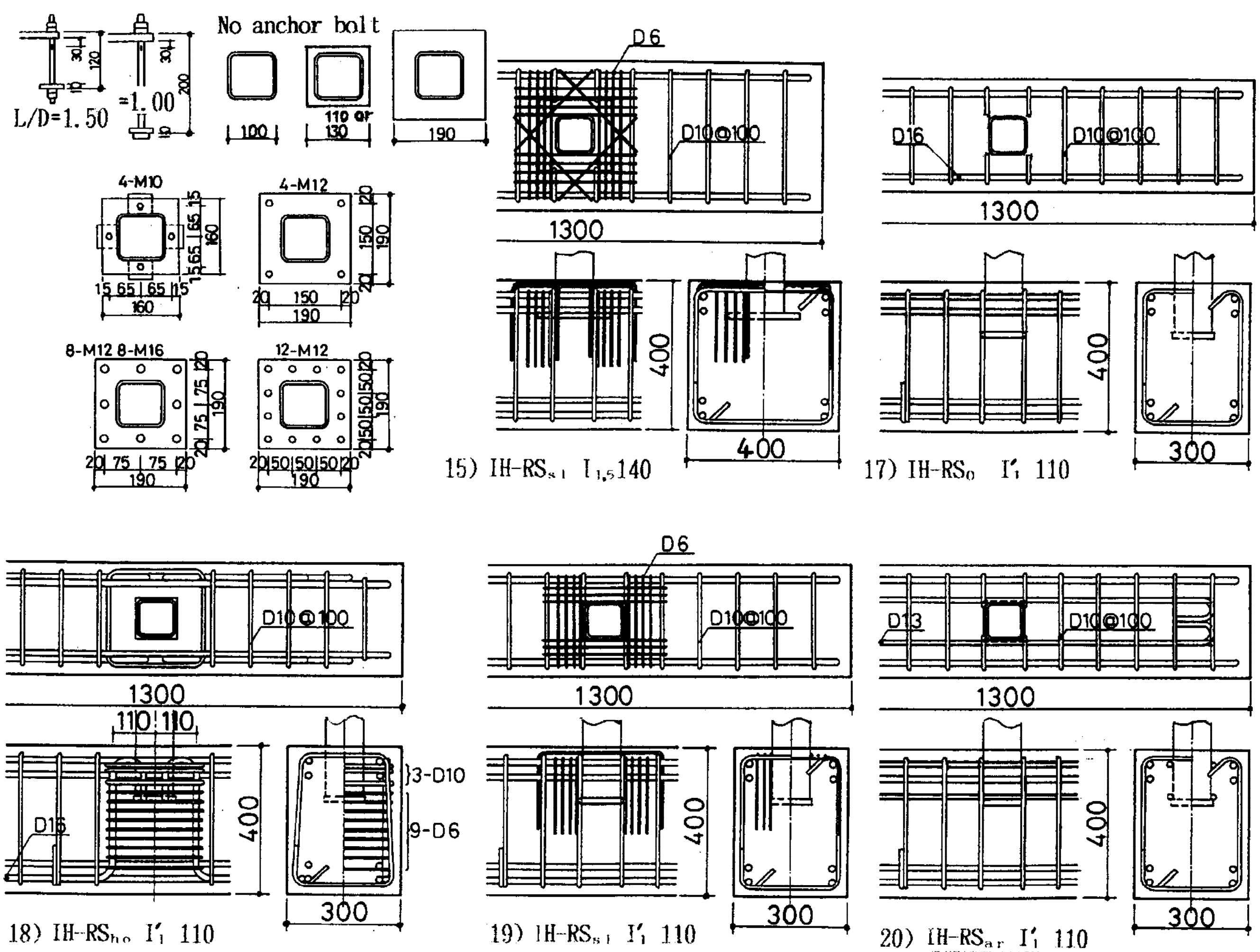


Fig. 2 Details of anchor bolts, baseplates and reinforcements for steel column bases

Table 2 Mechanical properties of steel

Element	Size	Material	σy (N/mm²)	σu (N/mm²)	Es ($\times10^5$ N/mm²)	ε (%)
Steel column	A:□-100×100×6.0	STKR 400	363	437	1.86	31.9
	B:□-100×100×6.0		423	488	1.93	28.9
	C: ———		—	—	—	—
	D:□-100×100×6.0		420	501	2.17	31.1
	E:□-100×100×6.0		441	505	2.08	33.6
	F:□-100×100×6.0		435	502	2.04	32.2
	G:□-100×100×6.0		447	506	1.97	21.2
Base plate	1: PL-16	SS 400	265	450	2.03	36.9
	2: PL-12		273	451	2.14	32.5
	3: PL-16		350	546	2.06	17.9
	4: PL-12		291	432	2.13	34.4
	5: PL-16		322	492	2.13	28.6
	6: PL-16		253	435	2.17	25.9
Steel bar	I: D 6	SD 345	479	522	1.82	21.0
	D 10		351	484	1.81	23.0
	D 16		478	703	1.92	21.0
	II: D 10	SD 345	380	566	1.71	16.2
	D 16		454	642	1.88	25.9
Anchor bolt	I: M 10	———	420	619	1.98	20.0
	M 12		380	508	2.36	—
	M 16		320	470	2.01	—
	II: M 12	———	371	520	2.30	32.9

Table 3 Mechanical properties of concrete and grout mortar

	Aggregate max. size (mm)	W/C (%)	Slump (cm)	σc (N/mm²)	σt (N/mm²)	Ec ($\times10^4$ N/mm²)
(1)	15	55	24.6	25.3	2.17	2.06
(2)	15	59	18.9	23.1	2.51	2.14
(3)	15	55	22.7	23.9	2.23	2.29
(4)	15	55	19.0	24.4	2.18	2.17
※ i	—	59	—	21.8	—	—
ii	—	59	—	23.5	—	—

The specimens were prepared by fixing the steel columns on the footing beam forms as shown in Fig. 3 and then by pouring concrete in one operation. In each specimen provided with anchor bolts, thin nuts were placed under the baseplate, too, in order to prevent dislocation of the anchor bolts. Then, with a baseplate being placed between pairs of nuts, the anchor bolts were tightened. Tables 2 and 3 indicate the mechanical properties of the materials used for the specimens.

EXPERIMENT RESULTS AND CONSIDERATION

Hysteretic Loops and Rigidity, Strength and Deformation

Fig. 4 shows the relations between the moments (M) acting on the top faces of the footing beams and the member rotation angles of the columns (R). The specimen numbers indicated in Table 1 agree with the figure numbers. Fig. 5 shows on a comparative basis the envelope lines for the positive loading side of the hysteretic loops in which (M) and (R) are made dimensionless by dividing them by the computed full plastic moments (M_P) and the corresponding computed member rotation angles (R_P) of the respective steel columns. In these computations, however, the corner curvatures of the column cross sections were disregarded. Fig. 6 shows the typical intrinsic loops at the respective displacement amplitudes. In this figure, (M) and (R) are made dimensionless by dividing them by the maximum loading and displacement on the positive side at the first cycle of the respective displacement amplitudes. Also, in this figure, the first cycle and the second cycle of the respective displacement amplitudes are shown in bold line and fine line respectively. The test results are shown in Table 4.

Effects of Embedment. Figs. 4-1), 10) and 21) show the hysteretic loops for the specimens all having the same baseplate size and anchor bolt layout; however, the first two specimens were provided with embedded baseplates (L/D = 1.0) while the last one was of an exposed baseplate type. The foregoing description also applies to Figs. 4-2), 3) and 11) and Fig. 4-22). It is known from Fig. 4 that the hysteretic loops for the exposed column base specimens were conspicuously characterized by slips while those for the embedded column bases have bulges near the point of zero loading. Further, it is known from Fig. 5-a) and Table 4 that the exposed type column bases are superior to the embedded type column bases in rigidity while the latter excels the former in strength.

Effects of Baseplate Sizes. Figs. 4-5) ~ 7) show the hysteretic loops for the specimens of embedded column bases (L/D = 1.0) provided with no anchor bolts but with baseplates with protrusions of 0 ~ 45 mm. Fig. 5-b) verifies that the strength of column bases increases as the length of baseplate protrusion increases. Compared with Specimen 5) which had no baseplate protrusion, Specimen 7) with a baseplate protrusion of 45 mm showed an increase in strength by about 90%; however, this type of specimen showed substantial strength lowering beyond the point of maximum strength and also great strength decrease under repeated loadings displaying slip type characteristics. The author once investigated the mechanical properties of embedded type column base specimens (L/D = 2.0) by taking their baseplate sizes as experiment parameters and based on the test results reported that the mechanical properties of column bases were not much affected by joint detailing for the bottom end

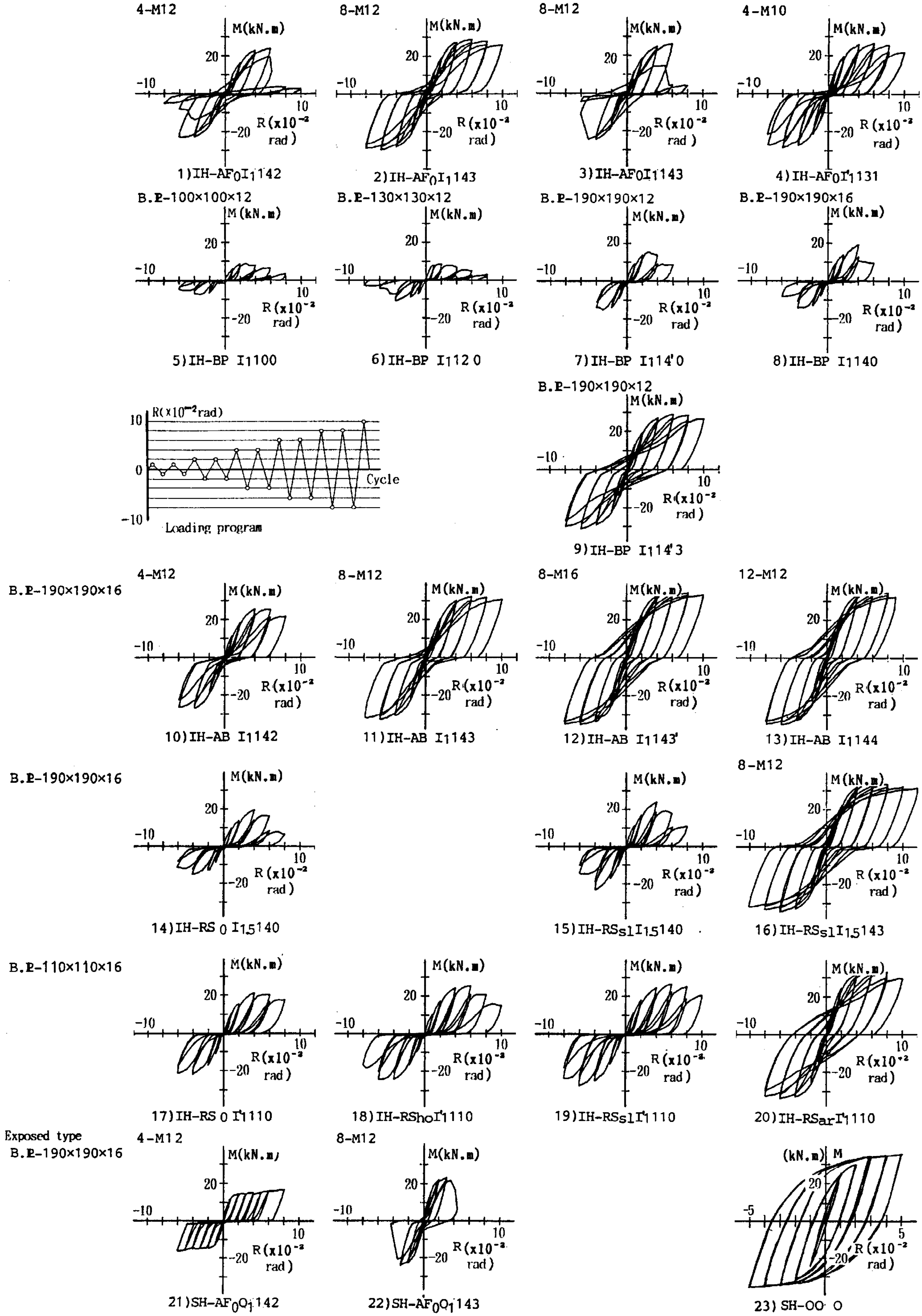


Fig. 4 M-R relations

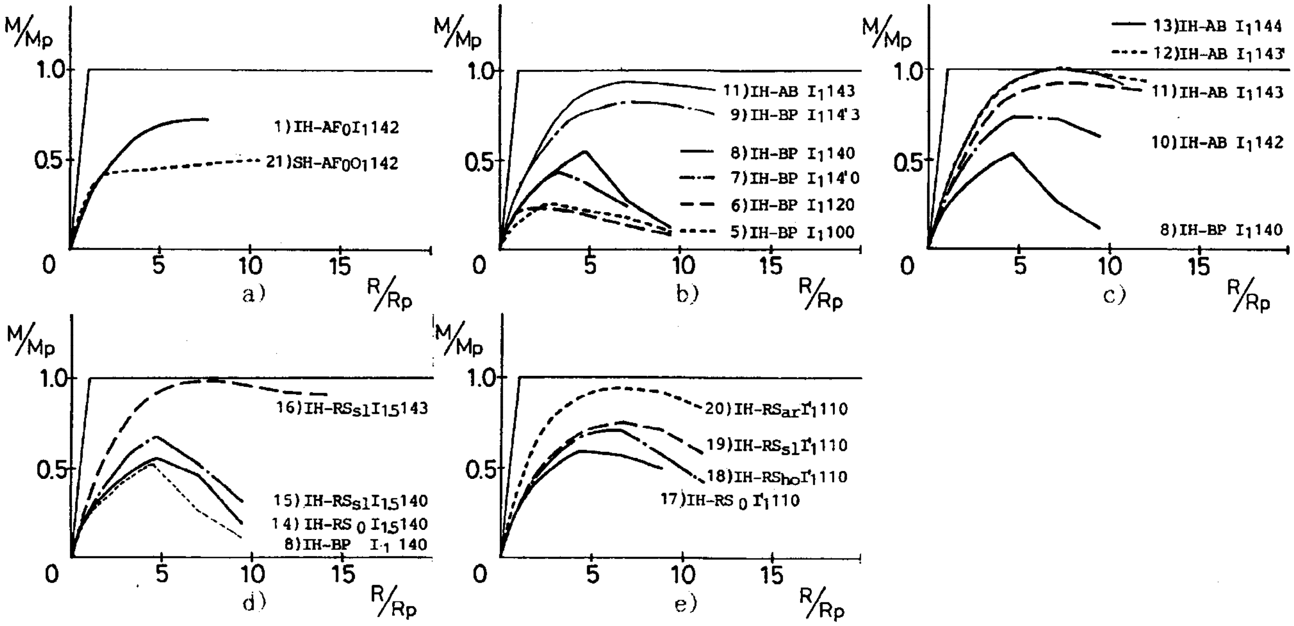


Fig. 5 Envelope curves of M/Mp-R/Rp relations

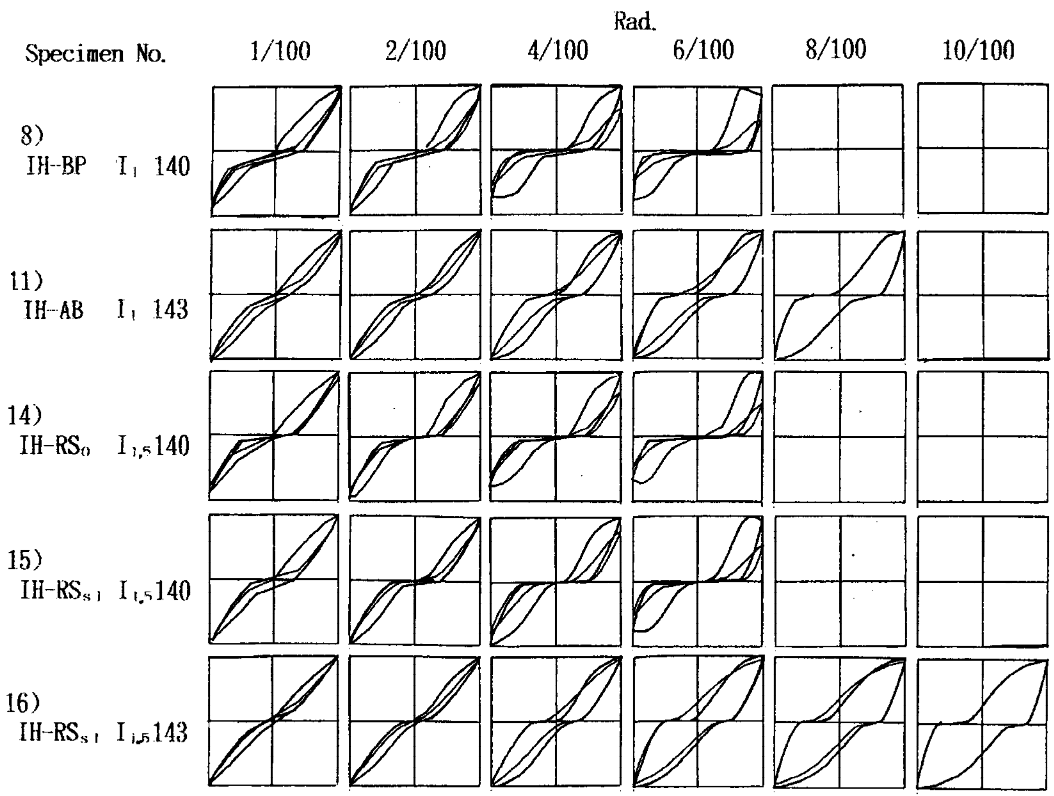


Fig. 6 Typical intrinsic loops

of steel columns (Nakashima, 1986). However, the present experiment results clearly indicate that in the case of embedded column bases where L/D is 1.0, their mechanical properties are substantially affected by the bottom end detailing of steel columns.

Effects of Baseplate Thickness. Figs. 4-7) and 8) show the hysteretic loops of the specimens provided with baseplates having the same size in plan but different thicknesses. While the strength of the specimen shown in Fig. 4-8) was 24% higher than that shown in Fig. 4-7) on the positive loading side, it was 8% lower on the negative loading side and further its strength lowered greatly beyond the point of the maximum strength. Specimens 9) and 11) were identical in baseplate size and layout in plan but different in baseplate thickness. Compared with the hysteretic loop of the former specimen, the latter specimen was characterized by a slight slip type tendency.

Effects of Baseplate Layout. Fig. 4-8) and Figs. 4-10) ~ 13) show the hysteretic characteristics of the column base specimens of which the first one was without anchor bolts while the latter four were provided with anchor bolts. From the foregoing figures as well as Fig. 5-c) and Fig. 6, it is recognized that the hysteretic loops of the specimens tended to change from a slip type to a spindle type and at the same time they began to attain greater strength and rigidity and also increased energy consumption as the sectional areas of anchor bolts increased. Since the anchor bolts used for Specimens 12) and 13) had nearly the identical strain characteristics and the strength of the specimens was primarily governed by the columns, very similar hysteretic loops were obtained. The test results for these specimens, too, indicate that the mechanical properties of column bases are greatly affected by the joint detailing of the bottom end of the columns in case L/D is 1.0.

Effects of Concrete Volume around Embedded Portions. Figs. 4-8) and 14) show the hysteretic loops for the specimens which are without reinforcement and provided with the baseplates of an identical size. The two specimens, however, have different footing widths, i.e., 30 cm and 40 cm for the former and the latter respectively. It is know from Fig. 5-d) that although the two specimens have the same maximum strength, the latter excels the former in respect of deformation properties.

Effects of Reinforcement of Embedded Portions. Figs. 4-14) ~ 16) show the hysteretic loops of the specimens which are identical in baseplate size but different in respect of reinforcement. Specimen 14) is without reinforcement, Specimen 15) is reinforced by utilizing slab reinforcing bars and Specimen 16) is strengthened by both slab reinforcing bars and anchor bolts. As seen in Fig. 5-d) and Fig. 6, the hysteretic loops for Specimens 14) and 15) are featured by prominent slip type hysteretic characteristics while that for Specimen 16) is indicative of remarkable increase in strength, rigidity and consumed energy. The effectiveness of anchor bolts as column base reinforcement can be clarified well by comparative study of these hysteretic loops. Figs. 4-17) ~ 20) show the hysteretic loops for the specimens whose L/D is 1.5. Specimen 17) is not reinforced while Specimen 18) is provided with main bars which surround the column base and is further reinforced with hoop bars. Specimen 19) and Specimen 20) are provided with floor reinforcement and anchor bars welded to the column respectively. As shown in Fig. 5-e), it was recognized that the strength of Specimen 18) was 19% and 11% higher than that of Specimen 17) on the positive side and the negative side respectively. Also, it was found that the deformation of Specimen 18) under the maximum loading was greater than that of Specimen 17); however, the strength of the former decreased rather drastically beyond the point of the maximum loading. Specimens 18) and 19) showed nearly identical hysteretic loops. However, decrease in strength of Specimen 19) was gentler than that of Specimen 18). Specimen 20) showed rigidity and strength which were about 50% higher than those of Specimen 17). Further, the former excelled the latter in respect of the deformation at the maximum strength. As endorsed by all these findings, direct anchorage of steel column bases was found to be as effective as anchorage by means of anchor bolts.

Cracking of Concrete Footings

Fig. 7 shows a general process of crack development in concrete footings. Providing baseplates with

Table 4 Experiment results

No.	Specimen No.		Mp (kN.m)	Rp ($\times 10^{-2}$ rad)	Mmax (kN.m) +	Mmax (kN.m) −	Mmax/Mp +	Mmax/Mp −	Rmax/Rp +	Rmax/Rp −	K ($\times 10^2$ kN.m/rad)	K/K$_0$	Failure Pattern ※
1)	IH-AF$_0$	I$_1$ 142	33.4	0.770	24.9	22.8	0.74	0.68	7.54	7.28	12.4	0.41	W
2)	IH-AF$_0$	I$_1$ 143	28.9	0.776	29.0	29.5	1.00	1.02	7.74	7.74	13.2	0.44	C, S
3)	IH-AF$_0$	I$_1$ 143	33.4	0.770	26.3	24.4	0.79	0.73	7.80	5.20	13.1	0.44	W
4)	IH-AF$_0$	I'$_1$ 131	33.6	0.873	26.6	28.5	0.79	0.85	6.41	6.90	16.3	0.54	C, S
5)	IH-BP	I$_1$ 100	35.1	0.844	8.9.	7.6	0.25	0.22	3.33	3.81	8.1	0.27	C
6)	IH-BP	I$_1$ 120	35.1	0.844	8.6	10.6	0.24	0.30	1.92	4.73	14.8	0.49	C
7)	IH-BP	I$_1$ 140	35.1	0.844	15.5	15.4	0.44	0.44	3.33	3.78	13.3	0.44	C
8)	IH-BP	I$_1$ 140	35.1	0.844	19.2	14.1	0.55	0.40	4.76	4.73	11.5	0.38	C
9)	IH-BP	I$_1$ 143	35.1	0.844	28.8	31.0	0.82	0.88	7.12	7.12	15.5	0.52	C
10)	IH-AB	I$_1$ 142	34.6	0.848	25.7	27.0	0.74	0.78	4.71	4.71	14.2	0.47	A, C
11)	IH-AB	I$_1$ 143	34.6	0.848	32.4	32.4	0.94	0.94	7.09	6.82	12.6	0.42	A, C
12)	IH-AB	I$_1$ 143'	35.1	0.844	35.7	35.1	1.02	1.00	7.15	7.11	15.6	0.52	S
13)	IH-AB	I$_1$ 144	35.1	0.844	35.3	34.8	1.01	0.99	6.90	6.87	16.2	0.54	S
14)	IH-RS$_0$	I$_{1.5}$140	35.1	0.844	19.7	15.0	0.56	0.43	4.77	4.85	11.5	0.38	C
15)	IH-RS$_{s1}$	I$_{1.5}$140	35.1	0.844	24.1	23.1	0.69	0.66	4.75	4.76	14.2	0.47	C
16)	IH-RS$_{s1}$	I$_{1.5}$143	34.6	0.848	34.2	34.5	0.99	1.00	7.13	7.13	14.3	0.48	C, A
17)	IH-RS$_0$	I'$_1$ 110	35.6	0.903	21.4	21.7	0.60	0.61	4.43	4.45	12.0	0.40	C
18)	IH-RS$_{h0}$	I'$_1$ 110	35.6	0.903	25.4	24.0	0.71	0.67	6.21	6.23	12.1	0.40	C
19)	IH-RS$_{s1}$	I'$_1$ 110	35.6	0.903	26.9	27.5	0.76	0.77	6.65	6.67	12.4	0.41	C
20)	IH-RS$_{ar}$	I'$_1$ 110	35.6	0.903	33.6	33.8	0.94	0.95	6.22	6.70	15.8	0.53	C, A
21)	SH-AF$_0$	O$_1$ 142	33.5	0.770	16.1	16.9	0.48	0.51	9.92	7.56	18.0	0.60	A,
22)	SH-AF$_0$	O$_1$ 143	33.5	0.770	23.4	23.9	0.70	0.72	—	—	21.7	0.72	W
23)	SH-00	O	32.1	0.740	34.6	35.0	1.08	1.09	—	—	30.0	1.00	S

※Failure pattern
A: Anchor bolt
C: Concrete
S: Steel column
W: Welded portion

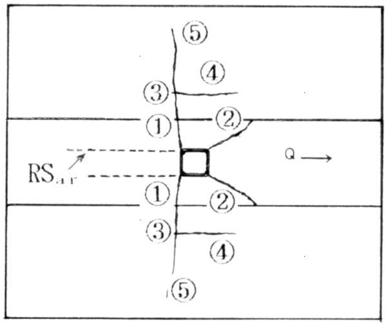
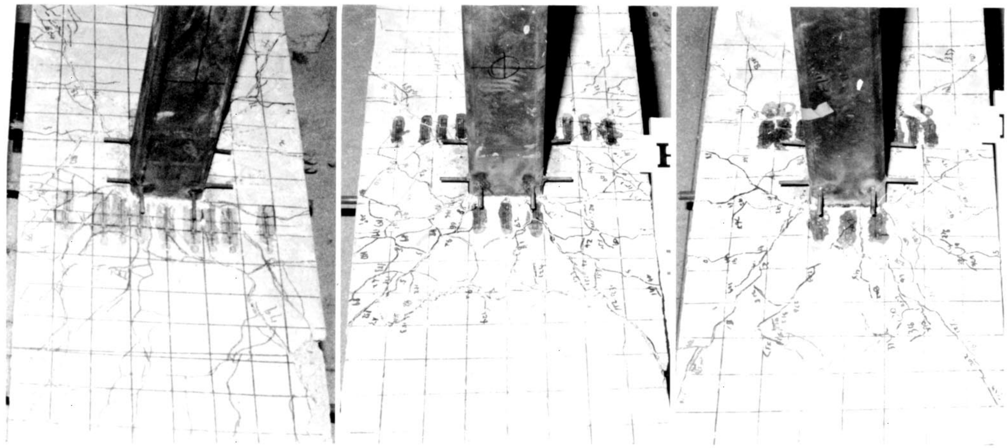


Fig. 7 Patterns of crack development in footings



14) IH-RS$_0$ I$_{1.5}$140 15) IH-RS$_{S1}$ I$_{1.5}$140 16) IH-RS$_{S1}$ I$_{1.5}$143

Photo 1 Specimens after tests

protrusions seem to have caused the appearance of horizontal cracks on the side face of the footing beams to be conspicuous. Anchor bolts placed in footing beams is thought to have made way for cracks to extend to the bottom of the footing beams. Slab reinforcing bars helped reduce cracks in the top face of the footing beams. Reinforcement by means of vertical bars and hoops does not seem to have made much difference to the state of crack developments. On the other hand, in the specimens reinforced with anchor bars, development of cracks along the anchor bars was observed. Photo 1 shows the views of some specimens which had been subjected to the testing.

CONCLUSIONS

A series of experiments reported herein has, within its limits, led to the following findings concerning the mechanical properties of cold-formed square tubular steel column bases.

i) By embedding exposed type tubular steel column bases in footing beams to a depth about equal to the depth of the tubular columns, it is possible to convert the hysteretic characteristics of the column bases from a slip type to one close to a spindle type characterized by high energy consumption.

ii) In case of column bases embedded shallowly, the presence of baseplates and anchor bolts plays an important role in enhancing the strength and ductility of the column bases.

iii) Anchor bars directly fixed to steel column are highly effective whereas hoops and slab reinforcing bars are less effective, and

iv) By embedding steel column bases shallowly in concrete footings, the sectional area, number and thickness of baseplates can be reduced compared with cases in which baseplates are exposed.

REFERENCES

Nakashima, S., S. Igarashi (1986). Behaviour of steel square tubular column bases embedded in concrete footings. *Proceedings of the International Conference on Steel Structures*. Part 1 Budva, 119-128.

Nakashima, S., S. Igarashi (1988). Influence of details of column bases on structural behaviour. *Prereport 13th Congress Seminar Session*. IABSE Helsinki, 705-710.

Nakashima, S. (1992). Experimental behaviour of encased steel square tubular column-base connections. *Proceedings of the 1st World Conference on Constructional Steel Design*, Acapulco, 240-249.

Nakashima, S. (1994). Behaviour of embedded type of steel column-bases with short embedment length under alternating repeated lateral loading. *Tubular Structures*, VI A. A. BALKEMA. ed. P. Grundy, A. Holgate & B. Wong, 519-526.

Nakashima, S., H. Kadoya and S. Igarashi (1995). A report concerning damage to steel structures caused by the Hanshin Earthquake of Jan. 17, 1995 in Japan – as to steel column bases and connections. *Proceedings of the Nordic Steel Construction Conference*, 95, Vol. 2, Malmö, 835-832.