SEISMIC BEHAVIOR OF STEEL-CONCRETE COMPOSITE COLUMN BASES

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SUMMARY

This paper deals with the experimental work that is part of an ongoing research project with the objective to gain a better understanding of the behavior of steel-concrete composite column bases under seismic loading. Seven specimens were tested to investigate structural behavior of steel-concrete composite column bases. The specimen consisted of concrete filled steel tube (CFT) column (or steel tube column), reinforced concrete footing beam, high base unit of cast steel designed by Hitachi Metal Corporation and 4 high strength anchor bolts. The following main influential elements were taken into consideration: axial load level and type of column (CFT or empty steel tube, rectangular section or circular section). Specimens were subjected to cyclic seismic lateral loading at the column tops under constant axial load. The cyclic lateral load was applied according to a predetermined sequence of rotation angle cycles of column base. Experimental results verified that the rotation stiffness and flexural strength of CFT column base calculated according to the formulas given by High Base Manual were in coincidence with the test results in cases of lower axial load without reference to the type of column. For the specimens under higher axial load, formulas underestimated their rotation stiffness and flexural strength. The comparison indicates that several modifications should be taken into consideration in column base design formulas of steel structure in order to make effective use of these formulas in CFT column base design, especially for column bases under higher axial load. It is made clear that ultimate flexural strength of this kind column base can be evaluated by ultimate strength with the coefficient of bearing stress of concrete taken into account.

INTRODUCTION

A new kind of ductile column base designed in bolt yield mode (yielding of anchor bolts precedes the concrete failure) was developed for steel structure and has been put into use since 1980s by Hitachi Metal Corporation in Japan. Design formulas of stiffness and flexural strength for these column bases have been specified in *High Base Manual* [1]. Statistics on damage of steel building structures by 1995 Hyogoken-Nanbu Earthquake indicated that almost no damage occurred in this kind of column bases, in contract, a large amount of damage was observed in the conventional type of column base plate connections. However, there is a lack of knowledge about the design of column bases using this new kind of column base plates in steel-concrete composite structures. This paper deals with the experimental work that is part of an ongoing research project with the objective to gain a better understanding of the behavior of steel-concrete composite column bases under seismic loading. The other objective of this paper is to propose suitable formulas to evaluate flexural strengths and rotation stiffness for these steel-concrete composite column bases.

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EXPERIMENTAL PROGRAM

Specimen Descriptions:

Seven specimens were tested to investigate the elastic-plastic behavior of steel-concrete composite column bases. The specimen consisted of concrete filled steel tube column (or empty steel tube column), reinforced concrete (RC) footing beam, cast steel base plate designed by Hitachi Metal Corporation, and 4 high-strength anchor bolts (yield stress =576Mpa, Grade SD490, Japanese Industrial Standard). Details of specimens are shown in figure1 and list of all specimens is shown in table 1. The following main influential elements were taken into consideration. No.1 specimen was selected as the basic type among all of the seven specimens, and it consisted of square concrete filled steel tube column (width 250 mm and thickness 12 mm), high-strength anchor bolts (normal diameter 30 mm), RC footing beam, and cast steel base plate. Specimen No.1 was tested under a lower axial load (*N*) equal to 49 kN. In specimen No.2, there was a bearing nut for each anchor bolt beneath the base plate with the purpose to investigate the resistance function of the anchor bolt under compression. No. 3 specimen was designed as same as No.1 specimen, but was tested under a higher axial load equal to 2480kN which was 30 percent of the squash load capacity of the column section. No.4 specimen was as the same as No.3 except there was a hollow (diameter 115mm) in the center of the base plate which was assumed for concrete casting for the connection of footing beam to the column. No. 5 specimen was using normal strength anchor bolt (yield stress=336Mpa, Grade SS490) and was tested under axial load *N*=49kN. Specimen No.6 was with a circular (diameter 250mm) section for the concrete filled steel column. And No.7 specimen was using empty steel tube column. Yield stresses of anchor bolts and cylinder compressive strength of footing beam concrete are shown in Table 1. Tensile test results of anchor bolts are shown in figure 2.

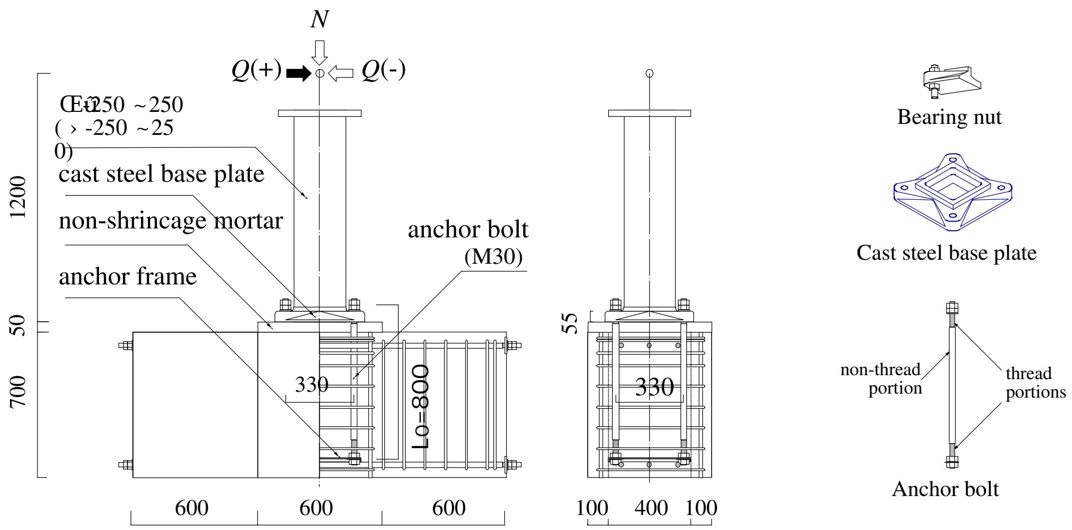


Figure 1: Specimens

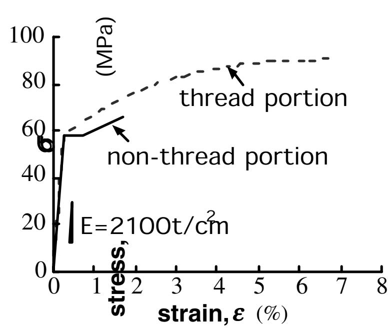


Figure 2: Stress – Strain Relations of Anchor Bolts

Loading System

All of the columns have been tested using the test setup system at the structural laboratory of Kyushu University. As shown in figure 3, the footing beam was fixed to the loading beam. The loading beam is supported by two sets of rollers on the reaction floor. The test setup was designed to subject the specimen to constant axial load and cyclic horizontal forces in a single curvature condition. The specimen is fixed to the loading beam by high-tension steel bars. The 5000-kN compressive capacity loading machine setting in the vertical-loading frame applied the axial load. Between the vertical loading machine and the specimen, there was a rotational pin to ensure the corresponding relative displacement of the top and the bottom of column. The lateral force was applied by a double-acting pseudocontrolled oil jack connected to the loading column at the top of the specimen (the level of loading pin). The loading column was fixed to the loading beam.

All specimens were subjected to cyclic lateral force and constant axial load. Load cells were used to monitor and record the applied axial load and lateral forces. The corresponding relative displacement between the tensile and compressive side of the base plate were measured by a pair of displacement meters, and the lateral forces were controlled by the difference of these two recorded disagreements which is in reference to the rotation angle of the base plate. The lateral loading sequence was controlled by deformation increment based on the reference rotation angle of the base plate.

Table 1 List of Specimens

Specimen No. (1)	Main Test Parameter (2)	Axial Force N (kN) (3)	Anchor Bolt (size: M30) σ_y(MPa) (4)	Cast Steel Base Plate (5)	Column (6)	Concrete for Footing Beam σ_B(MPa) (7)
1	Basic type specimen	49	576 (SD490) (H-AB490)	430~430 (thickness t=55mm)	CFT 250~250 (t=12mm)	25.4
2	with bearing nuts	49				25.7
3	under high axial force	2480				26.6
4	with a hole in the base plate (ϕ15)	2450				29.0
5	normal tension bolt SS490	49	336 (SS490)			29.3
6	circular section of column	49	576 (SD490) (H-AB490)		CFT ü250	29.4
7	empty steel tube column	49			250~250	23.7

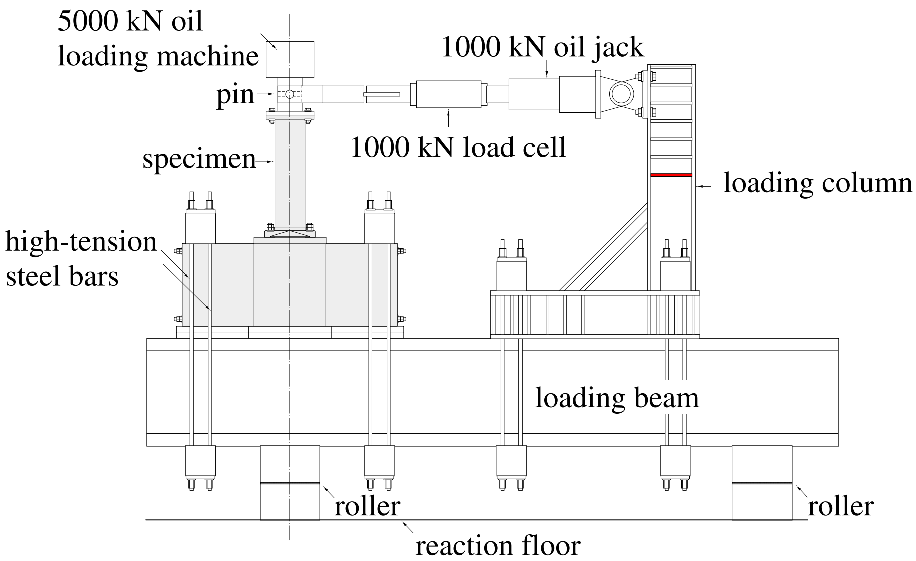


Figure 3: Test Setup

EXPERIMENTAL RESULTS

Moment - Rotation Angle Responses

Relations of flexural moment (*M*) to rotation angle (*R*) of column base from tests are shown in figure 4. Yield flexural strength of column base is defined as the flexural moment when the thread portions of the tensile anchor bolts first reach their yield stress. Points with black rectangles in moment – rotation angle curves represent the states when the anchor bolts reach tensile yielding stresses at first time. Notation *eMy* means the experimental value of yield flexural strength for each specimen in the *M* - *R* relation curves. Ultimate flexural strength of column base is defined as the flexural moment when the non-thread portions of the tensile anchor bolts first reach their yield stress and expressed as *eMu* in figure 4. Solid black circles in *M* - *R* relation curves represent the points that ultimate flexural strength is reached. Downward black triangles mean the maximum load carrying capacity or local buckling occurring in steel tubes.

All of the specimen except No.4 specimen, which was found after test that the steel used in column were of lower yield stress than the designed strength, failed in anchor bolts yield failure mode that is yielding of anchor bolts precedes the concrete failure. The No. 2 (with bearing nut), No. 6 (with circular section of column) and No. 7 (with empty steel tube column) specimens show almost the same behavior as that of the basic type specimen (No.1). The No.5 specimen (using normal strength anchor bolts) only displays 55~63 percent of the No.1 specimen's flexural strength. Effects of axial force can be observed by comparing the results of specimen No.1 and No.3 shown in figure 4(a) and (c). Ultimate flexural strength of the specimen under high axial force can be enlarged to twice of that of the specimen under lower axial force.

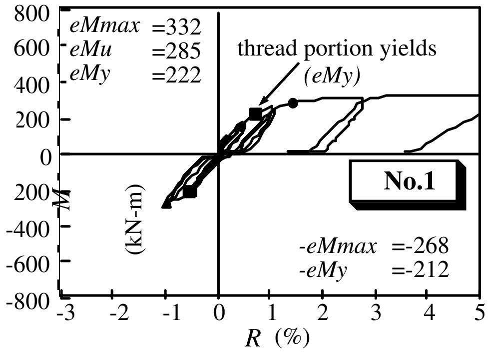
Calculation on Flexural Strength

Three kinds of ultimate flexural strengths of column base for specimens No.1 and No.3 are illustrated in figure 5. All of them are obtained using superposed method for evaluating ultimate strength of composite section (full plastic moment of the section). The first axial force – moment interaction curve was calculated using the specifications given by the Recommendations for design of steel tubes of Architecture Institute of Japan [2]. The second one was obtained according to the formulas in reference 3 [Kato 1984]. The third one used the superposed method for calculating ultimate strength of composite members and with coefficient of bearing stress of concrete taken into consideration [Nishimura 1986, Wakabayashi 1980]. Comparing these three kinds of ultimate strengths with the test results of specimen no.1 and No.3, it can be observed that the first one and the second one can evaluate specimen No.1 by great agreement, in contrast, the third method can estimate the ultimate flexural strength of specimen No.3. The differences among the three curves are the compressive stress of concrete used in calculating full plastic moment. Reduction factor for concrete strength of 0.85 is adopted in the AIJ Recommendations [2], a slight higher value 0.90 is supposed for reduction of concrete strength by Kato [3]. The third one was proposed by authors taking both reduction factor (0.85) and coefficient of bearing stress of concrete into considerations in calculating the full plastic moment of composite column bases.

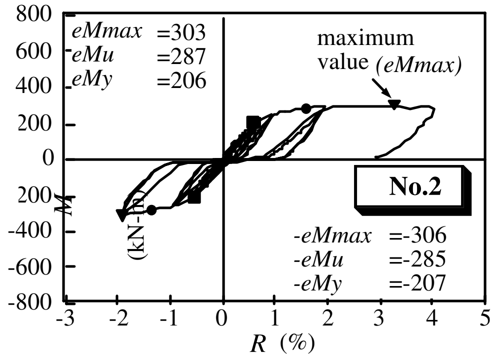
With bearing compressive stress function due to the enlarged concrete column base section considered, the maximum stress of concrete under the base plate can be obtained by multiplies a bearing stress factor λ which is expressed in equation (1).

$$F_B = \sigma_B \cdot \lambda, \qquad \lambda = \sqrt{\frac{A_1}{A_0}} \tag{1}$$

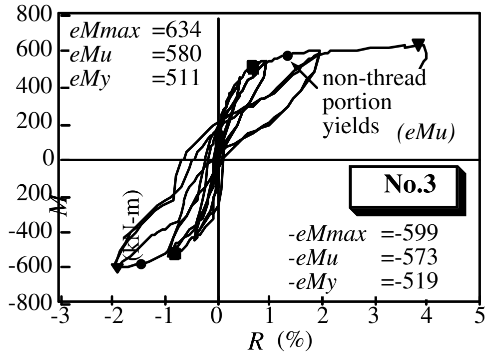
Where, σ_B=cylinder compressive strength of concrete, F_B=maximum stress of concrete with bearing stress effect considered, A_0=section area of steel column base (=430x430mm^2), and A_1=section area of the enlarged column portion (=600x600mm^2) (see figure 6).



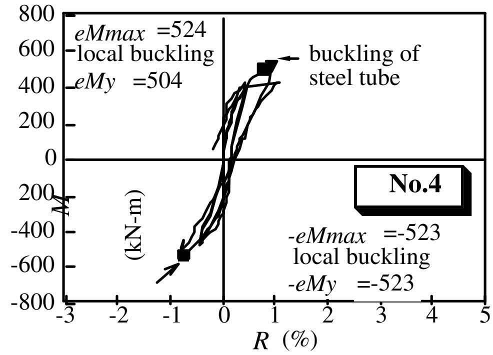
(a) Specimen No.1



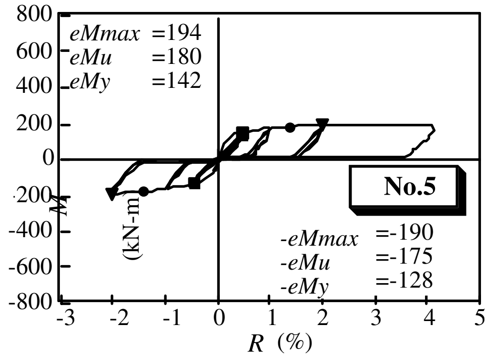
(b) Specimen No.2



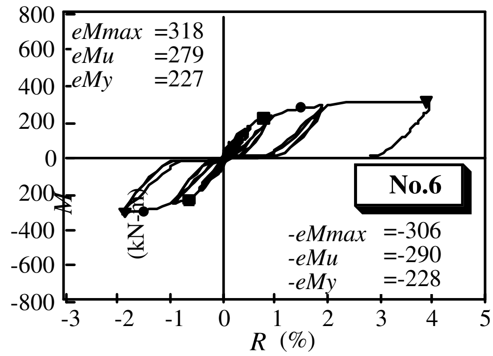
(c) Specimen No.3



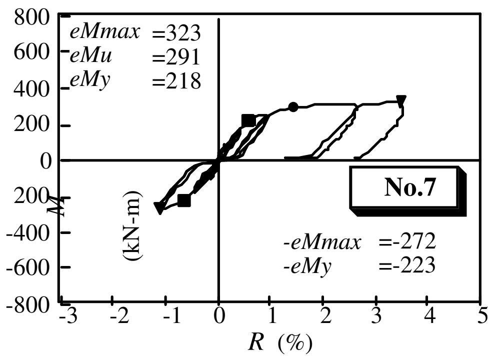
(d) Specimen No.4



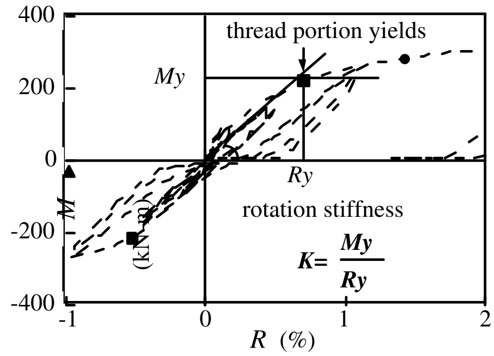
(e) Specimen No.5



(f) Specimen No.6



(g) Specimen No.7



(h) Definition of Rotation Stiffness

Figure 4: Test Results

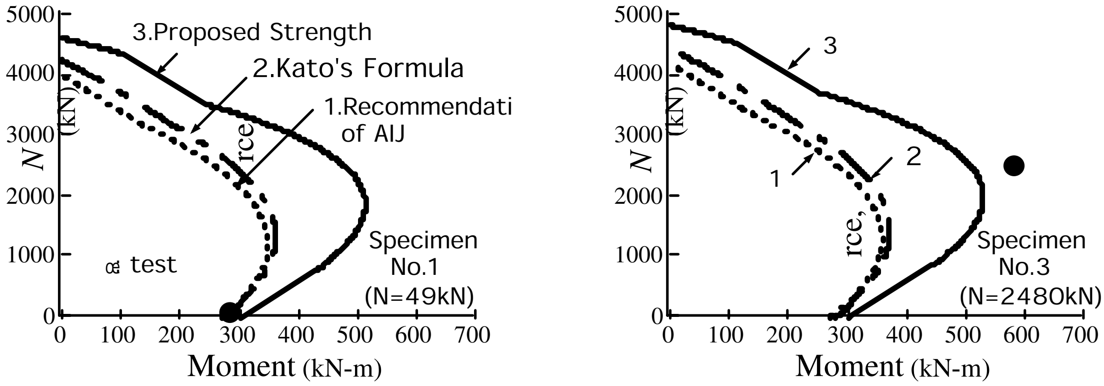


Figure 5: Axial Force – Moment Interaction Curves

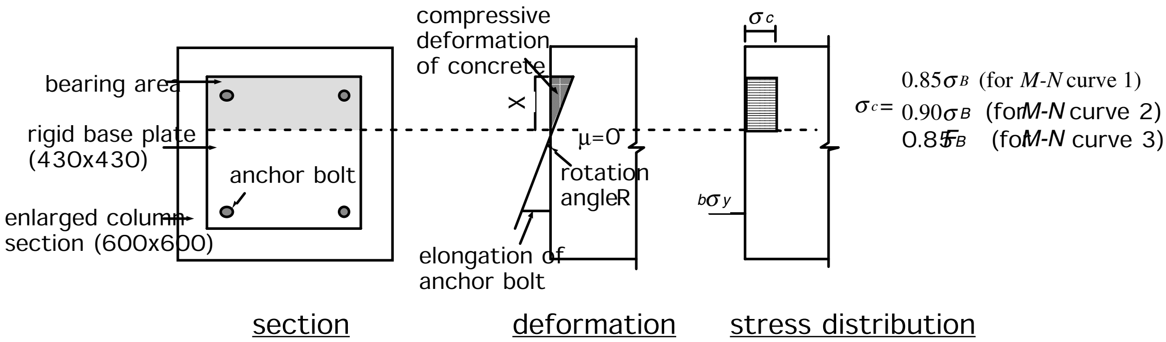


Figure 6: Column Base Section and Stress Distribution

Rotation Stiffness

Rotation stiffness is defined as the tangent gradient between the point where the thread portions yield and the original as illustrated in figure 4(g). The rotation stiffness can be calculated as follows [Kato, 1984],

$$K = \left(1 + 0.4\frac{N}{T_a}\right)\frac{0.5 \cdot E \cdot n \cdot A_b}{L}\left(d_t + d_c\right)^2 \quad (2)$$

Where, N =axial force, T_a = tensile load-carrying capacity when the thread portion yields ($= {}_b\sigma_y \cdot A_b$), E, n, A_b, L = modulus of elasticity, number, section area and length of the non-thread portion of an anchor bolt, d_t = distance between column flange and center of column base section, d_c=distance between anchor bolt and center of column base.

Equation 2 is introduced on the basis of the following assumptions:

(1) Anchor bolt s are elastic until the thread portion yields,
(2) Column base plate is a rigid body,
(3) Rotation center of column base is placed at the base plate center, and,
(4) Resultant force of compressive concrete is located beneath the extreme compressive flange fiber of steel tube column. Calculated rotation stiffness from equation (2) for all specimens except No.5 are compared with the test results shown in figure 7. The comparisons indicate that equation (2) can evaluate rotation stiffness for all specimens using high-tension anchor bolts safely.

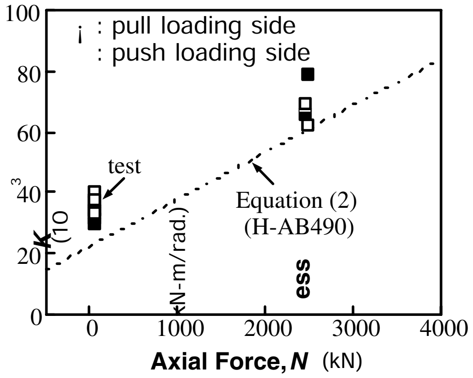


Figure 7: Rotation Stiffness of Column Base

CONCLUSIONS

1. Among all of the experimental parameters, the following elements have been proved that they almost did not influence the behavior of the composite column bases. They are 1) with or without bearing nut, 2) with or without a hole in the base plate, and 3) column type (concrete filled steel tube or empty steel tube, rectangular section or circular section).
2. Ultimate flexural strength was effected by the value of axial load. The ultimate strength of specimen increases with the applied axial load or strength of anchor bolt increased.
3. Axial force has effects on rotation stiffness of composite column bases. The rotation stiffness of specimen increases with the applied axial load increased.
4. Experimental results verified that flexural strengths of composite column bases calculated according to the formulas given by Recommendations of AIJ and Kato et al were in coincidence with the tests conducted under lower axial load without reference to the type of column. For the specimens under higher axial load, these formulas underestimated their flexural strengths.
5. With coefficient of bearing stress of concrete taken into account, ultimate strength obtained from superposed method can evaluates the test results under high axial loads in great agreement.
6. Rotation stiffness of composite column base can be estimated by equation (2).

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5. Wakabayashi M., Nakamura T., et al (1980), "Experimental Study on Ultimate Strength of Column Base in Steel Structure (part one)", *Summaries of Technical Papers presented at Annual Meeting of AIJ*, pp.1337-1338 (in Japanese)