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The effective cross section for strength and ductility

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ABSTRACT: In resent days, the necessity to assess the reliability of structures against expected severe loadings such as strong ground motions has emerged. In order to develop the proper design criteria of aseismic structures under complex cyclic loading, combined axial, shear and bending, conducted herein is an investigation on the effective cross sectional shape of steel bridge piers, paying attention to superiority in strength and ductility. Test specimens of different cross sections were subjected to bending and axial compression, and the comparative study was carried out by keeping the sectional area, slenderness parameter and section modulus as practically equal as possible. From the result, the circular section is found to be superior in strength and ductility.

1 INTRODUCTION

In order to develop the earthquake-resistant design criteria of structures, it is necessary to understand the inelastic load-deformation characteristics of structures under complex cyclic loading. Here, the strength and ductility, that is, the energy dissipation capacity is recognized as the important factor for the design. For the improvement of the strength and ductility, the followings have been studied extensively: 1)effect of the cross sectional shape; 2)effect of the inelastic characteristics of structural steel; 3)composite construction; 4)limitation on the thickness of plate/shell elements and slenderness of columns; and 5)effect of the redundancy of structures.

The objective of the current study is to assess the effective cross sectional shape of steel bridge piers experimentally, paying attention to both the strength and ductility. In the past, the box section and circular section have been used without recognition of any physical superiority or inferiority, but by the appearance and economical aspect. The different cross sections: box with sharp/round corners, stiffened box, and circular section were compared to each other regarding the strength and deformation by keeping the sectional area, slenderness parameter and section modulus as nearly equal as possible.

2 GENERAL DESCRIPTION OF EXPERIMENTS

In this study, the T-shape bridge pier as shown in Fig.1 is taken into consideration, in particular. The plastic hinge is considered to be formed at the bottom of column in case of excessive lateral forces due to strong ground motions. In order to investigate such a plastic hinge behavior, thin-walled beam-column segments were tested under cyclic bending and constant axial compressive force considering the local instability of plate/shell element .

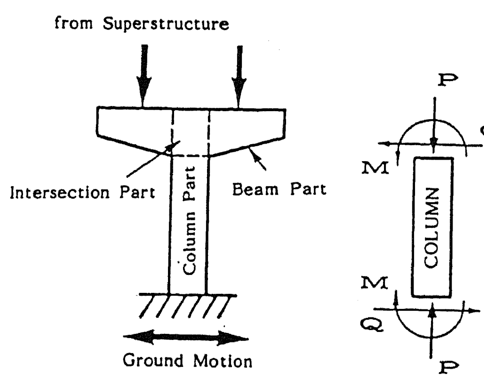


Fig. 1. T-shaped bridge piers

According to JSHB code (1973), the axial compressive stress(σ_c) and the compressive bending stress (σ_{bc}) must satisfy the following inequality:

$$\frac{\sigma_c}{\sigma_{ca}}+\frac{\sigma_{bc}}{\sigma_{ba}}\leq 1 \qquad (1)$$

where σ_{ca} and σ_{ba} refer to the allowable axial compressive stress and the allowable bending compressive stress, respectively. Fig. 2 shows the plot of σ_c/σ_{ca} vs.

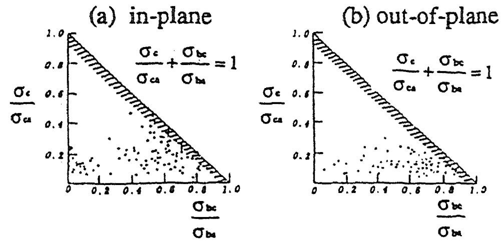


Fig. 2 Ratio of axial/bending stresses

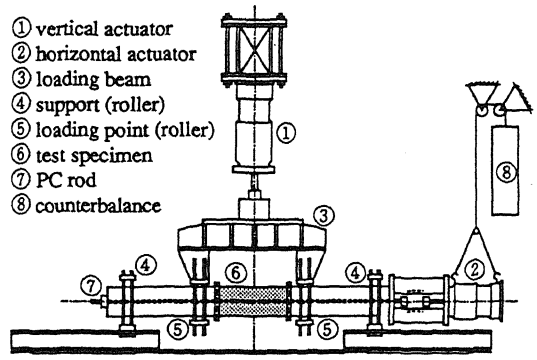


Fig. 3. Testing set-up

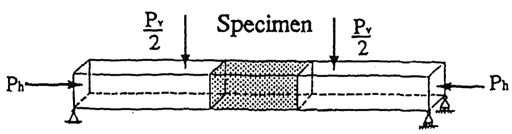


Fig. 4 Loading conditions

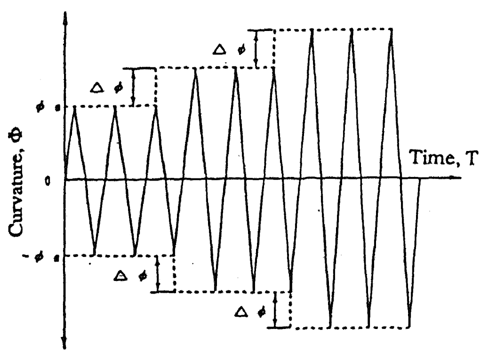
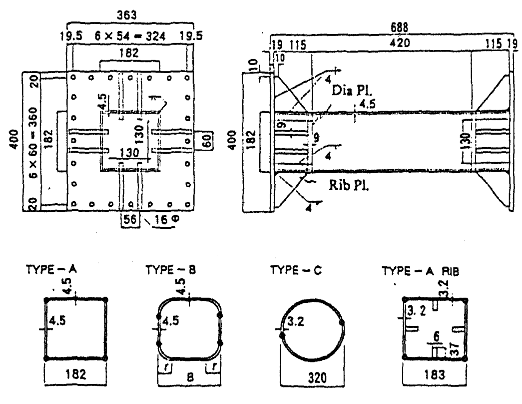


Fig. 5 Applied curvature amplitude vs. time history

σ_{bc}/σ_{ba} by Nakai et al. (1982), for 88 steel rigid frame bridge piers designed under the JSHB code(1973). From the plot, it may be apparent that the value of σ_{bc}/σ_{ba} varies from 0 to 1.0 uniformly and the maximum value of σ_c/σ_{ca} reaches in rare cases to 0.5; however, for design purposes, it may be thought to vary between 0.2 and 0.33.

In order to simulate such a loading condition, the testing set-up shown in Figs. 3 and 4 is utilized, which is consisting of the closed-loop servo-controlled hydraulic actuators and the personal computer for control and data acquisition. The specimen connected with nondestructive beam-columns at both ends by high tension bolts , is set as a simple beam on the testing bed and subjected to cyclic lateral two-point loads vertically, so that the test specimen is considered to have an uniform alternating bending moment. The axial compressive force is applied as its reaction force from the tensioned PC bar installed inside the specimen. Here, the application of the axial compressive force is precisely servo-controlled to be constant from the beginning to the end of test, and that of the alternating bending is controlled by computer to trace the specific average curvature-time history, namely, ramp-wave with a constant amplitude as shown in Fig. 5. Details of this structural testing system may be referred to Niwa,Y.(1983) and Watanabe,E.(1988).

The test specimens used in this study and loading condition for each specimen are summarized in Table1. The shapes and nominal dimensions of test specimens are shown in Fig. 6. In order to find the most efficient cross section for strength and ductility, a comparative study is conducted for several combinations of the cross sectional properties in such a way that some of these values are kept constant while the rest are varied. In this study, (1) the cross sectional area is constant considering economical aspect; (2) the slenderness parameter is constant for strength of global stability; (3) the width-to-thickness ratio is taken to guarantee the yield stress against the local stability; and (4) the rigidity of stiffeners is three times of required value by JSHB.



TYPE	B	r
TYPE - B34	195	34
TYPE - B40	198	40
TYPE - B50	202	50

Fig. 6. Dimensions of test specimen (Nominal, unit: mm)

Table 2 shows the cross sectional properties based on the actual measurement of specimens. There is slight difference from the designed value because of uncertainties in manufacturing process, however, it is small enough to be neglected and does not affect the comparative study.

Fig. 7 shows the outline of the comparative study. Firstly, the effect of cross sectional shape is sought among A, B34 and C types, keeping A, and R and $\bar{\lambda}$ constant. Secondly, the effect of radius of round corners is examined among, B34, B40 and B50 types by keeping A, Z and $\bar{\lambda}$ constant. Thirdly, the effective R-value including round corners is examined between A and BAll. Finally, the effect of stiffening by round corners and longitudinal stiffeners is discussed by comparing ARib and B types. Thus, 16 specimens are prepared for various loading condition as shown in this table.

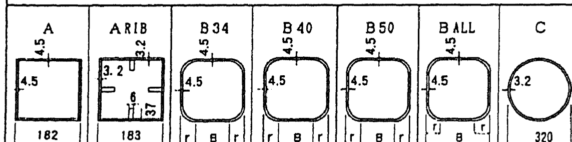
Table 1. Loading conditions and specimen names

Specimen Type	Monotonic Bending P/Py=0.20	0.33	Cyclic Bending P/Py=0.20	0.33
A	A-M1	A-M2	A-C1	A-C2
ARib	AR-M1			
B34	B34-M1	B34-M2	B34-C1	B34-C2
B40	B40-M1			
B50		B50-M2		
BAll	BA-M1			
C	C-M1	C-M2	C-C1	C-C2

Table 2. Cross sectional properties of test specimens (Actual)

Specimen Type	Thick-ness t(mm)	Width B(mm)	D(mm)	Radius r(mm)	Width-to Thickness Ratio Rf(Flat)	Rs(Shell)	Length l(mm)	Slenderness Prameter $\bar{\lambda}$	Cross Sectional Area A(cm²)	Section Modulus Z(cm³)
A-M1	4.25	181.4	181.6		0.755		419	0.063	30.13	174
AR-M1	3.05	182.5	182.2		0.572		402	0.070	30.01	151
B34-M1	4.25	194.5	195.2	33.3	0.561	0.127	440	0.065	30.13	178
B40-M1	4.25	197.4	198.2	39.7	0.518	0.139	443	0.065	30.16	179
BA-M1	4.25	181.8	182.3	29.7	0.778	0.120	410	0.065	28.21	156
C-M1	3.05	320.7	320.7			0.350	649	0.069	30.44	239
A-M2	4.25	181.2	181.7		0.754		419	0.063	30.12	174
B34-M2	4.25	194.7	195.7	33.8	0.557	0.128	438	0.065	30.15	179
B50-M2	4.25	201.4	202.4	48.5	0.458	0.153	449	0.065	30.22	180
C-M2	3.05	320.5	320.5			0.350	649	0.069	30.42	239
A-C1	4.25	182.3	181.6		0.759		419	0.063	30.21	175
B34-C1	4.25	194.6	195.2	33.4	0.561	0.127	439	0.065	30.13	178
C-C1	3.05	320.7	320.7			0.350	648	0.069	30.44	239
A-C2	4.25	181.8	181.8		0.757		419	0.063	30.18	175
B34-C2	4.25	194.3	195.3	33.2	0.561	0.127	439	0.065	30.13	178
C-C2	3.05	320.8	320.8			0.350	648	0.069	30.45	239

Note: Flat Plate Element $R_f = \frac{b}{t}\sqrt{\frac{12(1-\nu^2)\sigma_y}{K_E E \pi^2}}$ Shell Element $R_s = \sqrt{\sqrt{3(1-\nu^2)}\frac{\sigma_y}{E}\frac{r}{t}}$ $\bar{\lambda} = \frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}}\left(\frac{kL}{\sqrt{I/A}}\right)$



Specimen Type / Effects Examined by Comparative Study	Specimen Type: A	ARIB	B34	B40	B50	BALL	C	Parameters Related to Strength and Ductility: Cross Sectional Area A	Section Modulus Z	Width-to-Thickness Ratio R	Slenderness Parameter $\bar{\lambda}$
	R=0.700	0.500	0.500	0.465	0.403	0.700	0.307				
① Cross Sectional Shape	○		○				○	□		□	□
② Radius of Round Corners (r)			○	○	○	-		□	□		□
③ R Value Considering Round corners	○					○				□	□
④ Stiffening Effect		○	○					□		□	□

Fig. 7. Outline of comparative study

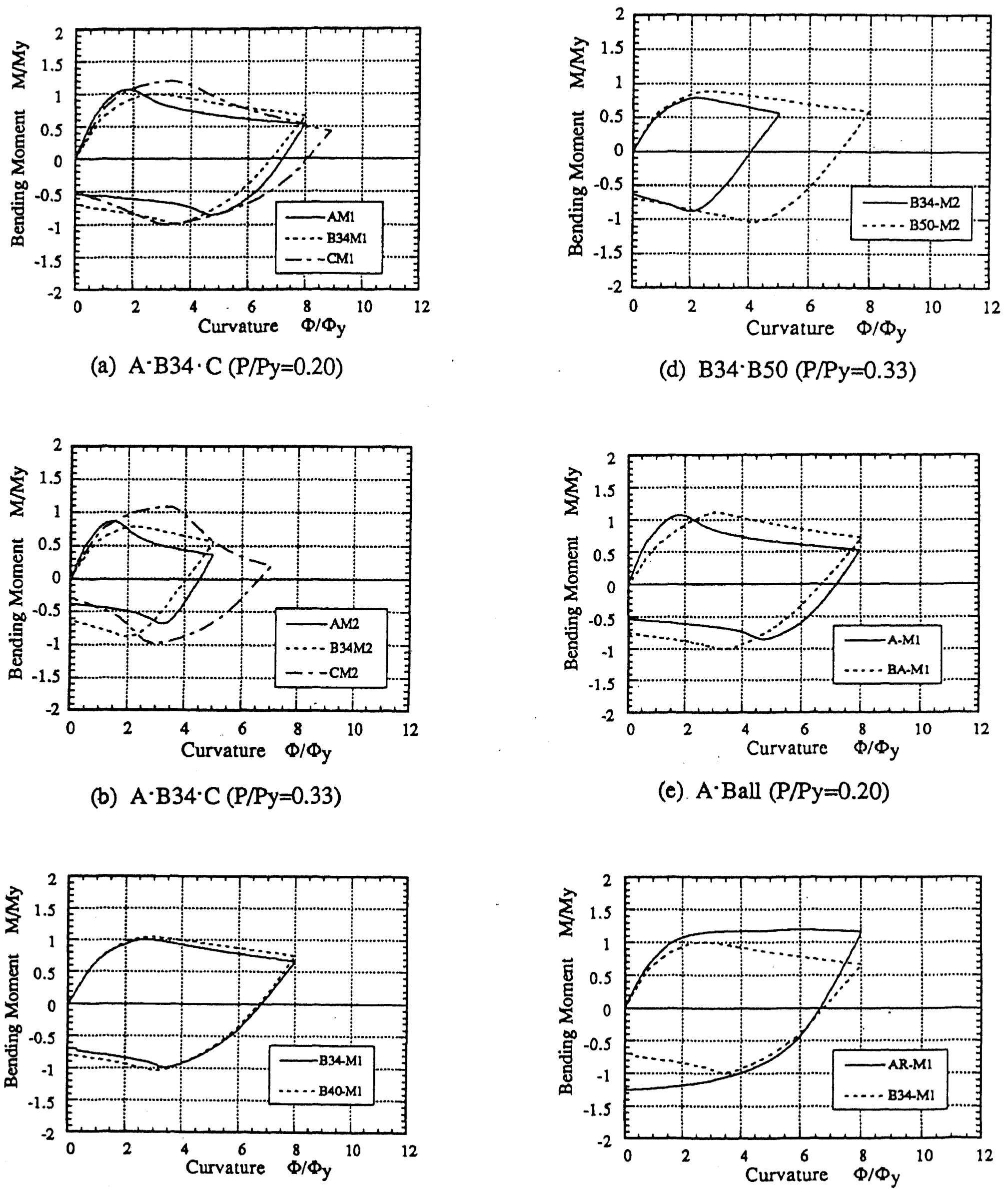
Note: Parameters (□) are kept constant

3 TEST RESULTS AND DISCUSSIONS

Figs. 8 and 9 show the bending moment(M)-curvature(ϕ) curves under monotonically increased curvature and cyclically applied curvature, respectively, where the bending moment and curvature are normalized by the yielding values, My and ϕy, respectively. From the comparison of these moment-curvature relations, the following observations may be made with respect to each parameter.

3.1 EFFECTIVE CROSS SECTIONAL SHAPE

The energy absorption ability is the most emminent in C-type. Thus, it may be concluded that C-type, the circular section is superior in strength and ductility according to the current design specifications. However, at the same time, the deterioration is also seen not insignificant after its peak due to rapid propagation of buckled wave along the circumference.



(a) A·B34·C (P/Py=0.20)
(d) B34·B50 (P/Py=0.33)
(b) A·B34·C (P/Py=0.33)
(e) A·Ball (P/Py=0.20)
(c) B34·B40 (P/Py=0.20)
(f) AR·B34 (P/Py=0.20)

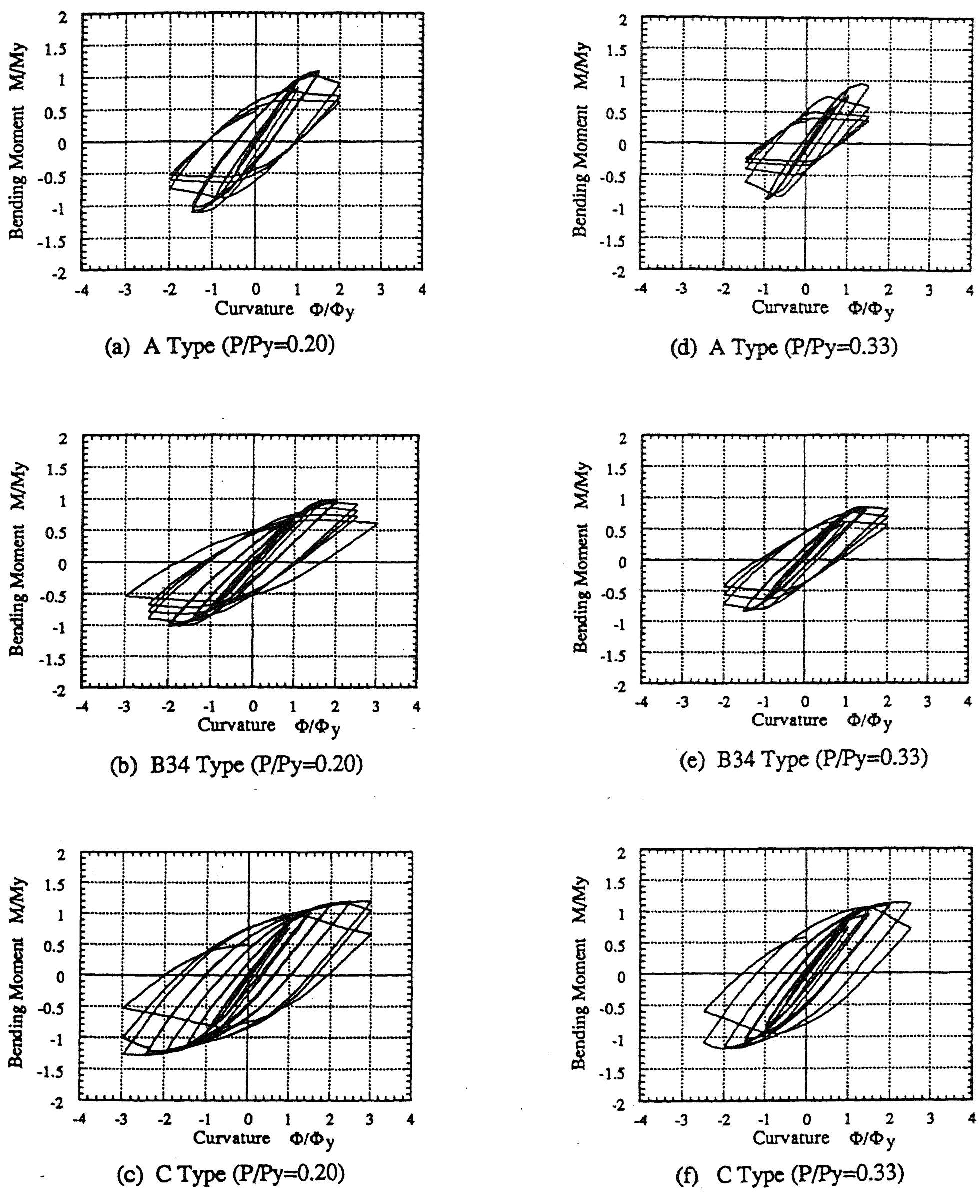
Fig. 8. Bending moment-curvature curves under monotonic bending

3.2 OPTIMAL RADIUS OF ROUND CORNERS

B34, B40 and B50 are types corresponding to the radius-to-width ratio of r/B= 1/6, 1/5and 1/4, respectively. As this ratio becomes larger, the strength and ductility are improved. It is concluded that the box with round corners is superior, since the propagation of buckled wave of flange plates may be delayed by the existence of round corners and the stress concentration becomes milder at corners.

3.3 STIFFENING BY ROUND CORNERS AND LONGITUDINAL STIFFENERS

In comparing ARib-type to B34-type, it is found that ARib-type, the stiffened box is superior in strength and ductility. No strength deterioration is observed even at $\phi/\phi y=8$. This is because the stiffened plate with rigidity ratio of 3 has the high strength by preventing the local deformation. The effectiveness of round corners may be equivalent to the use of stiffener plates with rigidity ratio of less than 3.



(a) A Type (P/Py=0.20)

(d) A Type (P/Py=0.33)

(b) B34 Type (P/Py=0.20)

(e) B34 Type (P/Py=0.33)

(c) C Type (P/Py=0.20)

(f) C Type (P/Py=0.33)

Fig. 9. Bending moment-curvature curves under cyclic bending

Table 3. Strength and ductility under monotonic loading

Specimen Type	M/My *1	Φ/Φy *2
A-M1	1.06	1.80
B34-M1	1.00	2.70
C-M1	1.21	3.20
A-M2	0.86	1.55
B34-M2	0.78	2.25
C-M2	1.10	3.30
B40-M1	1.05	2.90
B50-M2	0.90	2.55
BA-M1	1.12	3.15
AR-M1	1.15	8.00

*1 Maximum bending strength.
*2 Curvature when maximum strength is obtained.

Table 4. Strength and ductility under cyclic loading

Specimen Type	M/My *1	Φ/Φy *2
A-C1	1.08	1.50
B34-C1	1.00	2.00
C-C1	1.17	2.50
A-C2	0.82	1.00
B34-C2	0.80	1.50
C-C2	1.10	2.00

*1 Maximum bending moment of envelop.
*2 Maximum amplitude of curvature when the hysteresis is stabilized.

4 CONCLUSIONS

The monotonic/cyclic loading tests were carried out in order to investigate the effective cross sectional shape paying attention to both the strength and ductility. Conclusions drawn from the current study can be summarized as follows:

(1) Circular cross section is superior in the strength, ductility and aesthetic appearance if the intensity of axial compression is around 20% of the yielding value. The stiffened box is found to be superior as well.
(2) The use of round corners for box sections can improve the ductility. In addition, the strength and ductility can be improved by increasing the radius of round corners. However, it may not be so expected as to be equivalent to fully stiffened box section.
(3) The axial compressive force is one of the most destabilizing factors to reduce the strength and ductility, particularly, for the cyclic loading conditions.

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