STRENGTH AND BEHAVIOR OF SLENDER CONCRETE FILLED STEEL TUBULAR COLUMNS

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SUMMARY

Concrete filled steel square and circular tubular columns are tested. Test is composed of two Series. In Series I, columns are subjected to concentric and eccentric axial force at both ends. In Series II, columns are cantilever columns, and subjected to alternating horizontal load under constant vertical load. As a main experimental parameter, buckling length - section depth ratio of a column is selected. Strength and behavior are examined, and design methods for slender composite columns are investigated.

INTRODUCTION

Concrete filled steel tubular columns have many excellent structural properties, such as high compressive strength, large ductility and large energy absorption capacity. Then, composite tubular columns have been gradually used widely in the world.

The strength of steel and concrete for building structures is getting higher with the development of new materials. The cross section with high strength materials becomes smaller, and consequently a column becomes more slender. The design of a column considering buckling and $P\delta$ effect becomes more important in such situation.

There are many researches on composite tubular columns in Japan. However, these researches are mainly on short columns subjected to earthquake loading. There are no systematic and fundamental studies on concrete filled steel tubular columns under concentric and eccentric axial force in wide range of slenderness ratios. Moreover, the inelastic behavior of slender columns subjected to earthquake loading should be examined in a seismic region.

Objectives of this paper are to obtain the maximum load and behavior by performing an experimental work, and to examine design formulas for the slender concrete filled steel tubular columns, comparing with those of short columns.

TEST PROGRAM

General

The test specimen is a concrete filled steel tubular beam-columns of which steel portion is a cold-formed square and circular section. Width (Diameter)-thickness ratio of a steel plate element is 33 and 37, respectively. The material of steel portion is mild steel (STKR400 (square), STK400 (circular), Japanese Industrial Standards). The design strength of concrete is 300kg/cm^2. The concrete casting is carried out through a hole picked in an end plate of a specimen.

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Test is composed of two Series (that is Series I and Series II). In Series I, specimens are subjected to concentric and eccentric axial force at both ends as shown in Fig. 1. In Series II, specimens are subjected to alternating horizontal load under constant axial force (see Fig. 2).

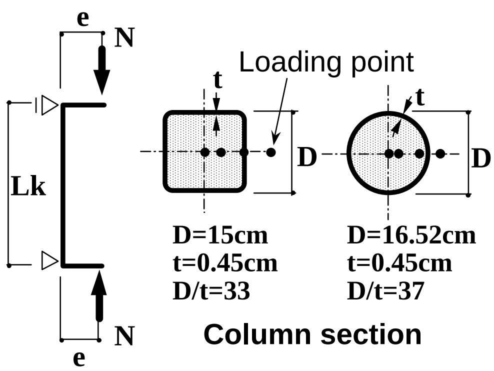

Figure 1: Loading condition (Series I)

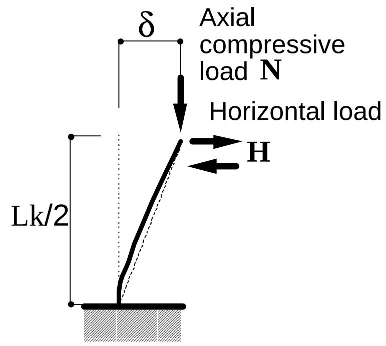

Figure 2: Loading condition (Series II)

Experimental Parameters

As the experimental parameters in Series I, buckling length (L_k)-the section depth (D) ratio L_k/D and magnitude of eccentricity e are selected, and they vary as follows; L_k/D = 4, 8, 12, 18, 24, 30 and e = 0, κ, 3κ, 5κ (κ: core of a section). Total sixty specimens are tested, including twelve vacant tubular columns under concentric loading. Test conditions of specimens are shown in Table 1.

In Series II, buckling length-the section depth ratio L_k/D (6, 9, 12,18, 24) and axial load ratio n ($=N/N_0=$ 0.2,0.4, 0.5, 0.6 , 0.7, N_0=axial compressive strength) are selected as the parameters. Total twenty specimens are tested. Test conditions of specimens are shown in Table 2.

Mechanical Properties

In addition to the tensile test of steel coupon, vacant stub columns of steel tubes and concrete cylinders are tested under compression to examine the stress-strain relations.

In Series I, average yield stress is equal to 4.47 (square), 4.22 (circular) t/cm^2, and average ultimate strength equal to 5.0 t/cm^2 (square, circular), both obtained from tensile tests. As the results of stub column test, yield stress σ_y of a tube obtained from 0.2% offset method is 4.2 (square), 3.6 (circular)t/cm^2 and ultimate strength σ_u is equal to 4.27 (square), 4.06(circular)t/cm^2. The average compressive strength F_c of concrete obtained from the cylinder compressive test is 325 (square) and 417 (circular) kg/cm^2.

In Series II, average yield stress is equal to 4.12 (square) and 4.20 (circular) t/cm^2, and average ultimate strength equal to 4.94 (square), 4.90 (circular) t/cm^2, both obtained from tensile tests. Yield stress σ_y of a tube obtained from 0.2% offset method is 4.04 (square), 3.62 (circular) t/cm^2 and ultimate strength σ_u is equal to 4.05 (square), 4.20 (circular) t/cm^2. The average compressive strength F_c of concrete obtained from the cylinder compressive test is 354 (square, circular) kg/cm^2. Mechanical properties of steel and concrete under compressive force are summarized in Table 3.

Table 1: Test program (Series I)

Specimen	Lk/D	e/κ	Lk(mm)		e(cm)	
				›		›
C4-0	4	0	600	661	0.0	0.0
C4-1	4	1	600	661	2.5	2.07
C4-3	4	3	600	661	7.5	6.20
C4-5	4	5	600	661	12.5	10.32
S4-0*	4	0	600	661	0.0	0.0
C8-0	8	0	1200	1322	0.0	0.0
C8-1	8	1	1200	1322	2.5	2.07
C8-3	8	3	1200	1322	7.5	6.20
C8-5	8	5	1200	1322	12.5	10.32
S8-0*	8	0	1200	1322	0.0	0.0
C12-0	12	0	1800	1982	0.0	0.0
C12-1	12	1	1800	1982	2.5	2.07
C12-3	12	3	1800	1982	7.5	6.20
C12-5	12	5	1800	1982	12.5	10.32
S12-0*	12	0	1800	1982	0.0	0.0
C18-0	18	0	2700	2974	0.0	0.0
C18-1	18	1	2700	2974	2.5	2.07
C18-3	18	3	2700	2974	7.5	6.20
C18-5	18	5	2700	2974	12.5	10.32
S18-0*	18	0	2700	2974	0.0	0.0
C24-0	24	0	3600	3965	0.0	0.0
C24-1	24	1	3600	3965	2.5	2.07
C24-3	24	3	3600	3965	7.5	6.20
C24-5	24	5	3600	3965	12.5	10.32
S24-0*	24	0	3600	3965	0.0	0.0
C30-0	30	0	4500	4956	0.0	0.0
C30-1	30	1	4500	4956	2.5	2.07
C30-3	30	3	4500	4956	7.5	6.20
C30-5	30	5	4500	4956	12.5	10.32
S30-0*	30	0	4500	4956	0.0	0.0

* : vacant

Table 2: Test program (Series II)

Name	Lk/D	n	shape
C03-05	6	0.5	Circular ›
C03-07	6	0.7	
C04-06	9	0.6	
C04-07	9	0.7	
C06-04	12	0.4	
C06-06	12	0.6	
C09-02	18	0.2	
C09-04	18	0.4	
C12-02	24	0.2	
C12-04	24	0.4	
R03-05	6	0.5	Square
R03-07	6	0.7	
R04-05	9	0.5	
R04-07	9	0.7	
R06-04	12	0.4	
R06-06	12	0.6	
R09-02	18	0.2	
R09-04	18	0.4	
R12-02	24	0.2	
R12-04	24	0.4	

Table 3: Mechanical properties (Compressive test)

Steel Tube	Yield stress $\sigma y(t/cm^2)$	Ultimate stress $\sigma u(t/cm^2)$	Fc (kg/cm^2)	Loading conditon
Square	4.20	4.27	325	Series I
Circular	3.60	4.06	417	
Square	4.04	4.05	354	Series II
Circular	3.62	4.20	354	

Table 4: Size of steel tube

Steel Tube	Depth (mm)	Thickness (mm)	Loading conditon
Square	149.8	4.27	Series I
Circular	165.2	4.08	
Square	150.6	4.36	Series II
Circular	165.4	4.18	

Measured dimensions of steel tube are shown in Table 4.

Loading Apparatus

In Series I, loading apparatus is shown in Fig. 3. Exact pin-ended conditions are obtained because the specimens are loaded through hemispherical oil film bearing at each end. The assigned eccentricity *e* is given to the specimen by moving the bearing plates. Axial load in one direction is applied to a specimen.

In Series II, the experimental apparatus is shown in Fig. 4. The vertical load *N* was applied to a specimen by a 500ton testing machine and kept constant value assigned in the test program during horizontal loading process. The horizontal load was applied to the top of a specimen by a hydraulic jack. Relative horizontal sway due to the application of horizontal load *H* actually occurs at the bottom of the specimen, with the movement of a supporting frame.

The horizontal loading program in Series II is as follows; Specimens are tested under the cyclic loading, where the amplitude of sway displacement is increased by 0.5% or 1% of the column height in a stepwise manner every one cycle of loading completed.

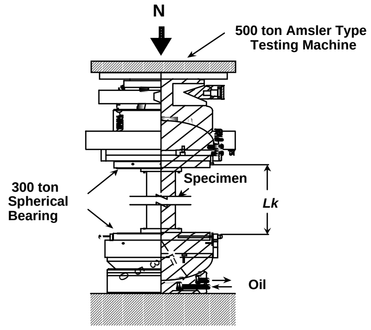

Figure 3: Loading apparatus (Series I)

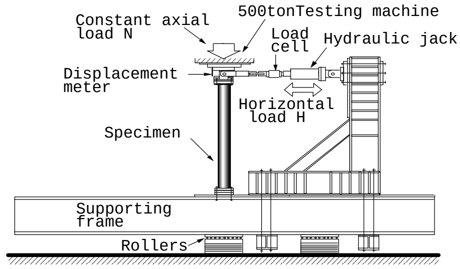

Figure 4: Loading apparatus (Series II)

DESIGN FORMULA

Design Formula

The experimental maximum strength is compared with a design strength. On the basis of the experimental results of Series I, AIJ (Architectural Institute of Japan) design method [1, 2] is examined and modified AIJ design methods has been proposed [3, 4, 5].

AIJ design formula [1, 2] for slender concrete filled steel tubular beam-columns is as follows:

$$N_u = {}_cN_u, \quad M_u = {}_cM_u + {}_sM_{u0}(1 - {}_cN_u/N_k) \qquad \text{if } N_u < {}_cN_{cu}$$
$$N_u = {}_cN_{cu} + {}_sN_u, \quad M_u = {}_sM_u\,(1 - {}_cN_{cu}/N_k) \qquad \text{if } N_u > {}_cN_{cu} \qquad (1)$$

Where subscripts s and c indicate forces carried by the steel and concrete portions of a concrete filled tubular columns. In Equation (1), ${}_cN_{cu}$ denotes strength of the concrete column subjected to the axial load only, ${}_sM_{u0}$ full plastic moment of the steel section subjected to the bending only. N_u and M_u denote the ultimate strength of a slender beam-column, and N_k Euler buckling load of a concrete filled tubular column.

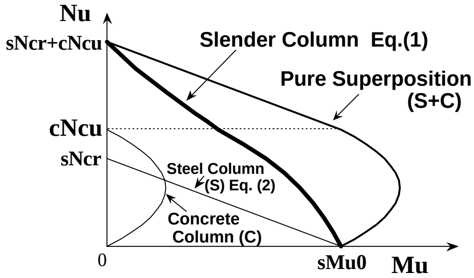

Figure 5: Superposed strength

AIJ strength formula for slender composite columns (Slender columns are defined as $L_k/D>12$) originated by Wakabayashi [6] is used as a design strength. The formula means that strength of a slender column is obtained by summing up the strength of concrete column and steel tubular column, while the effect of additional bending moment ($P\delta$ moment) is taken into consideration as shown in Fig.5.

Modified AIJ method has been proposed by authors [3, 4]. The difference between AIJ method and modified AIJ method is in the strength of concrete column. In modified AIJ method, approximately exact concrete column strength obtained from the numerical analysis is used. In this paper, more simple equation for the ${}_cM_u$-${}_cN_u$ relations are used.

Strength of Steel Column ($_s\boldsymbol{N_u}$, $_s\boldsymbol{M_u}$)

As an interaction between $_s\boldsymbol{N_u}$ and $_s\boldsymbol{M_u}$ appearing in Equation (1), a conventional strength formula [7] used in the plastic design of steel structures is adopted in the form of

$$\frac{{}_s\boldsymbol{N_u}}{{}_s\boldsymbol{N_{cr}}}+\frac{{}_s\boldsymbol{M_u}}{(1-\frac{{}_s\boldsymbol{N_u}}{{}_s\boldsymbol{N_E}})\,{}_s\boldsymbol{M_{u0}}}=1 \quad (2)$$

in which $_s\boldsymbol{N_u}$ denotes the axial load, $_s\boldsymbol{N_{cr}}$ the critical load, $_s\boldsymbol{N_k}$ Euler buckling load, $_s\boldsymbol{M_u}$ the applied end moment, $_sM_{u0}$ the full plastic moment.

Strength of Concrete Column ($_cN_u$, $_cM_u$)

In AIJ design formula, the strength $_cN_u$ and $_cM_u$ are calculated as the ultimate axial force and end moment by using a moment amplification factor, where the critical section becomes full plastic state with rectangular stress distribution of $0.85F_c$. End eccentricity not less than 5% of the concrete depth is considered in the above calculation.

In addition to the above strength, authors have proposed $_cM_u$-$_cN_u$ relations on the basis of the results of elasto-plastic analyses, where end moment-axial force interaction relations are calculated by assuming a sine curve deflected shape of a beam-column. The interaction relations are expressed by an algebraic equation [3]. The equation for the $_cM_u$-$_cN_u$ relations, however, is considerably complicated. In this paper, more simple equation are used in the form of

When $_cN_u < 0.9{}_cN_{cr}$ (=0.9 $_cN_{cu}$)

$$\frac{{}_c\boldsymbol{M_u}}{{}_c\boldsymbol{M}_{\max}}=4(\frac{{}_c\boldsymbol{N_u}}{0.9{}_c\boldsymbol{N_{cr}}})(1-\frac{{}_c\boldsymbol{N_u}}{0.9{}_c\boldsymbol{N_{cr}}}) \quad (3\text{-}1)$$

When $0.9{}_cN_{cr}\ {}_cN_u\ {}_cN_{cr}(={}_cN_{cu})$ $\quad {}_cM_u = 0$ (3-2)

Symbols appearing in equation (3) are shown in appendix.

Calculation of Design Strength

In this paper, the design strength is computed according to the Equation (1), though the strength of short beam-columns (L_k/D<12) is supposed to be calculated as the full plastic moment in AIJ Standard [1, 2]. In order to compare the design strength with the experimental maximum load N_{exp}, yield stress σ_y obtained from 0.2% offset method is used as the strength of steel tube shown in Table 3.

By substituting equations 2 and 3 for Equation 1 and equating $_cN_{cu}$ with $_cN_{cr}$, we get the strength equation (4).

When $N_u\ 0.9{}_cN_{cr}$

$$\boldsymbol{C_M M_u}=4(\frac{\boldsymbol{N_u}}{0.9{}_c\boldsymbol{N_{cr}}})(1-\frac{\boldsymbol{N_u}}{0.9{}_c\boldsymbol{N_{cr}}})_c\boldsymbol{M}_{\max}+{}_s\boldsymbol{M_{u0}}(1-\frac{\boldsymbol{N_u}}{\boldsymbol{N_k}}) \quad (4\text{-}1)$$

When $0.9{}_cN_{cr}\ N_u\ {}_cN_{cr}$

$$\boldsymbol{C_M M_u}={}_s\boldsymbol{M_{u0}}(1-\frac{\boldsymbol{N_u}}{\boldsymbol{N_k}}) \quad (4\text{-}2)$$

When N_u□$_cN_{cr}$□

$$\boldsymbol{C_M M_u}=(1-\frac{\boldsymbol{N_u}-{}_c\boldsymbol{N_{cr}}}{{}_s\boldsymbol{N_{cr}}})(1-\frac{\boldsymbol{N_u}-{}_c\boldsymbol{N_{cr}}}{{}_s\boldsymbol{N_E}})(1-\frac{{}_c\boldsymbol{N_{cr}}}{\boldsymbol{N_k}})_s\boldsymbol{M_{u0}} \quad (4\text{-}3)$$

RESULTS AND DISCUSSIONS

Elasto-Plastic Behavior

Figure 6 shows the relations between the axial load and the deflection at the mid-span section in Series I. In each figure, the buckling length -section depth ratio L_k/D is kept constant, changing the value of eccentricity. Solid line indicates the result of concrete filled steel tubular columns and dashed line vacant tubular columns.

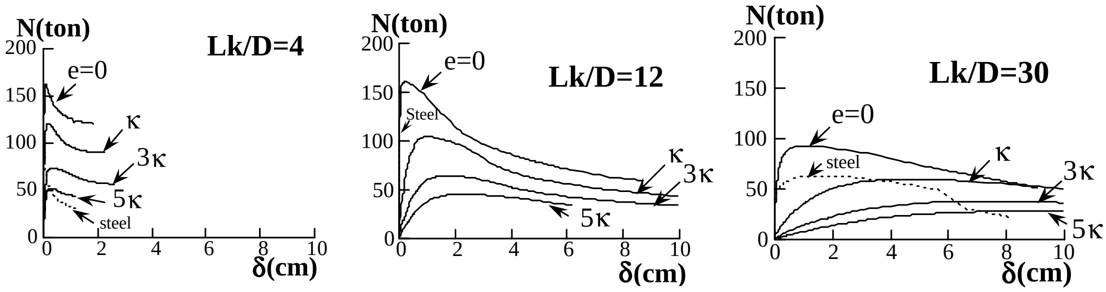

Figure 6: Axial load-lateral deflection relation (Series I: Square section)

It is observed that as the eccentricity becomes large the maximum load decreases, while the deflection at the load increases. Effect of the magnitude of eccentricity on the strength and behavior becomes small as the L_k/D ratio becomes large.

Figure 7 shows the horizontal load (H)- lateral displacement (δ) relations in Series II. The experimental behavior is shown by solid line. The dotted and dashed line indicates the plastic collapse mechanism line which is obtained by assuming a plastic hinge forming at the base of the beam-column, and dotted line the results of elasto-plastic analysis. Elasto-plastic analysis is performed under a monotonic increasing displacement condition.

Though all specimens could attain the strength given by the plastic collapse mechanism line, the deterioration of the restoring force of specimens with a square section becomes apparent in case of the axial load ratio $n > 0.5$. In case of a circular section, remarkable ductile behavior is observed even under high axial load. And the strength is much higher than that predicted by elasto-plastic analysis, when the L_k/D ratio becomes small. As to the effect of the value of L_k/D, specimens with large L_k/D shows a good behavior in the same manner as that with small L_k/D.

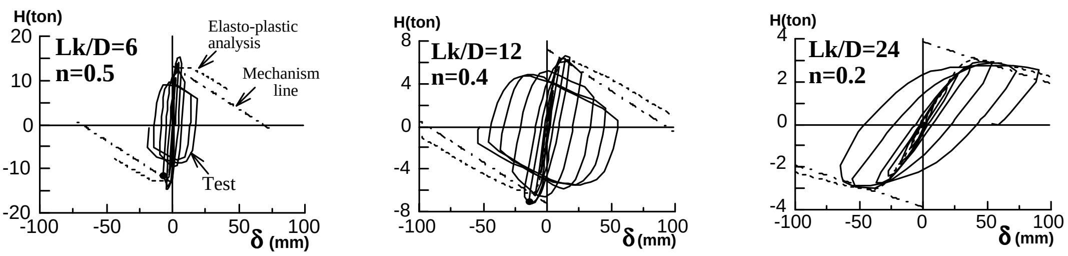

Figure 7: Horizontal load - lateral deflection relations (Series II: Square secton)

Comparison Between Experimental Maximum Load and Design Strength

Maximum Load in Series I Comparison of strength is shown in Fig. 8 in the end moment M_u (=N_u e) - axial load N_u relations. Experimental maximum loads are shown by circle, and proposed strengths are shown by solid line. In addition to these strengths, strength of a section is shown by thin dotted line.

As to the proposed strength, average value of a (experimental maximum load N_{exp} / proposed strength N_{mod}) of square and circular section is 0.99 and 1.03, and ranges from (0.91-1.06) and (0.93-1.16). It seems that M_u - N_u relations obtained from modified AIJ method agree with the experimental results fairly well when L_k/D ratio ranges from 8 to 30. In case of L_k/D =4, especially concrete filled steel circular columns, the M_u - N_u relations underestimate the test result. This is because that the confinement effect of a steel tube and strain hardening of the steel tube have not been taken into consideration. Moreover, the design method based on the simple superposed strength (strength is calculated by the simple sum of the strength of concrete column and steel tubular column) does not give the strength of a section, even if the column length becomes zero.

Maximum Load in Series II Figure 9 shows the M_u-N_u relations in Series II. The mark ○ and ● indicate the experimental strength up to the rotation angle of a column R=1% and 2%, respectively. In the calculation of design strength, no correction is performed such as equivalent moment factors.

Specimens with $L_k/D \leqq 9$ can attain the strength of the section. As the L_k/D ratio becomes small, proposed strength become conservative. As to the design method of beam-columns in which the joint translation is uninhibited, design formula should be refined.

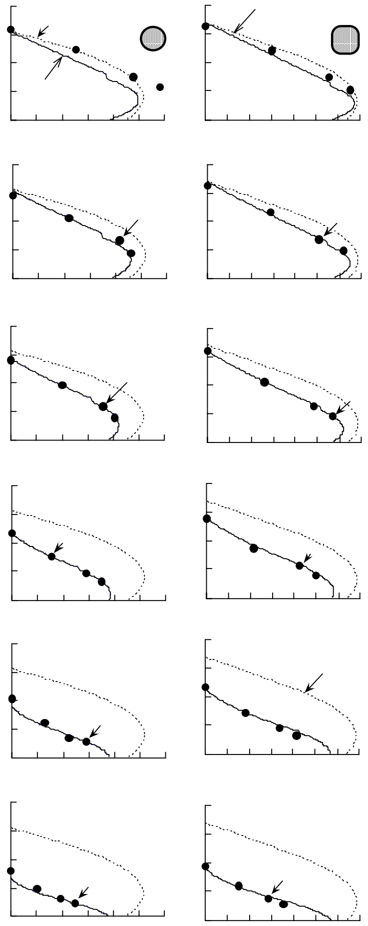

Figure 8: M_u-N_u relations (Series I)

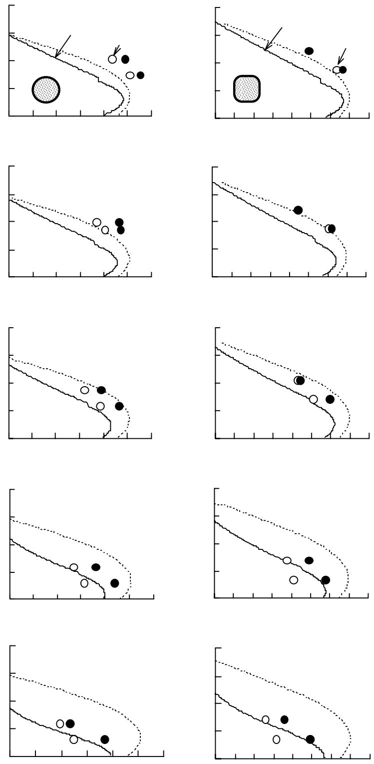

Figure 9: M_u-N_u relations (Series II)

CONCLUSIONS

The conclusions derived from the experimental Series I and Series II are as follows:

1. Proposed design method agrees with the experimental results well when L_k/D ratio ranges from 8 to 30. In case of L_k/D =4, it gives a conservative strength.

2. Design formula of the beam-columns in which the joint translation is uninhibited, should be refined.
3.

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APPENDIX

Symbols appearing in equation (3) are as follows:
Ultimate Compressive Strength of Concrete Column ${}_cN_{cr}$ and Buckling Stress ${}_cN_{cr}$

$${}_cN_{cr} = {}_cN_{cr}\,{}_cA$$

${}_c\lambda_1 \le 1.0$ $$\frac{{}_c\sigma_{cr}}{{}_c\sigma_B} = \frac{2}{1+\sqrt{{}_c\lambda_1^4+1}}$$

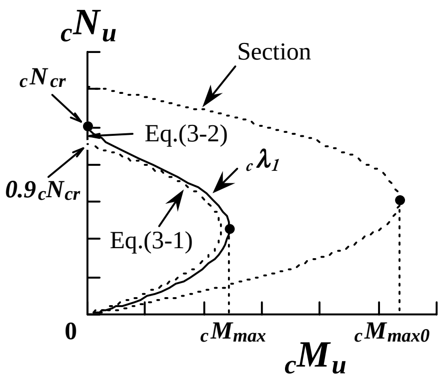
${}_c\lambda_1 \ge 1.0$ $$\frac{{}_c\sigma_{cr}}{{}_c\sigma_B} = 2(\sqrt{2}-1)\exp\{a_c(1-{}_c\lambda_1)\}$$

	0.70	(F_c = 240kg/cm^2)
	0.80	(F_c = 360kg/cm^2)
a_c =	0.86	(F_c = 480kg/cm^2)
	0.92	(F_c = 600kg/cm^2)
	1.02	(F_c = 960kg/cm^2)

$${}_c\lambda_1 = \frac{{}_c\lambda}{\pi}\sqrt{\varepsilon_u}$$ Square section $${}_c\lambda = 2\sqrt{3}\frac{L_k}{{}_cD}$$ Circular section $${}_c\lambda = 4\frac{L_k}{{}_cD}$$

ε_u = 0.52 $F_c^{\ 1/4}$ 10^{-3} (F_c : unit [kg/cm^2])

Maximum moment ${}_cM_{max}$



$$\frac{{}_cM_{\max}}{{}_cM_{\max 0}} = \frac{a_b}{a_b + {}_c\lambda_1^2}$$

	0.83	(F_c = 240kg/cm^2)
	0.75	(F_c = 360kg/cm^2)
a_b =	0.70	(F_c = 480kg/cm^2)
	0.67	(F_c = 600kg/cm^2)
	0.61	(F_c = 960kg/cm^2)

Square section ${}_cM_{max0} = F_c\,{}_cD^3 / 8$

Circular section ${}_cM_{max0} = F_c\,{}_cD^3 /12$

${}_cD$: depth of concrete portion