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Ductility Improvement of High-Strength Concrete Columns with Lateral Confinement

by H. Muguruma and F. Watanabe

Synopsis : The object of this study is to investigate the possibility of improving ductility of high-strength concrete columns with the lateral reinforcement. Eight column specimens confined by lateral reinforcements having 328.4 and 792.3 MPa in yield strength were tested under reversed cyclic lateral loads with constant axial compressive load levels from 0.254 to 0.629. The concrete compressive strengths were 85.7 and 115.8 MPa, respectively. Volumetric ratio of lateral reinforcement was 1.6 % in all specimens. Test results indicated that the very large ductility could be achieved by using high yield strength lateral reinforcement even for such high-strength concrete columns. Modifications of previously proposed stress-strain models on confined concrete were also made for applying them extensively into the calculation of moment-section curvature relationships of high-strength concrete columns with lateral confining reinforcement.

Keywords: columns (supports); confined concrete; ductility; high-strength concretes; lateral pressure; models; stress-strain relationships; structural analysis; tests

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INTRODUCTION

With the development of concrete technology it becomes possible to easily produce concretes of 100 MPa or more in 28 day compressive strengths, and recently its practical use in construction site is being examined in conjunction with reinforced concrete high-rise buildings and longer span bridges. However, two essential problems to be solved still remain for successful use of such high-strength concrete. One is concerning the field practice at the construction site and the other is on the ductility enhancement of structure in seismic area.

Recent seismic design code for reinforced concrete buildings requires designers provide the energy absorbing and dissipating capabilities necessary for structure to survive against strong earthquake motions. For this purpose, lateral confining of concrete is regarded as one of most practical method for enhancing the flexural ductility of structural member, because remarkable increase in ultimate crushing strain of concrete can be obtained by lateral confining. Many studies on the confined concrete and structural members with lateral confining had been carried out in the past. Recently, several stress-strain models of confined concrete have been idealized (1-5), and further, the flexural ductility design procedure, that is, the design procedure for obtaining the amount of confining reinforcement necessary to develop the required ultimate curvature at the critical section of structural member, has been proposed with the design chart (6,7). However, most of these past studies had been carried out on relatively small compressive strength of concrete. For instance, the Park and Kent model on the stress-strain curve of confined concrete had been proposed from the test results by using the compressive strength less than 50 MPa in unconfined concrete (1) and the Authors' one by using 70 MPa or less in compressive strength (2,3,5). Therefore, these stress-strain models might be not applied extensively to the high-strength concrete members.

On the other hand, reinforced concrete columns generally possess little flexural ductility under high axial compressive load. Such ductility may decrease further with the use of higher strength of concrete. Especially when using the high-strength concrete in high-rise building frames, seismic design of structure may be impossible without enhancement of column ductility. Thus, in this study, eight reinforced concrete columns with lateral confining reinforcement were cast by two different compressive strengths of concrete in 70 and 100 MPa in nominal and were tested under combined axial and flexural load for examining the possibility of flexural ductility enhancement by lateral confinement of concrete. The principal variables were the compressive strength of concrete, the amount of applied axial compressive load and the yield strength of confining reinforcement. Longitudinal reinforcement ratio for gross concrete sectional area and volumetric ratio of lateral confining reinforcement for core concrete section were 1.61 and 3.61 % in all specimens, respectively. Test results obtained were discussed in terms of the effects of these variables upon the flexural ductility enhancement of column. In addition, based on the test results obtained, modifications of previously proposed stress-strain models on confined concrete were made for their extending use in ultra-high-strength concrete up to 120 MPa.

TEST SPECIMENS

Outline of Test Specimens

Eight reinforced concrete column specimens were tested in this study in dividing into two series (i.e., Series A and Series B) of 4 specimens each. Nominal compressive strengths of concrete were 70 MPa in Series A and 100 MPa in Series B. All specimens were 200x200 mm in cross section and 1500 mm long, and had heavily reinforced stub of 200x300 mm in cross section and 500 mm long at the midheight. Dimensions and details of specimen are shown in Fig. 1. Longitudinal reinforcement used in all specimens was D-13mm deformed bar with 399.6 MPa in yield strength, and 12 bars are arranged in the section. Percentage of longitudinal reinforcement is 3.81 % for 200x200 mm gross concrete section. As the lateral confining reinforcement, ϕ 6 mm in diameter plain bars having two different yield strengths of 328.4 and 792.3 MPa are used. A set of confining reinforcement consisted of one 176x176 mm square peripheral welded tie and two 70x176 mm rectangular welded sub-ties, and is arranged in the spacing of 35 mm throughout the whole length of specimen. The volumetric ratio of lateral confining reinforcement is 1.61 % for 182x182 mm core concrete section. In Table 1, descriptions of specimens tested are summarized. Lateral confining coefficient Cc in Table 1 was calculated from

$$Cc = 0.313\ \rho w \frac{\sqrt{\sigma wy}}{fc'} \left(1 - 0.5 \frac{S}{W} \right) \qquad (1),$$

where,

ρw : Volumetric ratio of confining reinforcement (= 1.61 %)
σwy: Yield strength of confining reinforcement in MPa

fc' : Compressive strength of plain concrete in MPa
S : Spacing of confining reinforcement (= 35 mm)
W : Length of a side of core concrete section (= 182 mm).

Table 1 Details of Test Specimens

Series	Specimen	fc' (MPa)	Longitudinal Reinforcement σ y (MPa)	Longitudinal Reinforcement ρ (%)	Lateral Reinforcement σ wy (MPa)	Lateral Reinforcement ρ w (%)	Conf. Coef. Cc (1/1000)	Axial Load Level N/Agfc'
A	AL-1	85.7	399.6	3.81	328.4	1.61	2.47	0.400
	AH-2				792.3		3.83	
	AL-2				328.4		2.47	0.629
	AH-2				792.3		3.83	
B	BL-1	115.8			328.4		1.82	0.254
	BH-1				792.3		2.83	
	BL-2				328.4		1.82	0.423
	BH-2				792.3		2.83	

fc';Compressive strength of concrete, σ y, σ wy;Yield strength,
ρ ;Percentage for gross concrete section, ρ w;Volumetric ratio for confined core, N;Axial compressive load, Ag;Area of gross concrete section

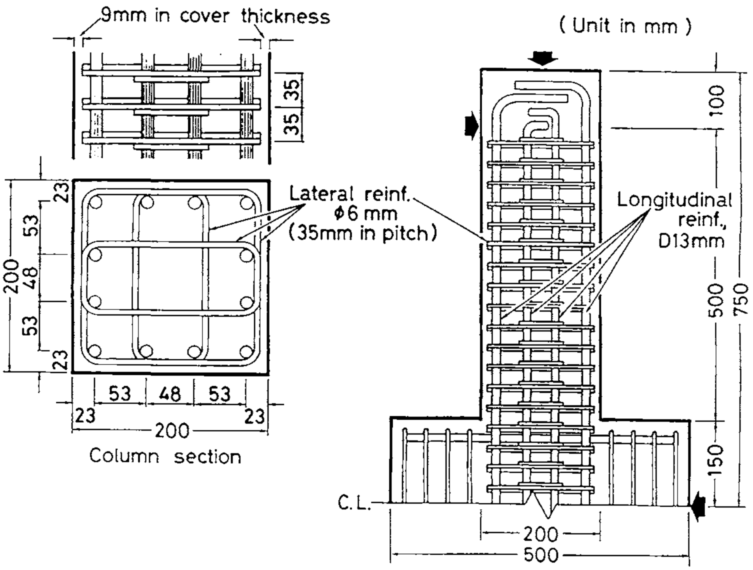

Fig. 1 Test Specimen

Table 2 Mix Proportion of Concrete (Unit in kg/m³)

Test Series	High Early Strength Cement	Silica Fume	Super-plasti-cizer *	River Sand	Crushed Stone Gravel	Water	Water-Cement Ratio (%) **	Nominal Comp. Str. (MPa)
A	450	25	10	723	1085	136	28	700
B	550	74	14	683	1025	120	19	1000

* Powder type superplasticizer was used.
** Water-cement ratio was calculated from water/ (cement+silica fume+superplasticizer) by weight.

Table 3 Properties of concrete at the test age of column specimens

Test Series	Test Age (Days)	Compressive Strength f_c' (MPa)	Elastic Modulus (MPa) *
A	52~64	85.7	4.37×10^4
B	40~49	115.8	4.63×10^4

* Secant modulus at the stress of one-third of compressive strength

Mix Proportions and Compressive Strengths of Concrete

To obtain the high strengths of 70 and 100 MPa in nominal, materials for producing the concrete were carefully selected, and mix proportions were determined as listed in Table 2 by using high-early strength portland cement, silica fume, superplasticizer, and relatively hard river sand and crushed stone gravel.

Column specimens in each series were cast vertically and were wet-cured in the laboratory until the test ages. Properties of concrete at the test ages of column specimens are listed in Table 3. They were obtained from the compressive tests on 100x200 mm concrete cylinder specimens cast with the column specimens simultaneously. As listed in Table 3, average compressive strengths of concrete attained at 85.7 MPa in Series A and 115.8 MPa in Series B, respectively.

TEST PROCEDURE AND MEASUREMENTS

Figure 2 shows loading arrangement of column specimens. The reversed cyclic lateral load was applied statically on the stub at midheight of specimen by 500 kN hydraulic jack by controlling the lateral displacement. During the tests, constant axial compressive load was applied by 3 MN capacity compressive testing machine. As listed in Table 1, axial compressive load levels calculated from N/fc'Ag, where N is the axial compressive load, fc' is the compressive strength of plain concrete and Ag is the gross sectional area, are 0.400 and 0.629 in Series A and are 0.254 and 0.423 in

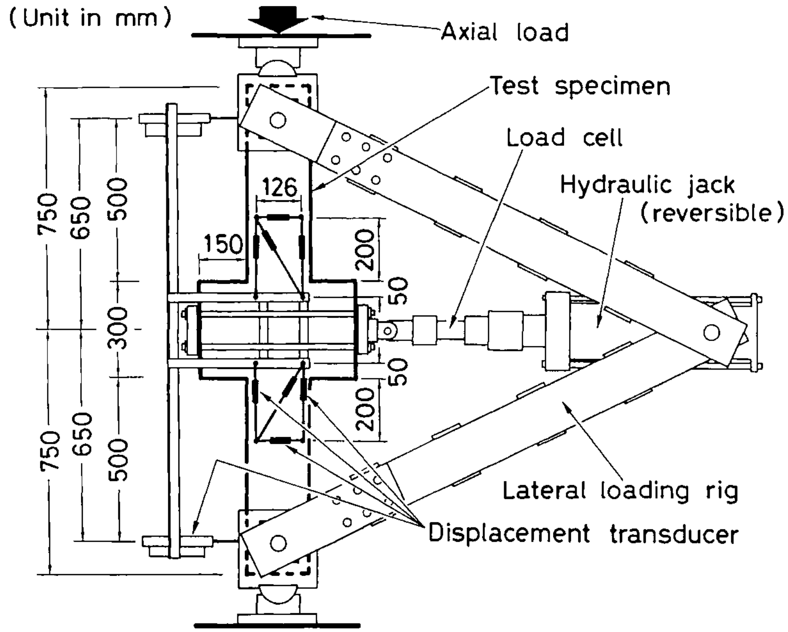

Fig. 2 Loading Arrangements and Measuring Devices

Series B, respectively. The lateral loads were applied cyclically so as to impose two reversed cycles of loading at increasing levels of deflection ductility factor until the useful load carrying capacity of the specimen was exhausted.

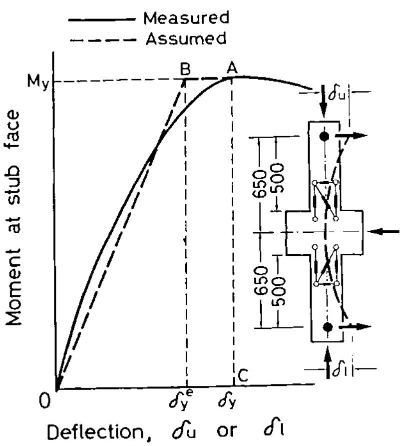

Fig.3 Definition of Equivalent Yield Deflection

The deflection ductility factor was defined as the ratio of lateral deflection during loading to the deflection at yield. The yield deflection was defined as the equivalent one at Point B on the assumed bi-linear moment-deflection relationship shown by dotted line in Fig. 3, where Point B is determined that the energy absorption up to Point A in the assumed bi-linear curve equals to that in the experimental curve. Similar definition of first yielding section curvature was made for calculating the section curvature ductility factor.

Instrumentation during the tests consisted of continuous monitoring of lateral load versus column lateral deflection at the top or bottom of the upper and lower halves of specimen and lateral load versus section curvature in the plastic hinge regions at the stub face sections. Measuring devices equipped are illustrated in Fig. 2.

TEST RESULTS AND DISCUSSIONS

Measured Moment-Deflection and Moment-Curvature Relationships

It is general that less flexural ductility is observed in the reinforced concrete column when subjected larger axial compressive load. Therefore, discussions are made mainly on the specimens with larger axial compressive load level in each test series, i.e., on Specimens AL-2 and AH-2 in Series A and on Specimens BL-2 and BH-2 in Series B. Measured moment at the stub face section versus lateral deflection hysteresis loops on these four specimens are shown in Fig. 4.

Specimens AL-2 and AH-2 were tested under very high axial compressive load level of 0.629.

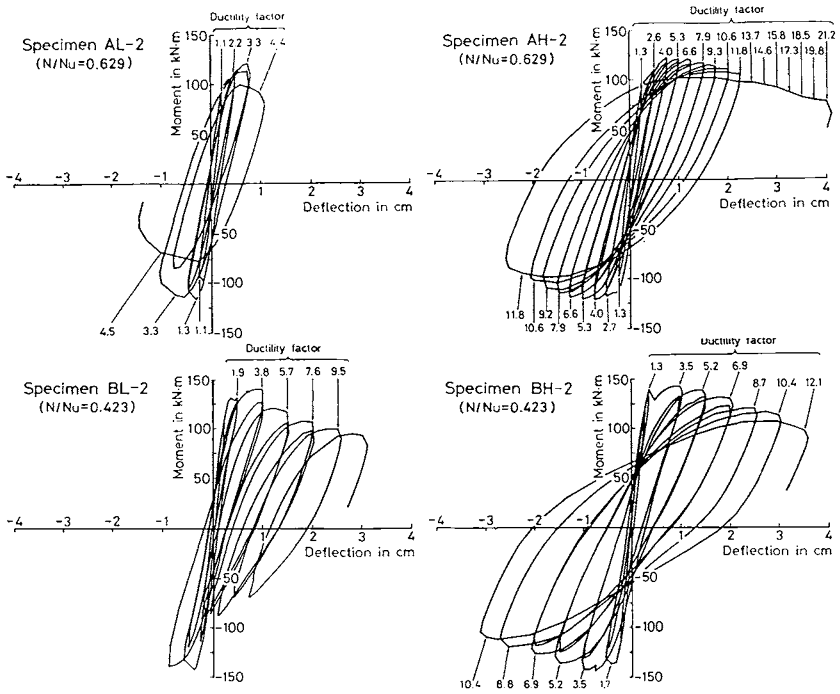

Fig. 4 Measured Moment-deflection Hysteresis Loops

Therefore, in Specimen AL-2 confined by ordinary yield strength lateral reinforcement of 328.4 MPa first yielding of lateral reinforcement took place when lateral deflection attained at 3.28 in deflection ductility factor, and further enhancement in ductility could not be observed. On the contrary, Specimen AH-2 which was confined by high yield strength lateral reinforcement of 792.3 MPa showed excellent ductile behaviour with stable moment-deflection characteristics over the deflection ductility factor of 17.3, although first yielding of lateral reinforcement took place at this deflection ductility factor. Similar test results were also obtained on Specimens BL-2 and BH-2 and good ductility enhancement can be seen in the latter as illustrated in Fig. 4.

The effect of concrete strength upon the ductility enhancement by lateral confinement of concrete can be discussed in comparison of deflection hysteresis curves between Specimens AH-2 and BH-2. They have same dimensions and same configurations of reinforcements, excepting that the compressive strengths of concrete are 85.7 MPa in the former and 115.8 MPa in the latter.

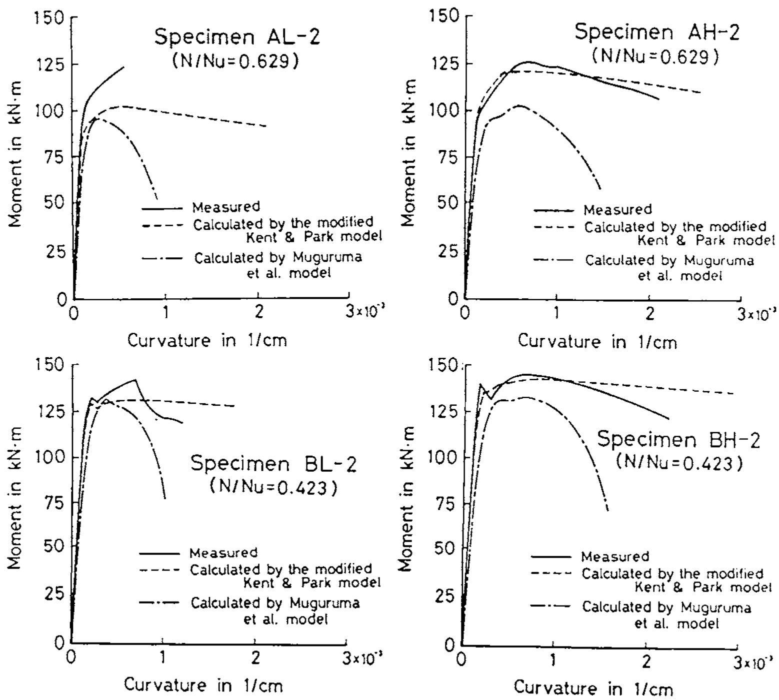

Fig. 5 Comparison between the Envelope Curves of the Experimental Cyclic Moment-curvature Responses and the Theoretical Monotonic Moment-curvature Curves obtained using Modified Kent and Park Stress-strain Model and Muguruma et al Model for Confined Concrete

In addition, axial compressive loads applied were almost same on these specimens, i.e., 2.156 MN in the former and 1.959 MN in the latter. However, smaller deflection ductility was obtained in Specimen BH-2 compared with Specimen AH-2 as can be seen in Fig. 4. This means that the ductility enhancing efficiency of lateral confining reinforcement is reduced with the increase of concrete compressive strength. As a reference, deflection ductility factors at first yielding of lateral confining reinforcement are 11.8 in Specimen AH-2 and 8.66 in Specimen BH-2, respectively.

Moment-curvature relationships obtained at stub face section of specimens are also very similar to moment-lateral deflection relationships. As a reference, only skeleton curves measured on Specimens AL-2, AH-2, BL-2 and BH-2 are shown by solid lines in Fig. 5.

Lateral Deflection Angle, and Lateral Deflection and Curvature Ductility Factor

Lateral deflection at column top or at column bottom at the first yielding of lateral reinforcement is defined as the available limit of ultimate lateral deflection in this study, and dividing it by column length of 500 mm, ultimate lateral deflection angle is calculated. Also, ultimate lateral deflection ductility factor as well as ultimate curvature ductility factor at stub face section is determined at the first yielding of lateral reinforcement. The results are summarized in Table 4. In Table 4, it is noted that high yield strength of lateral confining reinforcement gives excellent flexural ductility enhancing in high-strength concrete column even when the column is subjected to high axial compressive load. Especially, concerning the lateral deflection angle, the reinforced concrete high-rise building flame is commonly required to develop the maximum storey deflection angle of 2 % or more without significant decrease in lateral load carrying capacity in the seismic design.

Table 4 Summary of Available Deflection Angles and Ductility Factors measured at First Yielding of Lateral Confining Reinforcement

Test Series	No. of Specimen	Comp. Strength of Conc. (MPa)	Axial Comp. Load Level	Yield Strength of Confined Reinforcement (MPa)	Deflection Angle (%)	Deflection Ductility Factor	Section Curvature Ductility Factor
A	AL-1	85.7	0.400	328.4	6.0	10.20	17.90
	AH-1			792.3	>10.0	>17.30	>31.00
	AL-2		0.629	328.4	1.5	3.28	4.25
	AH-2			792.3	4.5	11.80	19.10
B	BL-1	115.8	0.254	328.4	6.3	10.80	13.10
	BH-1			792.3	8.5	15.00	22.80
	BL-2		0.413	328.4	3.0	5.70	9.68
	BH-2			792.3	5.0	8.66	17.90

Ultimate lateral deflection angles of 4.5 % or more obtained from the columns confined by high yield strength lateral reinforcement in this study satisfy above required value, and thus, it can be concluded that high strength concrete column with enough flexural ductility can be obtained by using high yield strength lateral confining reinforcement.

MODIFICATION OF PREVIOUSLY PROPOSED STRESS-STRAIN MODELS OF CONFINED CONCRETE

Several stress-strain models of confined concrete have been presented in the past. In this study, moment-curvature relationships at the stub face sections of tested columns were calculated by applying the Muguruma et al model (5) and the Modified Kent and Park model (4), and applicabilities of these models in section curvature calculation were examined in comparison with measured moment-section curvature relationship. Fig. 6 shows these models schematically.

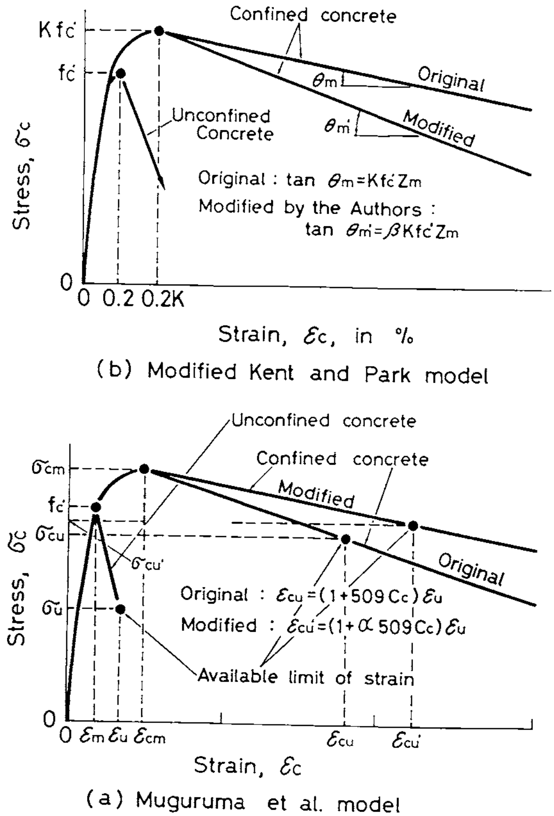

Fig. 6 Modification of Previously Proposed Stress-strain Models for Confined Concrete

Detailed explanation of the originally proposed stress-strain models are omitted in this report (see Ref. 4 and 5). Moment-section curvature relationships calculated on Specimens AL-2, AH-2, BL-2 and BH-2 are shown in Fig. 5 with measured those. As can be seen in Fig. 5, calculation results by the Muguruma et al model give smaller curvature ductility than the measurements, while those by the Modified Kent and Park model give larger. The reason is the inadequate estimation of the descending part in the stress-strain models, that is, ductility enhancement of concrete is underestimated in the Muguruma et al model and is overestimated in the Modified Kent and Park model. Also, the Muguruma et al model was proposed from the test results on the confined concrete without any longitudinal reinforcement and without any supplementary tie. And the Modified Kent and Park model was proposed from the test results on the confined members having 50 MPa or less in plain concrete strength. Therefore, for applying these stress-strain models to high-strength concrete member section, modification shall be made on the inclination angle of their descending parts.

In this study, based on the comparison between experimental and analytical moment-section curvature curves, modifications of inclination angle of descending part were performed on these two models. In the Muguruma et al model the modification can be done by revising the value of available limit of compressive strain εcu (see Fig. 6 (a)). Modified value of it is given as

$$\varepsilon'cu = (1 + \alpha \cdot 509\ Cc)\ \varepsilon u \qquad (2),$$

where, α is the modification coefficient. The value of α varied from 1.22 to 1.43 in this study. However, α = 1.2 can be recommended to use in the practical calculation of section curvature.

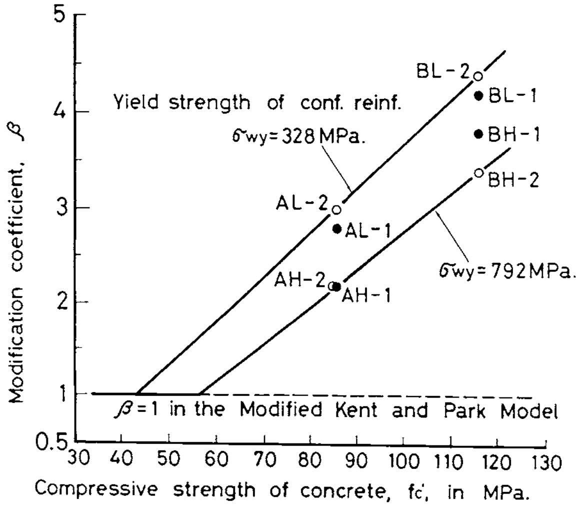

Fig. 7 Modification Coefficient β for Modified Kent and Park Model

For the Modified Kent and Park model, originally proposed inclination angle of descending part can be modified by using multiplying coefficient β. The modified expression is given as

$$\mathrm{Tan}\ \theta'm = \beta\ K\ fc'\ Zm \qquad (3),$$

where, **K** is the ratio of compressive strength of confined concrete to that of plain concrete and **Zm** is the base value of inclination angle which is given as a function of plain concrete strength, volumetric ratio and spacing of confining reinforcement, yield strength of confining reinforcement and width of core concrete section, etc. Coefficient β varies with increase of concrete strength as shown in Fig. 7.

Using the stress-strain models modified in this study, moment-section curvature relationships were re-calculated. Calculation results agree fairly well with the measurements as shown in Fig. 8.

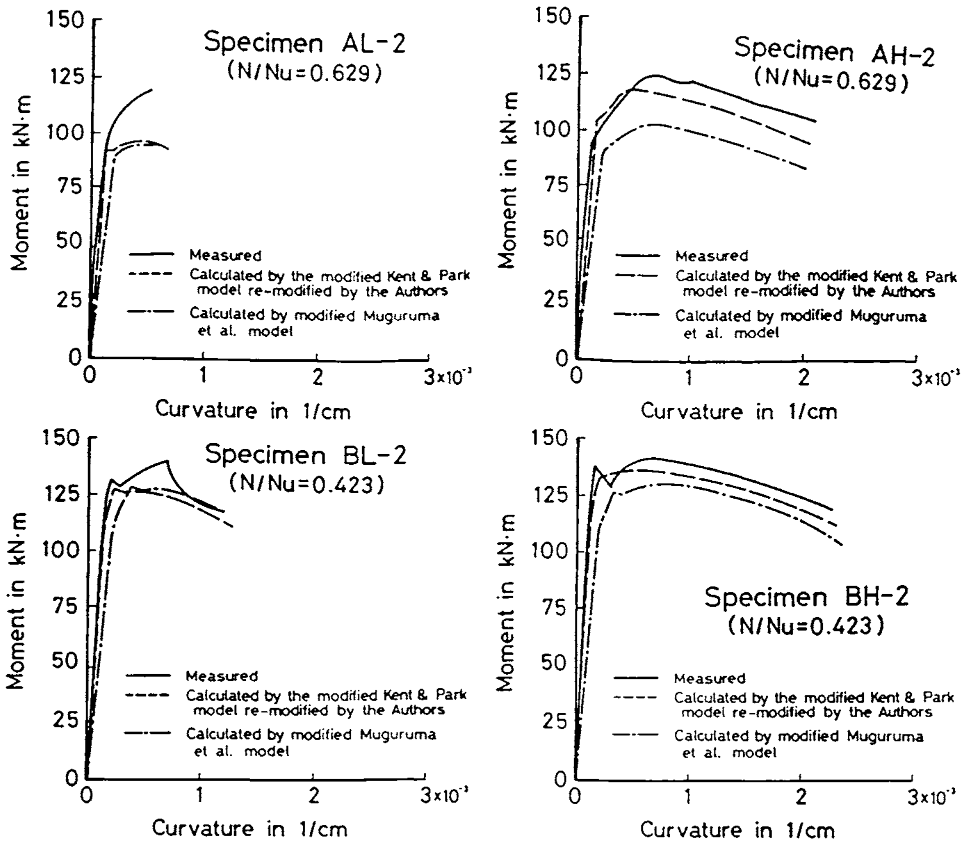

Fig. 8 Comparison between the Envelope Curves of the Experimental Cyclic Moment-curvature Responses and the Theoretical Monotonic Moment-curvature Curves obtained using Re-modified Kent and Park Model and Modified Muguruma et al Model for Confined Concrete

However, test range in this study is very limited and hence above mentioned modifications in previously proposed stress-strain models might need to be modified again based on a future research including more wide variables.

CONCLUSION

Following conclusions can be obtained in this study.

(1) Test results indicate that the very large ductility could be achieved by using high yield strength lateral confining reinforcement even for high strength concrete columns. For example, in case of a column with concrete strength of 115.8 MPa, deflection ductility factor of more than 8 could be achieved without any significant decrease of load carrying capacity under the axial compressive load level of 0.423.

(2) The ductility enhancing efficiency of lateral confining reinforcement is reduced with the increase of concrete compressive strength. Therefore, when applying the high strength concrete more than 100 MPa into the reinforced concrete high-rise building in seismic area, the use of high yield strength lateral confining reinforcement becomes indispensable for providing necessary flexural ductility in column.

(3) Based on the test results obtained, the Muguruma et al stress-strain model and the Modified Kent and Park model on confined concrete were so modified as to apply to the calculation of column section curvature with high-strength concrete. Calculated moment-section curvature relationships showed good agreement with the measurements.

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