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On the confined high-strength concrete and need of future research

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Abstract

Investigation about requirements of confining reinforcement on the structure of high-strength concrete has been progressed significantly since the last three decades. Research carried out intensively on high-strength concrete, produces a material which has a relatively brittle nature. Various parameters of the confining reinforcement design have been varied to obtain the optimal results regarding the behavior of high-strength concrete, especially for columns comprehensively. This paper discussed about the development roadmap of confined high-strength concrete research, includes constitutive equations of confined high-strength concrete developed by researchers. In this paper modified of analytical model for confined normal to high-strength concrete is also proposed. Results of this further discussion were associated with the need of the development research of confining reinforcement on high-strength concrete material adapted to the material properties and zones in Indonesia.

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Keywords: High-strength concrete; strength; constitutive equations; confinement model

1. Introduction

Infrastructure development requires excellent material quality and durable so many innovations to produce a material that has a high quality have been intensively conducted. High strength-concrete ($f'_c \geq 50$ MPa) has superior mechanical properties and durability compared with normal-strength concrete because of the hardness of the breakdown of a high and a lower porosity. However, high-strength concrete material is brittle, less ductile and more sensitive to aspects of the planning and execution of construction compared with materials made of normal strength

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concrete. High-strength concrete material's brittleness is characterized by the occurrence of crack propagation occurring faster than the crack propagation on normal strength concrete. This in turn leads to a more rapid loss of effectiveness of the concrete cover on the column, or the occurrence of which is premature shear failure on reinforced concrete beams. Brittle effect of high-strength concrete is generally solved by installing a confining reinforcement so that high-strength concrete is more ductile. Some researchers have been investigating the behavior of high-strength concrete columns by reviewing the compressive strength of concrete, confining reinforcement (i.e. ratio, spacing, yield stress) or configurations reinforcement and proposing design equations especially to ensure the safety and ductility of the columns that accept earthquake loads [1, 2].

This paper discusses the behavior of high-strength concrete, especially in the column structure that aims to evaluate some design equations that have been developed and adopted in the planning regulations. Confined concrete constitutive equations that affect the need of confining reinforcement are also discussed and compared to identify the accuracy of each model against experimental results that have been done by the author. At the end of the paper the development model of confinement of a general nature, which can be applied to normal and high-strength concrete.

2. The axial capacity of the concrete column

The axial capacity of the concrete column (P_o) to the concentric axial load is determined by the equation below.

$$P_o = \alpha f_c' (A_g - A_c) + A_s f_y \quad (1)$$

Equation (1) does not take into account the effect of confinement. SNI 2847-2013 [3] to stipulate the value of α is equal to 0.85 for various concrete compressive strength. NZS 3101-2006 [4] also sets the value of α of 0.85 in the equation above but applies for concrete compressive strength up to 55 MPa. If the concrete compressive strength is higher then:

$$\alpha = 0.85 - 0.004\,(f'_c - 55) \quad (2)$$

The α value is limited to no less than 0.75. Equation (2) shows that NZS has been accomodating the decrease of the column axial capacity when using high-strength concrete.

Next the above equation accuracy with experimental results of high-strength concrete column against concentric load which has been done by several researchers have evaluated [5]. Figure 1 shows the relationship between $\rho_s.f_s/f'_c$ and the ratio between the axial load test results ($P_{exp.}$) to the axial capacity of columns by SNI (Equation 1). From these relationships show that the confining reinforcement ratio (ρ_s) significant role in increasing the capacity of the axial column. The higher the ratio of the installed confining reinforcement, the more increase the axial capacity will be. Generally from the image it is also be seen that the value of α is quite safe in the value of 0.85 when the value $\rho_s.f_s/f'_c$ is higher than 30. Conversely, when the ratio $\rho_s.f_s/f'_c$ lower, even below 20, then it is quite risky when using the 0.85 factor in the calculation of the column axial capacity. The results show that α values espoused in the SNI need to be modified to accommodate high-strength concrete.

Besides affecting the amount of axial capacity, one of the failure mechanism of high-strength concrete column is results cover spalling prematurely. Figure 2 shows data of test results by Cusson & Paultre [6] and Antonius [7] that the strain ratio at the time of the cover concrete spalling of the unconfined concrete peak strain under 1 on columns made of high-strength concrete. Cover spalling behavior of high-strength concrete column that affects the equation stress blocks of concrete which is often used for design against bending. Modification of the equation block stress for high-strength concrete has also been proposed by several investigators, including by Bae & Bayrak [8] and Mertol [9].

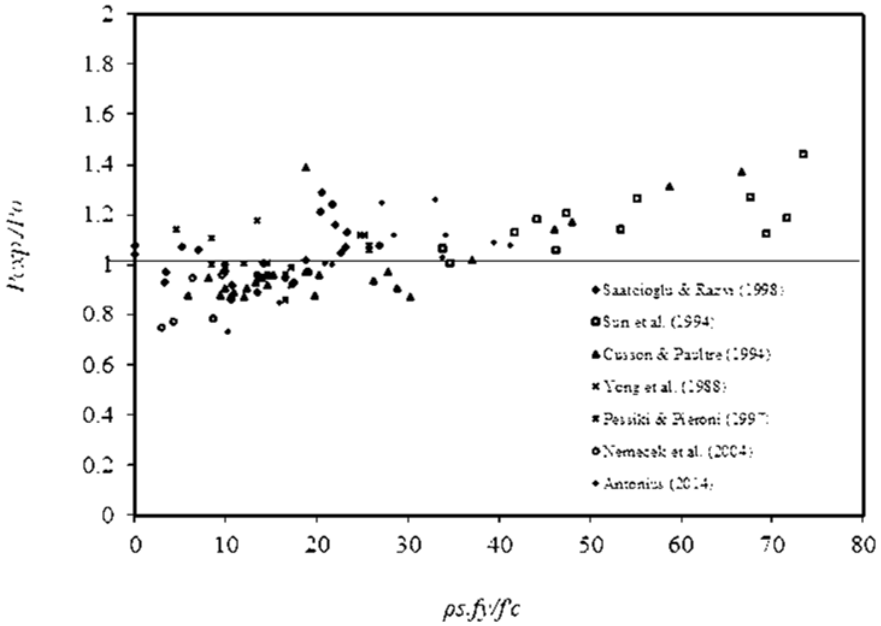

Figure 1. Axial Capacities of columns [5]

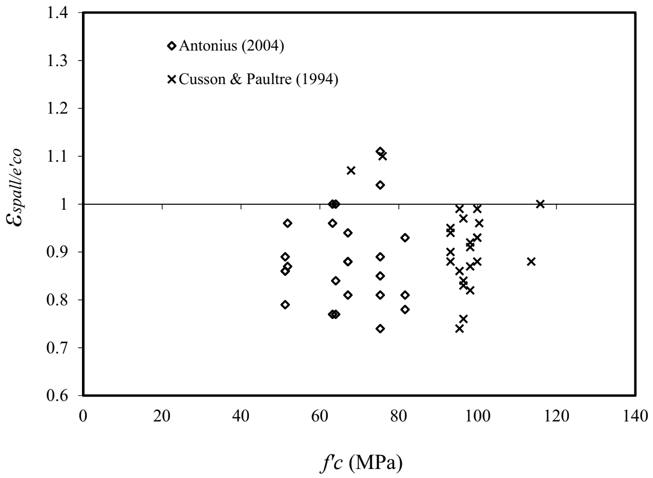

Figure 2. Relation between concrete strength and vs εspall/ε’co

3. Constitutive equations of confined high-strength concrete

It is known that the design philosophy of confining reinforcement is that when it receives a seismic load the column axial force after the cover spalling remains well preserved. Volumetric ratio of confining reinforcement required in the column is determined by the magnitude of the increase in the strength of confined concrete or *K* value. Equation *K* value up to now has been widely proposed and generally adapted to the conditions in each researchers’ country.

3.1. Strength enhancement of confined concrete (K)

3.1.1. Model by Muguruma et al.

Muguruma et al. [10] proposed a K value equation based on experimental results on the concrete with the compressive strength of 20-160 MPa. Therefore, the model can be applied to normal and high-strength concrete. It is reported that the model can be used to analyze the concrete with confinement that have a normal and high yield strength strength.
K value equation is mathematically written:

$$K = \frac{\overline{\sigma}_m}{f'c} = \left(1 + 49.C_c\right) \tag{3}$$

$$C_c = 0.313\,\rho\,\frac{\sqrt{\mathrm{f_{yh}}}}{\mathrm{f_c}'}\left(1 - 0.5\frac{s}{w}\right) \tag{4}$$

C_c coefficient depends on the ratio of confining reinforcement (ρ), yield stress of confining reinforcement (f_{yh}), compressive strength of concrete (f'_c), spaced confining reinforcement (s) and the core cross-sectional area of reinforcement (w). The above equation does not take into account the effect of the configuration of the reinforcement. Confining reinforcement assumed has been yielded at the time of peak response.

3.1.2. Model by Diniz & Frangopol

Diniz & Frangopol [11] developed a constitutive model that can be applied to concrete compressive strength of 120 MPa. K value is determined by the following equation:

$$K = \frac{f'_{cc}}{f'_c} = 1 + \left(1.15 + \frac{3048}{f_c'}\right)\frac{f_{le}}{f'_c} \tag{5}$$

Equation (5) in units of psi. Confinement index is calculated by the formula:

$$f_{lat.} = \frac{A_{sh}.f_{yt}}{d_e.s_p} \tag{6}$$

in which $A_{sh} = \lambda\ .\ A_{st}$.

Equation (6) shows that Diniz considers the confining reinforcement has been yielded at the time of maximum response. λ form factor is the reinforcement configuration. C_f factor is used to correct the value of the stress supplied by confining reinforcement by the following equation:

$$C_f = 1 - \frac{s}{d_c} \tag{7}$$

So that the effective lateral stress is:

$$f_{le} = C_f\ .\ f_{lat.} \tag{8}$$

3.1.3. Model by Legeron & Paultre

Legeron & Paultre [12] proposed a model of confinement that can be applied to normal and high-strength concrete. K value is calculated by:

$$K = \frac{f'_{cc}}{f'_c} = 1 + 2.4\left(I_c'\right)^{0.7} \tag{9}$$

Confinement index I'_e formulated:

$$I'_e = \frac{f'_{le}}{f'_c} \tag{10}$$

Where f'_{le} is the effective lateral stress. The stress on the confining reinforcement is obtained by calculating the first strain of confinement at the time of the concrete reinforcement stress reaches a maximum, and then calculate the stress that corresponds to the stress on the stress-strain diagram. Legeron model has been used as the main reference to lower the design equation reinforcement of confinement with regard axial load level as well as in the design of confining reinforcement against seismic loads [13].

3.1.4. Model by Antonius et al.

Antonius et al. [1] proposed a high-strength concrete confinement model based on experimental results of concrete concentric round cross-section of the load. Strength enhancement of the confined concrete is below:

$$K = \frac{f'_{cc}}{f'_{co}} = 1 + 3.7\left(\frac{f_2}{f'_{co}}\right)^{0,9} \tag{11}$$

f_2 is a effective lateral stress where the coefficient of confinement effectiveness for square section who adopt the equation proposed by Mander [14]. Results of investigations conducted by Antonius, stress of confining reinforcement at the time of peak response is not always yield, hence the stress to a square cross-section column is calculated by the equation below.

$$f_s = E_s\left\{0.0004.\ln\left[\frac{(s/d_c)}{\rho_s\sqrt{f'_c}}\right] + 0.002\right\} \tag{12}$$

3.2. Validation of K equations to the experimental results

The K equations above will then be validated with data from experiments conducted by Antonius & Imran [15] on the testing of confined normal and high-concrete with square cross-section (Table 1).

Table 1. Experimental data of square section under concentric loadings [15]

Specimen	f'_c (MPa)	Confining steel			$P_{max.}$ (kN)	f'_{cc} (MPa)	K
		Conf.	∅-spacing	ρ_s (%)			
AL5	34		5.5 – 50	2.01	301.84	33.80	1.16
AM5	45	A	5.5 – 50	2.01	381.77	42.75	1.12
AH5	67		5.5 – 50	2.01	533.23	59.71	1.10
BL5	34		5.5 – 50	3.43	300.86	33.69	1.37
BM5	45	B	5.5 – 50	3.43	453.39	50.77	1.33
BH5	67		5.5 – 50	3.43	631.64	70.73	1.29
CL5	34		5.5 – 50	3.02	329.26	36.87	1.27
CM5	45	C	5.5 – 50	3.02	375.25	42.02	1.24
CH5	67		5.5 – 50	3.02	606.63	67.93	1.10
DL5	34		5.5 – 50	3.63	390.88	43.77	1.50
DM5	45	D	5.5 – 50	3.63	444.01	49.72	1.30
DH5	67		5.5 – 50	3.63	558.41	62.53	1.16

Figure 3 is a validation result value *K* based on models that have been developed with a *K* value of experimental results in Table 1 above. Prediction value *K* based on Legeron proposed is generally over-estimating the value of *K* the experimental results. While it is generally the value of *K* based on the proposal Muguruma, Diniz and Antonius underestimate the experimental results. These results indicate that each proposed *K* value depends on the nature of the material used by each researcher. The reviewed parameters are also vary, depending on the estimated highly influential and appropriate conditions of each country.

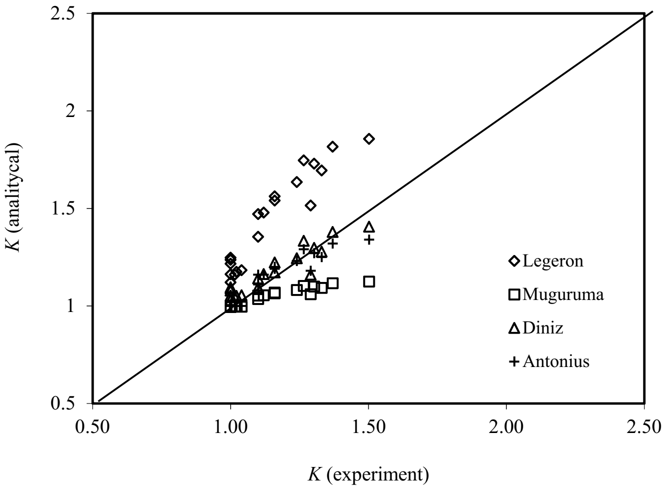

Figure 3. *K* values of models versus experimental values

4. Modification of confinement model

K values discussed above basically determines the stress-strain behavior of confined concrete too. The results of investigations of confinement models for high-strength concrete are very different from each other especially in modeling the behavior of post-peak [16]. In this paper, a confinement model that will be validated with experimental results based on the data in Table 1 above is going to be developed, wherein the compressive strength of concrete cover normal and high-strength concrete with various configurations of confining reinforcement. The base-model proposed by Antonius et al. [1], derived based on a large volume of test data from concentrically tested columns which is modified to develop a general confinement models with a wide range of compressive strength. Stress-strain parameters were unchanged from the model proposed in 2001 are outlined below. Ascending and descending branch are:

$$f_c = \frac{f'_{cc}\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right).r}{r-1+\left(\frac{\varepsilon_c}{\varepsilon'_{cc}}\right)^r} \qquad (13)$$

$$f_c = f'_{cc} - (\varepsilon_c - \varepsilon'_{cc})\frac{0.15.f'_{cc}}{(\varepsilon_{85c} - \varepsilon'_{cc})} \qquad (14)$$

Furthermore, the parameters strain are:

$$\varepsilon_{co}' = 0{,}0004\ .\ (f'_{co})^{0.45} \qquad (15)$$

$$\varepsilon'_{cc} = \varepsilon'_{co}\left[1.94(K-1)+1\right] \tag{16}$$

Stress of confining reinforcement is determined by equation (12). Furthermore, the model modification made is the value equation of K, ductility parameters (ε_{85c}), effective lateral stress and residual stress (f_r).

4.1. Strength enhancement of confined concrete (K) and residual stress (f_r)

The K equation based on triaxial tests of high-strength concrete has been developed by Imran et al. [17] using Ottosen criteria which is adopted to estimate the strength increase in normal and high-strength concrete columns due to confinement. The K equation is:

$$K = \frac{f'_{cc}}{f'_{co}} = \left(\frac{f_l}{f'_{co}} - 0.327\right) + \sqrt{1.7606 + 16.1714\frac{f_l}{f'_{co}}} \tag{17}$$

And for the residual strength envelope:

$$\frac{f_r}{f'_{co}} = \left(\frac{f_l}{f'_{co}} - 0.327\right) + \sqrt{0.1069 + 19.479\frac{f_l}{f'_{co}}} \tag{18}$$

Failure strength envelope shown in figure 4 states that the value equation K proposed in this model has a non-linear shape and tend to be equal to the value equation K of Mander et al. [14], Xie et al. [18] and Ansari & Li [19]. The K value equation is also derived from the triaxial testing in which each uses yield criteria. Another phenomenon that is visible in the picture is the value equation K by Richart [5], and is the basis for determining the volumetric ratio of confining reinforcement by SNI, is under estimation of lateral low stress (up to f_2/f'_{co} ~ 0.5), compared with other equations.

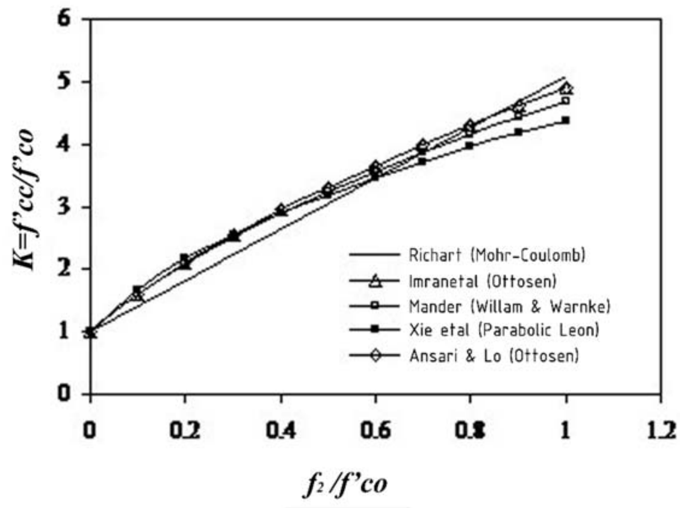

Figure 4. Failure strength envelope of K models

4.2. Ductility parameter

In the value of K in the above equation affects the behavior of confined concrete ductility. The data of test results round cross-section column by Antonius [1] and a square cross-section column test data by Antonius & Imran to be subsequently combined to determine the parameters of the new ductility. Results of regression yields the equation (see Figure 5):

$$\varepsilon_{85c} = \varepsilon'_{cc} + 3.10^{-5}.\ e^{3.1K} \tag{19}$$

4.3. Effective lateral stress

It has been observed that for confined concrete with square sections that for spacings of ties greater than least dimension of the column the confining effects are negligible [15], therefore the lateral stress for square section with a correction factor proposed by Diniz & Frangopol [11] is adopted:

$$f_2 = k_e\left(1 - \frac{s}{d_c}\right)\left(\frac{\rho_s}{2}.f_s\right) \qquad \varepsilon_{85c} = \varepsilon'_{cc} \tag{20}$$

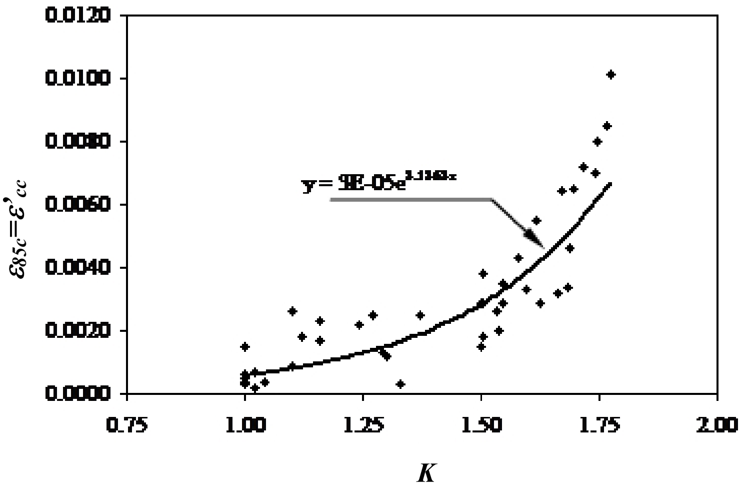

Figure 5. Regression of ε_{85c} equation

5. Corroboration with the experimental results

The modified stress-strain relationship for confined concrete is then used to simulate experimental results of reinforced concrete columns in Table 1 above. The comparisons of the modified model with specimens for square sections showed in Figure 6 through 9. It can be seen from those figures that the modified model simulate the stress-strain of confined normal and high-strength concrete on the pre and post peak response satisfactorily.

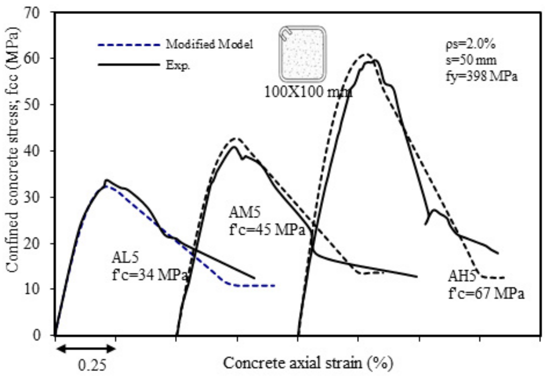

Figure 6. Modified model vs experimental results for A configuration

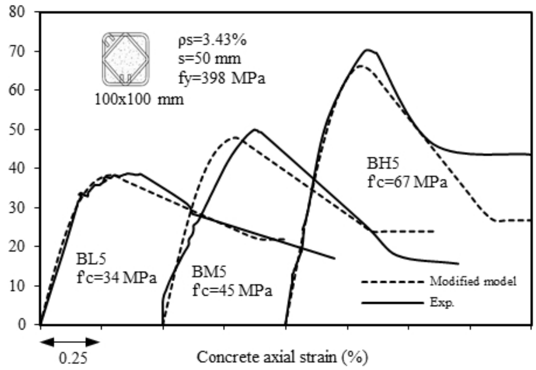

Figure 7. Modified model vs experimental results for B configuration

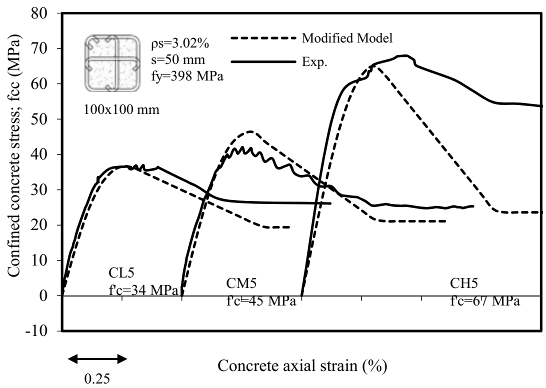

Figure 8. Modified model vs experimental results for C configuration

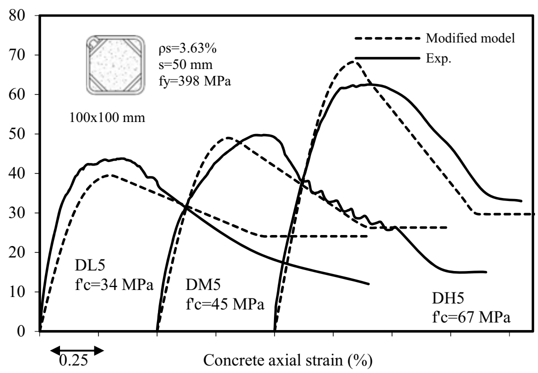

Figure 9. Modified model vs experimental results for D configuration

6. Conclusion

Further studies on calculation of axial capacity on high strength concrete columns are needed, where the coefficient α in equation (1) needs to be reviewed and modified. Premature cover spalling occurs in high strength concrete, even data from previous study cover spalling occurs in concrete compressive strength from 50 MPa. Equation of the increases of the strength of confined concrete developed by researchers has different characteristics from one another, and in general the results of performed tests are verified by yield criteria. In general, the K value especially for high-strength concrete uses non-linear equations. Modification of confinement models applied for concrete with a wide range of compressive strength was presented.

In the derivation, the concrete strength increase (= K), due to the symmetrical confinement was adopted with triaxial stress of data through the Ottosen criteria. Within the verification, the performance of the modified simulation models in the stress-strain behavior of the confined normal and high-strength concrete columns to the column tests under concentric loadings was found satisfactory. In line with previous author recommendation [20], research progress has been achieved regarding with the confined high-strength concrete, it still needs to be developed further mainly experimental program to cyclic loading is expected very useful in order to complete the concrete regulations in Indonesia (SNI).

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