DUCTILITY EVALUATION OF REINFORCED CONCRETE COLUMN MADE OF NORMAL- TO HIGH-STRENGTH CONCRETE UNDER CONSTANT AXIAL LOAD LEVEL COMBINED WITH FLEXURAL LOADING USING NONLINEAR SECTIONAL FIBER BASED MODEL

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***Abstract**: This study presents the ductility evaluation of reinforced concrete column made of normal-strength material using various empirical stress-strain model with nonlinear sectional fiber based analysis. The purpose is to evaluate the confinement requirement for reinforced concrete column under high axial load level. The concrete strength considered in the analysis are varies from 30 to 70 MPa while the steel reinforcing bar yield strength considered is only 400 MPa. The ductility is evaluated by using the customized ductility index measurement. The ratio of the concrete cover to the concrete core is set to 0.1 but not more than 40 mm. Attard and Setunge's concrete constitutive model is used in this investigation. Cover spalling behavior is considered in the analysis by including the restrained shrinkage effect on the concrete strength and the softening behavior. From this study, it was found that extra confinement is necessary to maintain the expected minimum level of ductility.*

Keywords: *High-strength concrete, empirical stress-strain model, fiber-based analysis*

INTRODUCTION

It is well known that the behavior of RC column is greatly affected by the applied axial load level. At the same amount of confinement level, the post-peak behavior of RC column degenerates as the axial load level increases [1-17]. Existing building codes, such as ACI 318-14 [18], CSA A23.3-04 [19], NZS 3101:2006 [20] and SNI 2847-2019 [21], provide additional clause for the minimum confinement reinforcement [22] if the column were loaded with high axial load level. This additional clause was added to ensure the minimum ductility level provided by the confinement rebar still satisfy the minimum requirement.

CSA A23.3 [19] and NZS 3101 [20] standards have considered the axial load effect in the confinement formulation since 2004 and 2006, respectively. The building code SNI 2847 [21] which was used in Indonesia is adopted from ACI 318 [18] building code. ACI 318 [18] have considered this axial load effect in the confinement formulation since 2014. One of the interesting facts is that this additional confinement requirement is applied not only for RC column loaded with high axial load level but also for high-strength concrete (HSC) regardless of the axial load level applied on the column. Therefore, this paper is allegedly trying to find out why additional clause for confinement is required by investigating the ductility level of RC column made of NSC and HSC under varying axial load level.

For that purpose, nonlinear sectional fiber-based analysis is carried out to investigate whether the additional clause for confinement rebar in ACI 318-14 [18] is necessary and is adequate to maintain the same ductility level as low axially loaded RC column. The concrete constitutive model is using the Attard and Setunge's model [23]. The ductility level of the RC column is computed by using the I_{10} ductility measurement [24, 25] which is somewhat different than the common method used in ACI 318-14 [18]. To maintain the discussion on the effect of the concrete strength, three concrete strengths are investigated.

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RESEARCH SIGNIFICANCE

This paper investigates the ductility level of RC column made of NSC and HSC by using nonlinear sectional fiber-based analysis. The ACI 318-14[18] building code is used to ensure the investigated RC columns are designed conform to the design guidelines. The axial load level investigated varies from zero up to eighty percent of the RC column concrete capacity. The measured ductility level is computed using the I_{10} ductility index. This I_{10} ductility index [24, 25] use the energy under the load-deflection curve which is a more reasonable approach to measure the ductility level of RC column.

METHODOLOGY

The research methodology in this paper consisted of four stages. The first stage of this research is the input data preparation. At this stage, the corresponding RC-HSC data are prepared. The data consisted of the strength of concrete and rebar materials, the geometry configurations of the columns, and the rebar configuration for both the longitudinal and transversal directions. The ratio of the longitudinal reinforcement is set to 1.5 % and the number of longitudinal rebar is set to eight. Therefore, the diameter of rebar may not conform with any standard size but is explicitly set such that the demanded ratio is exactly equal.

The transversal reinforcement is designed based on ACI 318-14 [18] for minimum confinement rebar. Two configurations of the transverse rebar are investigated. The pitch spacing is set to 100 mm. The diameter of the transverse rebar is computed such that the value for the confinement rebar is in exact match with required rebar area based on ACI 318-14 [18]. The column geometry considered is square with the width of the column is 400 mm. The cover thickness for 400 mm width column is set to 40 mm which is ten percent of the total width.

In the second stage, the existing Attard and Setunge's model formulation is modified to include the effect of cover spalling. The cover spalling effect is only applied for the concrete cover element while the concrete core element is computed by considering the confinement provided by the transverse steel reinforcement. In the third stage, nonlinear sectional fiber-based analysis is carried out with varying axial load level, as well as the transverse steel rebar configurations. In the fourth stage, the ductility index for each moment-curvature curve was computed by considering the average nominal strain of the section.

A. MINIMUM CONFINEMENT REINFORCEMENT BASED ON ACI 318-14 [18]

ACI 318-14 [18] provides minimum confinement reinforcement to ensure the ductility of RC column under combined axial load and bending moment can still be satisfied. In the previous ACI 318 design codes [26], only two equations should be satisfied. These equations are:

$$\frac{A_{sh}}{sb_c} = 0.3\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f_c^{'}}{f_{yh}} \quad (1)$$

$$\frac{A_{sh}}{sb_c} = 0.09\frac{f_c^{'}}{f_{yh}} \quad (2)$$

In the above, A_{sh} is the area of the transverse steel rebar in mm^2, s is the pitch spacing in mm, b_c is the width of the column core in mm, A_g is the gross cross sectional area of the column in mm^2, A_{ch} is the core cross sectional area of the column in mm^2, f_c is the concrete compressive strength in MPa and f_{yh} is the transverse steel yield strength in MPa.
In the case of the ratio of the factored axial load (P_u) over the gross sectional capacity of the concrete ($A_g f_c$) higher than 0.3 or for concrete with compressive strength higher than equal to 70 MPa, additional clause was provided by ACI 318-14 [18]:

$$\frac{A_{sh}}{s} = 0.2k_f k_n \frac{P_u}{f_{yt}A_{ch}} \quad (3)$$

where k_n is a factor that decrease the required confinement for column with closely spaced longitudinal reinforcing bar, k_f is the factor that consider the brittleness of the concrete material for HSC. The expression for k_n and k_f were proposed by Legeron and Paultre [22] and are:

$$k_f = \frac{f_c^{'}}{175} + 0.6 \geq 1.0 \quad (4)$$

$$k_n = \frac{n_l}{n_l - 2} \quad (5)$$

In the above, n_l is the number of longitudinal bars. Since the pitch spacing was determined (100 mm) and with the number of ties leg (n_h) is three, the diameter of the transverse steel reinforcing bar can be calculated as:

$$d_h = \sqrt{\frac{4s\chi}{n_h \pi}} \quad (6)$$

where χ is the required A_{sh}/s computed using Eqns.(1)(2) and (3).

B. MODIFICATION IN THE STRESS-STRAIN MODEL TO INCLUDE THE COVER SPALLING BEHAVIOR

Cover spalling behavior plays an important role on the behavior of RC column especially under high axial load. The existence of restrained shrinkage strain [27, 28] at the cover shell provides an initial tensile pressure which lowered the concrete compressive strength of the concrete cover. In addition, the weak plane at the interface between the cover shell and the concrete core can exist especially if the configuration of both the longitudinal and the transverse steel rebars is sufficiently dense. In normal-strength RC column, when the cover spalling occurred, the cover shell still carries some portion of axial load [29].
To include the cover spalling behavior in the stress-strain model due to restrained shrinkage, some properties of the stress-strain models should be modified. In [28], there are three basic properties should be adjusted for the concrete constitutive model. These properties are the uniaxial peak concrete compressive strength, the uniaxial peak axial strain, and the uniaxial strain at the inflection point of the softening curve. In this paper, the concrete constitutive model which can cope with three basic parameter in the above are the model of Attard and Setunge [23].

C. NONLINEAR SECTIONAL FIBER BASED MODEL

To evaluate the behavior of RC column under combined axial load and bending moment, an analytical simulation tool is required. In this paper, a nonlinear sectional fiber-based model analysis using MatLab is used [30]. The RC column section is discretized using Constant Strain Triangle (CST) and the cover and cover elements are differentiated. Figure 1 shows an example of RC column meshed using the CST element [31]. The red circle on Figure 1 represent the longitudinal bar position.

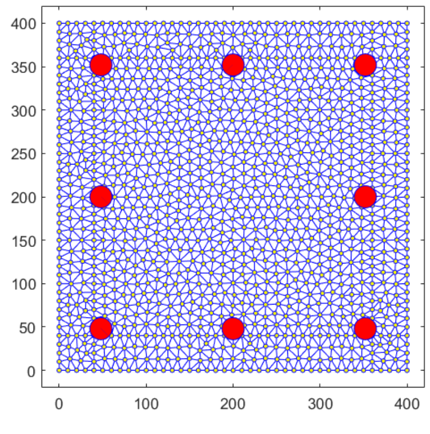

Figure 1 Discretized Meshed Fiber-Based Element with Triangular Constant-Strain-Triangle (CST)

The axial force and the bending moment of the cross section can be computed by [30]:

$$F = \sum_{i}^{nele} \sigma_i A_i \quad (7)$$

$$M_{yy} = \sum_{i}^{nele} \sigma_i A_i \left(y_i - \overline{y}\right) \quad (8)$$

$$M_{xx} = \sum_{i}^{nele} \sigma_i A_i \left(x_i - \overline{x} \right) \tag{9}$$

where F is the axial force, M_{yy} is the moment in the Y-direction, M_{xx} is the moment in the X-direction, σ_i is the axial stress in the element, A_i is the area of the element, y_i and x_i is the centroid location of the element, $\overline{y}$ and $\overline{x}$ is the centroid of the whole cross section.

D. MEASUREMENT OF THE DUCTILITY INDEX

To measure the ductility index of RC, an extended formulation for I_{10} ductility measurement is used. I_{10} ductility measurement often used to measure the ductility of RC column under either concentric or eccentric loading. The internal work done in I_{10} can be defined by [32]:

$$\int_R \left(N\varepsilon_{avg} + Ne\kappa \right) dx = \int_R N \left(\varepsilon_{avg} + e\kappa \right) dx \tag{10}$$

where ε_{avg} is the average strain, N is the axial load, e is the load eccentricity and κ is the curvature. For RC column fixed supported at the base and is loaded under constant axial load and were displaced horizontally, the internal work done can be computed by:

$$\int_R \left(N\varepsilon_{av} + \left(Ne + HL \right) \kappa \right) dx = \int_R \left(N\varepsilon_{av} + M\kappa \right) dx \tag{11}$$

where H is the horizontal load, L is the column height and M is moment acting on the cross section of the column. The second term in Eqn.(11) above consisted of a second order moment plus the primary bending moment. By noting that the axial load is constant, the nominal strain can be reduced to:

$$\xi = \frac{\left(N\varepsilon_{av} + M\kappa \right)}{N} \tag{12}$$

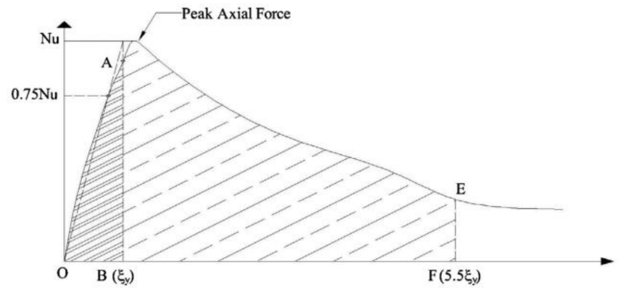

Figure 2 The axial force versus the combined nominal strain (ξ) curve [32]

Figure 2 shows the axial force as function of the combined nominal strain (ξ) curve. In the case of axially loaded RC column and by assuming a perfectly elastoplastic responses, the value for I_{10} must be exactly equal to ten. Therefore, the ultimate strain should be at least 5.5 times the nominal yield strain. The area of OAB with normalized N_u equal to one would be 0.5. The area of OAEF would be equal to 5.0. By dividing area OAEF with OAB the value for I_{10} is exactly equal to 10 [24].

From Figure 2, it should be noted that the initial secant modulus of the load-nominal strain curve is measured at 75% of the maximum load applied on the column. In AS3600-2018 [33], the value for I_{10} ductility index used to ensure the column is sufficiently ductile is set to 5.6. This means that the confinement reinforcement should be provided such that the value for I_{10} must be greater than 5.6.

In ACI 318-14 [18], the ductility measurement is measured from the peak once the peak load reduced to 85% of the maximum capacity. By including the softening responses at a nominal strain 5.5 times higher than the nominal yield strain gives a minimum ductility index value equal to 9.33 (see Figure 3). It is therefore in this paper, the ductility index measured using ACI 318-14 [18] codes is measured using $I_{M9.33}$. If the investigated columns have the value of $I_{M9.33}$ less than 9.33 means that the columns are assumed to not have sufficient ductility based on ACI 318-14 [18].

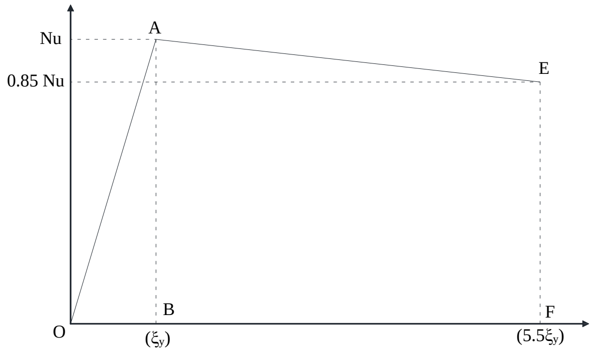

Figure 3 Used axial force versus the combined nominal strain (ξ) curve for measuring ductility index

ANALYSIS AND DISCUSSIONS

The computed I_{10} ductility index as functions of the axial load level (P_u/f_cA_g) are shown in Figures 4, 5 and 6 for 30, 50 and 70 MPa concrete, respectively. The confining rebar for those concrete strength are designed only using Eqns.(1) and (2) plus two ratios of Ash/s with non-conforming design guidelines (1.01 mm and 1.57 mm). As shown in Figure 4, the RC columns design using Eqns.(1) and (2) show the I_{10} value greater than 9.33 which means for 30 MPa concrete, additional confinement reinforcing bar as stated in ACI 318-14 [18] is not necessary.

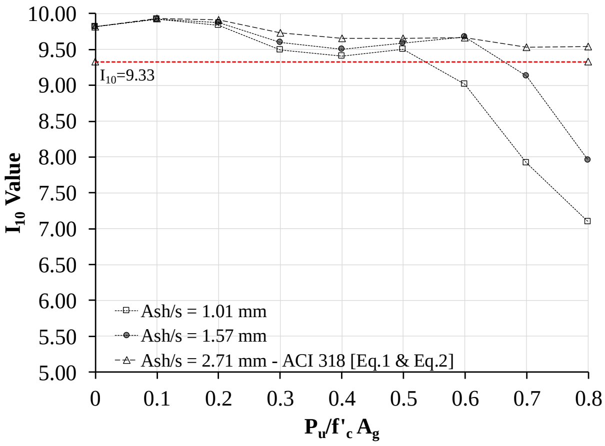

Figure 4 The I_{10} ductility index versus the RC column axial load level for 30 MPa concrete

For non-conforming confinement rebar, the I_{10} value drops when the axial load level ratio is greater than 0.5. However, as the concrete strength increases, the I_{10} value for 50 MPa drops below 9.33 at the axial load level ratio higher than 0.6 and for 70 MPa drops at the axial load level ratio higher than 0.5. This finding shows that as the concrete strength increases, the additional clause for the confinement rebar is necessary. It is expected that as the concrete strength goes higher, the axial load level ratio which shows the I_{10} value less than 9.33 will be lower.

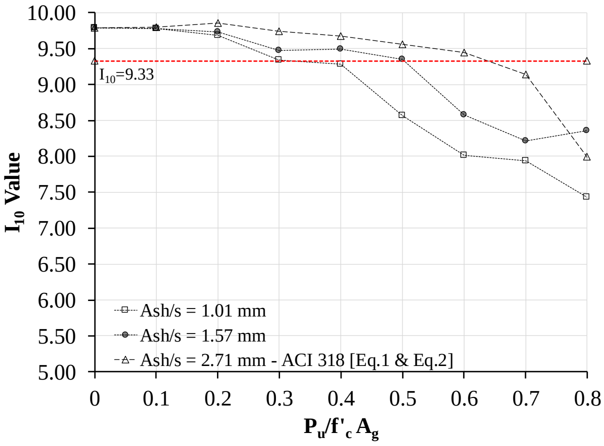

Figure 5 The I_{10} ductility index versus the RC column axial load level for 50 MPa concrete

Figure 7 shows the I_{10} ductility index as function of the axial load level ratio for 70 MPa concrete designed using Eqns. (1)(2) and (3). As shown in Figure 7, using the additional clause for confinement rebar does significantly improve the ductility level of the RC column. The I_{10} value is only barely lower than 9.33 when the axial load level ratio between 0.5 to 0.6. Figures 8 and 9 shows the axial force as function of the combined axial strain for 70 MPa concrete design using only Eqn. (1) and (2), and Eqns. (1)(2) and (3), respectively. As shown in Figure 8, the softening response of the RC column was observed for axial load level ratio higher than 0.4. Cover spalling behavior is observed when the axial load level ratio is greater than 0.4.

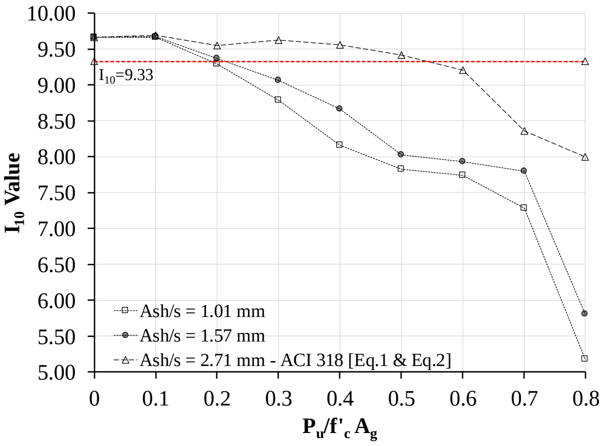

Figure 6 The I_{10} ductility index versus the RC column axial load level for 70 MPa concrete using Eqns.1 and 2

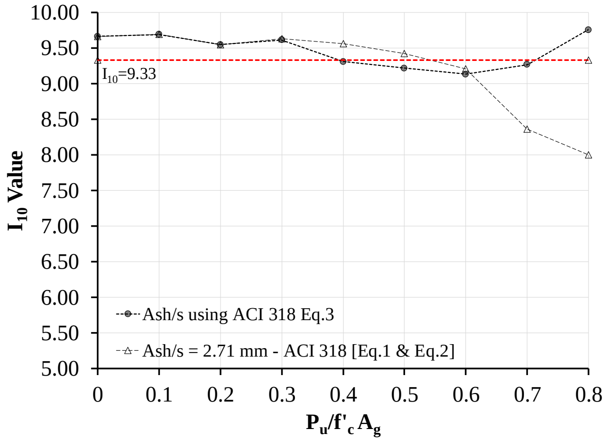

Figure 7 The I_{10} ductility index versus the RC column axial load level for 70 MPa concrete using Eqn.1&2 and Eqn.3

On the other hand, in Figure 9, a slight softening response only occurred when the axial load level ratio between 0.2 to 0.3. This can be understood because of the softening response on the cover elements under flexural loadings. As the axial load level ratio is further increased, the softening response changed to hardening.

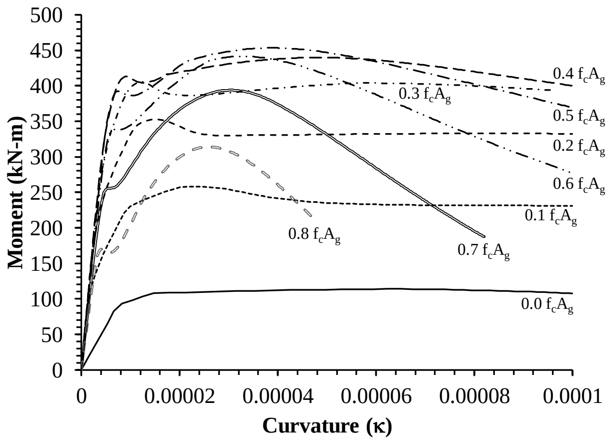

Figure 8 The bending moment capacity versus curvature for 70 MPa concrete using Eqn.1 and Eqn.2

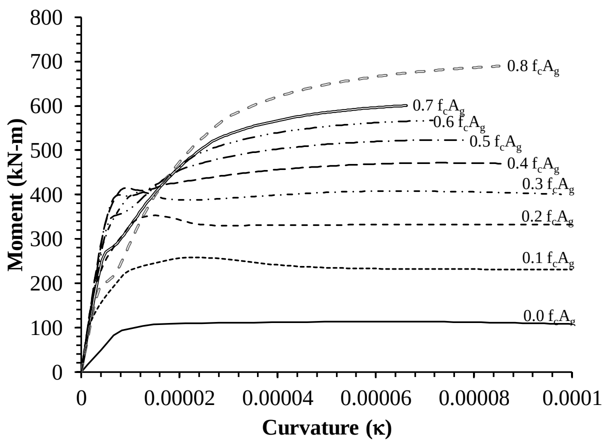

Figure 9 The bending moment capacity versus curvature for 70 MPa concrete using Eqn.3

CONCLUSIONS

This paper had presented the axial ductility level of RC-column made of HSC evaluated using the nonlinear sectional fiber-based model. Energy based ductility index [24, 25] was used to evaluate the ductility level of RC-column. The investigated RC columns were designed based on ACI 318-14 [18]. One group was designed using only the first two confinement equations while the other group was designed based on all the three confinement equations. From the investigation, it was found that for normal strength concrete, the additional clause for axial load level ratio higher than 0.3 was not necessary. However, for medium- to high-strength concrete, the additional clause for confinement rebar was required to ensure the minimum ductility level was achieved. Further investigation for RC column made of very high-strength concrete, as well as RC column with different cross section configuration should be investigated.

Furthermore, the use of size-dependent empirical concrete constitutive model [34], inclusion of the confining pressure and lateral strain dependent analytical model [35], as well as other behavior impacted phenomena such as buckling of longitudinal bars [36, 37] should be considered in the future. To further verify the numerical simulation carried out in this paper, numerical investigation using a more sophisticated concrete constitutive model [38-40] and numerical simulation tool [41, 42] which consider the cover spalling [28] should be carried out in the future.

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