“Research Note”

DUCTILITY OF HIGH STRENGTH CONCRETE IN BENDING WITH OR WITHOUT CONFINEMENT*

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Abstract– One of the important principals of RC structural design in earthquake regions is ductility considerations, which need a different design approach. In this paper, the parameters affecting high strength concrete HSC are considered and the tools (tables and curves) are prepared for ductile design of reinforced HSC bending sections. Using these tools, it is possible to easily and safely design for ductility of singly and doubly reinforced flexural confined and unconfined HSC sections. The worked examples are also presented.

Keywords– Ductility, flexural section, HSC, confined or unconfined concrete

1. INTRODUCTION

Current knowledge of HSC shows that there are definite advantages in using HSC in structures. Greater strength, increased modules of elasticity, reduced shrinkage, and creep are some of these advantages. However, the nature of failure of the HSC is brittle and not even ductile as normal strength concrete (NSC). Therefore, designing the HSC structures for ductility is important. A considerable amount of ductility can be ensured by a few relatively simple and inexpensive design details, especially when the structures are made of NSC [1]. In other words, a limited research report is available when considering the HSC structures.

2. DUCTILITY OF REINFORCED HSC BEAMS

Here, the easiest and most common method of defining the ductility of a cross section called curvature ductility ratio, \( \mu = \phi_y / \phi_u \) is taken [2]. Using Fig.1a; the yield curvature \( \phi_y \) of a section can be computed with adequate accuracy from the straight line theory of Eq. (1).

\[
\phi_y = \frac{\varepsilon_y}{d(1-K)}
\]

\[ (1) \]

where, \( kd \) is depth of the compression zone computed using straight line theory;
\[ K = -\rho n + [2\rho n + \rho^2 n^2]^{1/2}, \rho = A_s / bd, n = E_s / E_c \] and the ultimate curvature, \( \phi_u \), can be calculated as
\[ \phi_u = \varepsilon_u / c \] (2)
where \( c = \rho(f'_s / f'_c) \) and \( \varepsilon_u \) is concrete compressive strain at crushing of concrete with a uniform stress block of \( \alpha f'_c \). However, for NSC the \( \alpha \) is respectively assumed equal or smaller than 0.85 \( f'_c \) for HSC (see the following). Using Eq. (1) and (2) gives;
\[ \mu = \varepsilon_u (\alpha \beta f'_c) E_s (1 + \rho n - (2\rho n + \rho^2 n^2)^{0.5}) / \rho f'_y \] (3)
The value of \( \mu \) in Eq. (3) is directly affected by the value of ultimate strain \( \varepsilon_u \) assumed in the calculation and is a function of a number of variables including the concrete strength. When stirrups are not available in the beam, it seems this value can be replaced by \( \varepsilon_{cu} \). Although the ultimate compressive strain varies with concrete strength a value equal to 0.003 represents the test results satisfactorily [3,4]. This value is specified in standards [5-7]. Thus for design use it is recommended that \( \varepsilon_u = \varepsilon_{cu} = 0.003 \) be used, unless special binding reinforcement is provided to increase \( \varepsilon_u \) [1,7]. Now, substituting in Eq. (3), the Eq. (4) can be used to compute design values of the ductility ratio of both (NSC and HSC).
\[ \mu = 600(\alpha \beta f'_c)(1 + \rho n - (2\rho n + \rho^2 n^2)^{0.5}) / \rho f'_y \] (4)
b) Doubly reinforced beams

Here, \( \phi_y = f_y / E_s (1 - k) \) and \( \phi_s = \varepsilon_s / C_s \) and \( K = \left[ n^2 \left( \rho + \rho' \right)^2 + 2n \left( \rho + \rho' d' / d \right) \right]^{1/2} - n \left( \rho + \rho' \right) \)

However, when the \( A'_s \) yields or does not yield we have respectively;
\[ \phi_y = \varepsilon_u \alpha \beta f'_s b (A_s - A'_s) / f_y \text{ or } \mu = \phi_u / \phi_s = E_s \varepsilon_u (1 - k) d / f_y C_s \cdot \]

In a beam without \( A'_s \) and limiting the value of \( \rho_{max} = 0.75 \rho_b \), the Eq. (5) can be obtained as;
\[ \rho_{max} = 0.75(\alpha \beta f'_c / f_y) (\varepsilon_{cu} / \varepsilon_u + \varepsilon_y) \] (5)
So, where the confinement mechanism is available the \( \varepsilon_u \) is calculated with the actual value.

3. HIGH STRENGTH COMpressive CONCRETE STRESS BLOCK'S PARAMETERS

Although the ultimate compressive strain varies with concrete strength for HSC a value equal to 0.003 represents, satisfactorily, the test results. This value is specified in the ACI, Australian and New Zealand standards [5-7]. However, in the Canadian standard [8] it is taken as 0.0035.
\[ \alpha = 0.85 - 0.004 \left( f'_c - 55 \right) \] It is generally accepted that the uniform stress should be smaller than 0.85 \( f'_c \) for HSC [3]. In [7], the depth of equivalent rectangular stress block is taken as \( \gamma \) times the depth of neutral axis and the uniform stress is taken as \( \alpha f'_c \), where, \( \gamma = 0.85 - 0.008(f'_c - 30) \); within the limits 0.65 \( \leq \gamma \leq 0.85 \) (it is assumed that \( \gamma = \beta_1 \)), and within the limits 0.75 \( \leq \alpha \leq 0.85 \), note that \( \alpha = 0.85 \) when \( f'_c \geq 55 \) MPa and \( \alpha = 0.75 \) when \( f'_c \geq 80 \) MPa.

However, when \( f'_c \geq 80 \) MPa, \( \alpha \beta_1 (1 - 0.5 \beta_1) b c^2 f'_c = C y \) and \( \alpha \beta_1 b c f'_c = C_y \), and \( C \) is the resultant compressive force which is placed in \( y \) distance from the neutral axis. For variables \( \alpha \) and \( \beta_1 \) in HSC, comprehensive information is available in [9].
4. CONFINEMENT EFFECT OF TRANSVERSE REINFORCEMENT

Enhancement of strength and ductility has been observed for all grades of concrete with lateral confinement. This leads to the speculation that the beneficial effect of lateral confinement would reduce with the increase in compressive strength. Data reported for Poisson’s ratio of HSC are evident in that there is a large scatter of results. However, the value proposed by [9] which is 0.2, appears to be the median of the experimental results.

Analytical model for confinement mechanism in rectangular beams including closed stirrups is shown in Fig. 2. Based on this assumption, the stress-strain relationship for confined core concrete (imprisoned concrete on the central line of stirrups), shown in Fig. 2.

Fig. 2. General model for stress-strain concrete curve proposed by [10]

This model includes: the OA part, which is a parabolic curve with the peak point, A, at $f'_c$ stress and $\varepsilon_s$ strain, $f'_c$ is confined concrete's compressive strength and is equal to $K_s f'_c$, $f'_c$ is unconfined concrete's compressive strength and $K_s$ is increasing strength's factor. Strains $\varepsilon_s$ and $\varepsilon_{s2}$ are the minimum and maximum strain values associated with maximum stress, and $\varepsilon_{s85}$ is strain associated with 85 percent of maximum stress on the declining part of the stress-strain curve. AB and BC are the straight lines on the curve.

$$K_s = 1 + \frac{b^2}{140 P_{oc}} \left[ \left( 1 - n_1 \frac{S_c}{2} \right) \left( 1 - \frac{S_c}{2bh} \right) \right] \left( \rho_s f_{y_s} \right)^{0.5}$$

The value of $\varepsilon_{s2}$ is a concrete ductility index and is obtained by transverse reinforcement. Here, an equation proposed by Sargin's model is proposed for $\varepsilon_{s2}$, which includes stirrups shape and spacing, and the magnitude and characteristic of transverse reinforcement. The proposed equation is in the following form;

$$\varepsilon_{s2} / \varepsilon_{oo} = 1 + \frac{248}{S_c} \left[ \left( 1 - S_c / b \right)^2 \right] \left( \rho_s f_{y_s} / (f'_c) \right)^{0.5}$$

$\varepsilon_{oo}$ is strain corresponding to the maximum stress in the plain concrete (i.e., 0.0022), $S_c$ is the spacing of longitudinal reinforcement in the compressive concrete region (mm) and stresses are in MPa, and the stirrup reinforcement's strain corresponding to 85 percentage of maximum stress is $\varepsilon_{s85} = 0.225 \rho_s (b / S_c)^{0.5} + \varepsilon_{s2}$ and therefore, ultimate compressive concrete strain is;

$$\varepsilon_u = \varepsilon_{s85}$$

So Eq. (8) can be substituted in Eq. (3) to calculate ductility [10].

5. FLEXURAL DUCTILITY DESIGN OF HIGH STRENGTH CONCRETE SECTION

There are different opinions on what should be taught in the way of design and design office work for ductility design of HSC sections. In this paper, the tools such as design tables and graphs are prepared and presented for both HSC unconfined and confined bending sections.
**a) Singly reinforced bending sections**

Considering (Fig.1) an ultimate compressive concrete strain for unconfined conditions and for different steel ratio, concrete compressive and steel yield strength, by using Eq. (4), the ductility ratios are calculated and their corresponding values are given in Table 1a.

**Table 1(a). Steel percentages for various ductility ratios in unconfined state**

<table>
<thead>
<tr>
<th>$f'_c$ MPa</th>
<th>$\rho$ or $(\rho - \rho')$</th>
<th>Ductility ratio $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>280 MPa</td>
<td>0.0196 0.0099 8</td>
<td></td>
</tr>
<tr>
<td>420 MPa</td>
<td>0.0247 0.0127 6</td>
<td></td>
</tr>
<tr>
<td>600 MPa</td>
<td>0.0340 0.0178 4</td>
<td></td>
</tr>
<tr>
<td>800 MPa</td>
<td>0.0234 0.0119 8</td>
<td></td>
</tr>
<tr>
<td>1000 MPa</td>
<td>0.0295 0.0152 6</td>
<td></td>
</tr>
<tr>
<td>1200 MPa</td>
<td>0.0406 0.0213 4</td>
<td></td>
</tr>
<tr>
<td>1400 MPa</td>
<td>0.0287 0.0146 8</td>
<td></td>
</tr>
<tr>
<td>1600 MPa</td>
<td>0.0360 0.0186 6</td>
<td></td>
</tr>
<tr>
<td>1800 MPa</td>
<td>0.0495 0.0260 4</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 3. Relationship between $\rho$ and ductility, unconfined HSC ($f'_c = 280$ MPa)**

**Table 1(b). Different stirrups percentages $\rho_s$ for $\mu_s = \varepsilon'_c / \varepsilon_{cu}$ value in confined sections**

<table>
<thead>
<tr>
<th>$\rho_s$</th>
<th>$f_y / (S_c \sqrt{f'_c})$</th>
<th>$f_y / (S_c \sqrt{f'_c})$</th>
<th>$\mu_3 = \varepsilon'<em>c / \varepsilon</em>{cu}$</th>
<th>$b / S_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.00423 0.00285 1.33</td>
<td>0.00892 0.00601 2</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>0.00316 0.00192 1.33</td>
<td>0.00668 0.00404 2</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>0.01020 0.00617 2.67</td>
<td>0.00830 0.00416 3.33</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

**Fig. 4. Relationship between $\rho$ and ductility, unconfined HSC ($f'_c = 420$ MPa)**

**a) Doubly reinforced unconfined bending sections**

Considering the affecting parameters on the ductility of bending section having compressive steel reinforcement, the ductility factor $\mu$ can be calculated using, $\phi_a = \varepsilon_y / \alpha$, $f'_c b / (A_s - A'_s) f_y$. By referring the parameter $\mu$ in Eq. (4) as $\mu_1$ with the value of $\rho - \rho'$ instead of $\rho$, $K = -\rho n + [2 \rho n + \rho^2 n^2]^{1/2}$ as $k_2(\rho)$ and also the parameter $K = n [1 + (\rho + \rho')^2 + 2 n (\rho + \rho' d' / d) - n (\rho + \rho')]$ as $k_2(\rho, \rho', d'/d)$, we can compute the ductility factor $\mu$ in the form of $\mu = \mu_1 (\rho - \rho') (k_2 / k_1 (\rho - \rho'))$. It is important that the parameters $k_2$ and $k_1$ are functions of $\rho, \rho', d'/d, n$, where $n = E_s / E_c$ is a parameter of $f'_c$, while numerical calculations proved that the affect of $n$ in $\mu_2$ is less than 4%. By referring the $k_2(\rho, \rho', d'/d) / k_1(\rho - \rho')$ as the compressive steel index $\mu_2$, the ductility factor is obtained as $\mu = \mu_1 \times \mu_2$. The value of parameter $\mu_2$ has been calculated and drawn in Figs. 5 and 6.
The significance of a particular value of the ductility ratio $\mu$ for HSC sections is difficult to define. Since this term is only an arbitrary measure of the inelastic rotation capacity of a cross section and the value of $\varepsilon_u$ used in computing $\mu$ [9].

Akbarzadeh and Maghsoudi [11] tested HSC beams singly or doubly reinforced with different steel percentage and concluded that the minimum lower value of $\mu = 3$ can be reached when for the singly reinforced beams the value of $\rho$ is greater than 2.0%, whereas for doubly reinforced beams the ratio of $\rho$ can be increased even up to 4.0%. For design purposes, it is recommended that the ductility ratio for HSC from Eq.(4) or Figs. 3, 4 should be at least 4 in structures in seismic regions and at least 3 in structures requiring limited ductility.

c) Confined bending sections

Considering parameters affecting the ductility of sections having transverse steel (confined sections), the value of $\varepsilon_u$ has been determined using Eq. (8) for values $f_{ys}/S_c(f_y)^{0.5}$, $b/S_c$ and $\rho_s$ and also the parameter confinement index $\mu_3 = \varepsilon_u/\varepsilon_{cu}$ has been calculated and given in Table 1b. Then, using previous data for ductility, the value of $\mu$ (ductility ratio) in HSC confined sections is obtained in the form of $\mu = \mu_1 \times \mu_2 \times \mu_3$. To design for ductility of sections, the charts 7 and 8 are prepared. As can be seen, for confined sections, the confinement index parameter $\mu_3 = \varepsilon_u/\varepsilon_{cu}$ is obtained by interpolating charts 5 and 6, which are referred to $f_{ys}/S_c(f_y)^{0.5}$ = 0.15, 1.0 respectively, and then by substituting in $\mu = \mu_1 \times \mu_2 \times \mu_3$ the ductility ratio ($\mu$) in HSC confined sections can be determined.
6. WORKED EXAMPLES FOR UNCONFINED AND CONFINED HSC SECTION OF BEAMS

It is desirable to determine the ductility factor of the unconfined HSC section shown in Fig. 9a for the beam properties of \( f'_y = 80 \text{ MPa}, \ f_y = 420 \text{ MPa}, \ A = 4 \Phi 25, \rho = 0.0201; \)

Using equivalent stress block for HSC; thus, \( \gamma = 0.65 \) and \( \alpha = 0.75; E_c = 3.66 \times 10^4 \text{ MPa}, \)
\( n = 5.46, \rho = 0.0201 \) and therefore the ductility factor is;

\[
\mu = 600 (\alpha \beta_1 f'_y)(1 + \rho n - (2 \rho n + \rho^2 n^2)^{0.5}) / \rho f'_y = 4.16
\]

Also, for the given values, the ductility factor can be calculated using Fig. 4 and it is as \( \mu = 4.2. \) To determine the ductility factor of the confined HSC section of Fig. 9b with the following properties;

\( f'_y = 80 \text{ MPa}, \ f_y = 420 \text{ MPa}, \ A = 4 \Phi 32, A' = 4 \Phi 20, \rho = 0.0201, b = 300 \text{ mm}, n_l = 3, S_c = 53 \text{ mm}, \)
\( A_l = 2 \Phi 8, \ S_y = 10 \text{ mm}, \rho_s = 0.0087 \text{ mm} \) and \( P_{occ} = 3500 \text{ KN}. \) Again using equivalent stress block for HSC;

\[
K_s = 1 + b^2 / 140 P_{occ} \left[ \left| 1 - n_l S_c^2 / 5.5b^2 \right| (1 - S_c / 2b)^2 \left| \rho_s f'_y \right| \right]^{0.5} = 1.24, f'_c = K_s f'_y = 99.2 \text{ MPa},
\]
\( \epsilon_{v2}/\epsilon_{00} = 1 + 248 / S_y \left[ 1 - 5 (S_y / b) \right] \left( \rho_s f'_y \right) \left( f'_y \right)^{0.5} = 1.84, \epsilon_{v2} = 1.84 \times 0.0022 = 0.0041, \epsilon_{xs} = 0.225 \rho (b / S_y)^{0.5} + \epsilon_{v2}, \)
\( \epsilon_{u} = \epsilon_{xs} = 0.0074, \ n = 5.46, \rho = 0.0330, \rho' = 0.0129, k = 0.42. \)

Therefore, by substituting, the value of \( \mu = \alpha \beta_1 f'_y E_u / f'_y \left( \rho - \rho' \right)(1 - k) = 11.71. \)

The ductility factor can also be calculated using charts (i.e., Fig. 4) for \( f_y = 420 \text{ MPa}, \) the value of \( \rho - \rho' = 0.0201 \) and the \( f'_c = 88.8 \text{ MPa}, \) therefore the ductility index is as \( \mu_1 = 5.1. \)

Using proposed Figs. 5 and 6, from \( \rho'/\rho = 0.39, \rho = 0.0330 \) and \( d' / d = 0.21, \) the obtained compression steel index value is \( \mu_2 = 0.92. \)

Using proposed Figs. 7 and 8, from \( b / S_y = 3, \ \rho_s = 0.0087 \) and \( f'_y / S_y (f'_y)^{0.5} = 0.88 \) the obtained confinement ductility is \( \mu_3 = 2.5. \) Therefore the ductility factor is obtained as:

\[
\mu = \mu_1 \times \mu_2 \times \mu_3 = 5.1 \times 0.92 \times 2.5 = 11.7.
\]

So, ductility design of HSC sections can be computed using the proposed equation, tables or (charts), which will cause a reduction in numerical errors.

7. CONCLUSION

By considering the affecting parameters on ductility of confined or unconfined HSC sections, the equations are drawn and also for more convenience, the tables and curves are prepared. Using these tools,
it is possible to determine easily and safely the ductility factor of singly or doubly reinforced flexural confined and unconfined sections.

For singly reinforced unconfined section, the ductility factor is calculated easily by determining the ductility index $\mu_1$ from the prepared curves to calculate the ductility index and replacing it as $\mu = \mu_1$. For doubly reinforced unconfined section the ductility factor is calculated by determining the compression steel index $\mu_2$ from the prepared curves to calculate the compression steel index and replacing it as $\mu = \mu_1 \times \mu_2$. For doubly reinforced confined section the ductility factor is calculated by determining the confinement index $\mu_3$ from the prepared curves to calculate the confinement index and replacing it as $\mu = \mu_1 \times \mu_2 \times \mu_3$.

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