EFFECT OF CONCRETE CRACKING ON THE LATERAL RESPONSE OF RCC BUILDINGS

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Abstract

In the present study, the effect of concrete cracking on the lateral response of building structures has been investigated and discussed. The research work related to the study of effect of concrete cracking on its stiffness has been surveyed. The controversies in the expressions of the prime parameter related to the cracking of the reinforced concrete are also discussed. The modification factors and equations recommended in literature as well as in different country standards to introduce the non-linearity of concrete are also given. The framed building design examples are presented for quantitative effect of lateral response incorporating the concrete cracking under seismic loading based on Indian seismic code.

Keywords: Cracking; effective stiffness; RCC buildings; building standards; drift; deflections

1. Introduction

In buildings structures, the flexural stiffness reduction of beams and columns due to concrete cracking plays an important role in the nonlinear load-deformation response of reinforced concrete structures under service loads. The concrete cracking amplifies the lateral deflection of the building. The excessive lateral deflection may also result in large second-order P-delta effects and out of order of nonstructural components. Several research studied have been devoted to propose the variations in concrete member stiffness caused by cracking. Yu and Winter [1] has suggested modification factors for the flexural rigidity while Branson [2] identified an effective moment of inertia for cracked concrete. Other procedures for concrete non-linear effect are due to Beeby [3], making adjustments to the curvature along the span and at critical sections and due to Ghali, et al. [4], making use of a section-curvature incremental evaluation. CEB commission [5] adopted an approach to alter the M/I ratio for concrete cracking reflection. A review of the advanced cracking models proposed for finite element analysis of structural elements is given in the ASCE report [6]. Stafford, Smith and Coull [7] treatise has an extensive treatment of the cracked concrete stiffnesses in tall buildings. A trilinear bending moment–curvature model is used by Ahmed and Perry [8] to develop a procedure for determining the effective flexural stiffness of

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The main parameters affecting the stiffnesses of the cracked concrete elements are modulus of elasticity and so-called effective moment of inertia. The recommendations for main parameters vary significantly mainly due to different interpretations of test data and different behavior models. In the following paragraphs, the expressions for the modulus of rupture, modulus of elasticity, moment of inertia in cracked state proposed by different investigators and codes are outlined.

1.1 Concrete modulus of rupture
There is wide variability in the values of the modulus of rupture reported in literature. The value reported by various investigators for the modulus of rupture range from 0.33 to 1.0 $\sqrt{f_c}$ MPa and the actual deformation values can vary between 25 to 40 percent using different expressions of modulus of rupture. Sbrounis [14] and Branson [2] proposed the modulus of rupture as 0.62 $\sqrt{f_c}$ MPa while Graham and Scalon [15] predicted it as low as 0.33 $\sqrt{f_c}$ MPa. ACI:318-02 [16] had specified the modulus of rupture as 0.62 $\sqrt{f_c}$ MPa and modify it to 0.517 $\sqrt{f_c}$ MPa in the latest edition. The Iranian Code [17] guidelines to use as 60 $\sqrt{f_c}$ MPa. The Indian code [18] has standardized the value of modulus of rupture as 0.7 $\sqrt{f_c}$ MPa (0.626 $\sqrt{f_c}$, equivalent cylindrical strength).

1.2 Concrete modulus of elasticity
The modulus of elasticity is strongly influenced by the concrete materials and proportions used. Researchers have established several empirical equations for predicting the elastic modulus of concrete. The noteworthy studies for the calculation of the modulus of elasticity are due to Ahmad et al. [19] and Carrasquillo et al. [20]. The value of the secant modulus of elasticity ($E_c$) for normal-strength concretes at 28 days is usually around 28,000 MPa, whereas for higher-strength concretes, values in the range of 49,000 to 56,000 MPa have been reported. As per American code, for normal weight concrete, modulus $E_c$ shall be taken as ‘4700. $f_c^\prime$’ and Indian code has specified the elastic modulus of concrete as ‘5000 $\sqrt{f_c}$’ MPa (5590 $\sqrt{f_c}$, equivalent cylindrical strength). The British code [21] expression to calculate the modulus of elasticity for normal weight concrete is

$$E_c = K_0 + 0.2 f_{cu}$$

Where $E_c$ is the static modulus of elasticity and $f_{cu}$ is the characteristic cube strength (in
MPa). $K_o$ is a constant closely related to the modulus of elasticity of the aggregate (taken as 20 kN/mm²).

### 1.3 Effective moment of inertia

The cracking of concrete is a dominant component in RCC buildings response. The member moment of inertia, $I$, used in the analysis should incorporate the degree of cracking, as tension cracks are inevitable when the imposed loads produce bending moments in excess of the cracking moment. The effective moment of inertia, $I_e$, concept to reflect the concrete cracking was conceived originally by Branson. He assumed bilinear load-deflection behavior of cracked section and proposed an Effective moment of inertia $I_e$ as a function of the level of cracking. Later, the concept is developed and used by other authors. The equations and modification factors recommended in literature as well as in different country standards to introduce the non-linearity of concrete are presented below.

#### 1.3.1 Equations proposed for effective moment of inertia

The equation proposed by Branson [2] for $I_e$ is as given below.

$$I_e = \left( \frac{M_o}{M_{cr}} \right)^3 \cdot I_g + \left[ 1 - \left( \frac{M_o}{M_{cr}} \right)^2 \right] I_e \leq I_g$$

Grossman [22] has suggested the following approximate $I_e$ without prior knowledge of area of flexure reinforcement.

For $M_o/M_{cr} \leq 1.6$

$$I_e = \left( \frac{M_o}{M_{cr}} \right)^4 \cdot I_g \leq I_g$$

For $1.6 \leq M_o/M_{cr} \leq 10$

$$I_e = 0.1 K_e \left( \frac{M_o}{M_{cr}} \right)^4 \cdot I_g \leq I_g$$

where $K_e$ is a factor depending on the density of concrete and grade of steel but $I_e$ should not be less than $0.35K_eI_g$.

The following relation for effective moment of inertia ($I_e$) is proposed by Wang [23].
Elwood and Eberhard [24] propose the following values for columns effective stiffness.

\[
\frac{EI_{\text{eff}}}{EI_g} = 0.2 \quad \frac{P}{A_g f_c'} \leq 0.2
\]

\[
= \frac{5 P}{3A_g f_c'} - \frac{4}{30} \quad 0.2 \leq \frac{P}{A_g f_c'} \leq 0.5
\]

\[
= 0.7 \quad 0.5 \leq \frac{P}{A_g f_c'}
\]

Priestley equation [25] for determining \(I_e\) for columns and structural walls is as under.

\[
E_c I_e = \frac{M_n}{\phi_y}
\]

where \(E_c\) = modulus of elasticity of concrete, \(M_n\) = nominal flexural strength of the section and \(\phi_y\) = curvature at first yield. Since \(\phi_y\) is essentially constant for a given \(f_y\), the equation implies that the flexural rigidity is proportional to the flexural strength of the member. He also reported that it is inappropriate to assume \(I_e\) in a constant proportion of \(I_g\) regardless of the reinforcement content and yield strength.

Equation of the effective stiffness for columns followed by FEMA-356 [26] is as under

\[
E I_{\text{eff}} = \frac{M_n}{6 \Delta_y} L^3
\]

Where \(\Delta_y\) is the yield displacement of the column taking into account the displacement due to flexure, bar slip and shear.

Equation of Effective stiffness for columns recommended by Mirza [27] is as under.

\[
EI = [(0.27 + 0.003l/h - 0.3e/h) E I_e + E I_{\text{fl}}] \geq E I_{\text{w}}
\]
For Columns............................................. $I_g$
For Walls—Uncracked.............................. $I_g$
—Cracked........................................... $0.5 I_g$

$I_e$ values for beams, columns and walls at the ultimate limit state as per ACI are as follows.

For Beams........................................... $0.35 I_g$
For Columns.......................................... $0.70 I_g$
For Walls—Uncracked.............................. $0.70 I_g$
—Cracked........................................... $0.35 I_g$

Eurcode 8 [28] recommends the effective flexural rigidity of reinforced concrete elements as $0.5 I_g$. While, as per the Iranian standards guidelines, the flexural rigidity of reinforced concrete elements may be taken as $0.35 I_g$ for beams and $0.70 I_g$ for columns.

The New Zealand Standard for the design of concrete structures [29] specify the following $I_e$ values for beams, columns and walls at the ultimate limit state:

For Beams $0.40 I_g$ for rectangular sections
$0.35 I_g$ for T or L sections

For Coupling Beam
$$\frac{0.4I_g}{1+8\left(\frac{h}{I_g}\right)^2}$$

For Columns $0.80 I_g$ when $N^* / f_c' A_g > 0.5$
$0.60 I_g$ $N^* / f_c' A_g = 0.2$
$0.40 I_g$ $N^* / f_c' A_g = -0.05$

For Structural Walls $0.45 I_g$ when $N^* / f_c' A_g = 0.2$
$0.25 I_g$ $N^* / f_c' A_g = 0$
$0.50 I_g$ $N^* / f_c' A_g = -0.1$

where $N^*$ = design axial load on the section, (positive if compression) $f_c' = $ cylinder strength of concrete and $A_g =$ gross area of the section.

The commentary for the Canada code of standard [30] suggest the following $I_e$ values for beams, columns and walls at the ultimate limit state:

For Beams $0.4 I_g$
For Coupling Beam
$$\frac{0.2I_g}{1+3\left(\frac{h}{I_g}\right)^2}$$

For Columns $\alpha_c I_g$
For Structural Walls $\alpha_w I_g$

where $\alpha_c$ and $\alpha_w$ are the factor depend on the ratio of axial stress in the member and cylinder strength of concrete.

Basically, two approaches are being followed for taking into account the cracking effect of concrete in the design and analysis of multi-story buildings. The one is computationally
expensive and time consuming using advanced non-linear theory while other is direct approach considering these effects by reducing the stiffness of cracked members by arbitrary factors. The direct approach because of its computation efficiency and simplicity are most popular. For the structure element design, the effective moment of inertia based on the level of cracking is used while for global lateral response, effects of concrete cracking are incorporated in most of the country codes by reducing the stiffness of members by modification factors. However, British and Indian codes are silent on the introduction of cracking effects for the global lateral response. The design of a high-rise building is generally governed by the overall lateral stiffness in terms of lateral deformation and inter-storey drifts rather than the strength criteria on the elemental level and also the accuracy of deformation calculations depends upon the thoroughness of the analysis method and the accuracy of the material parameters used as given data. There are many approximations made in the analysis and wide variations exist in the material parameters related to the concrete cracking. With the use of high strength concrete having high brittle behavior and designs using load-resistance philosophy have resulted in smaller sections that are prone to smaller serviceability safety margins. It is apparent that concrete buildings designed by without taking cracking effect may be short of meeting serviceability requirements. For these reasons, cracking effects must be considered in the serviceability analysis and design process of reinforced concrete buildings. It is also emphasized that unified and more accurate recommendations for the effective flexural rigidity of reinforced concrete members are necessary to enable better estimates of the lateral deflections including the effect of cracking of the concrete. In order to present quantitative effect of the concrete cracking on the lateral response as per seismic loading code of India, different building structures have been analyzed in the present work.

2. Illustrative Building Design Examples

The four-storey building with different aspect ratio is used to study the effect of concrete cracking. The space frame has an equal bay width of 4.5 m in both direction and a story height of 3.4 m. One building is 5×5 bay and other is 3×5 bay space frame. In 5×5 bay building, the equal numbers of column are oriented along the width and the length directions. In 3×5 bay building, outer columns are orientation along width direction while inner columns are orientation along length direction. A eleven-storey building, height-to-width ratio of 5.35:1 exhibiting slender building behavior, is also analyzed to study the effect of concrete cracking for high-rise structures. The assumed loading and material data for the building structures are given below:

Dead load = 6.00 kN/m² (excluding self weight)
Live load = 4.00 kN/m²
Wall load = 15 kN/m (for outer wall)
Wall load = 7.5 kN/m (for inner wall)
Wall load = 10 kN/m (for tall building)
Size of columns: 300 mm x 650 mm
Size of beams: 300 mm x 450 mm
Cube compressive strength = 20 MPa
Concrete Elastic Modulus = 223685 MPa

The lateral loads are generated as per the Indian code IS:1893-2002. The zone II of the standard and structure foundation resting on medium soil has been assumed in the analysis. The ACI guidelines for effective flexural rigidity are followed to include the concrete cracking in absence of Indian standard recommendations for cracking. The full flexural rigidity for columns and half flexural rigidity for beams have been taken during analysis to incorporate the concrete cracking. The analyses of the structures are carried out using the commercial package STAAD PRO. The results for storey drift and top storey deflection from different building analysis cases are obtained and presented in Table 1 and Table 2. Table 1 presents results for top storey deflection and storey drift of the example buildings using linear structural analysis. The top storey deflection and storey drift of the example buildings with the concrete cracking consideration are given in Table 2. The inter-story drift ratio profiles of the eleven-storey structure obtained using linear and non-linear analysis are shown in Figure 1. It is evident from the results that the top storey deflection and storey drifts increase to a sizable amount after incorporating the cracking of the concrete members.

Table 1. Maximum storey drifts and top storey deflections for different structures using linear structural analysis

<table>
<thead>
<tr>
<th>Building Structure</th>
<th>Storey Drift (mm)</th>
<th>Top Storey Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-direction</td>
<td>Y-direction</td>
</tr>
<tr>
<td>Building Structure with Aspect Ratio (L/B)</td>
<td>6.279</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building Structure with Aspect Ratio (L/B)</td>
<td>8.087</td>
<td>7.380</td>
</tr>
<tr>
<td>1.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Rise Structure (H/B=5.2)</td>
<td>12.454</td>
<td>13.969</td>
</tr>
</tbody>
</table>

Table 2. Maximum storey drifts and top storey deflections for different structures using cracked concrete structural analysis

<table>
<thead>
<tr>
<th>Building Structure</th>
<th>Max. storey drift (mm)</th>
<th>Top storey deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X-direction</td>
<td>Y-direction</td>
</tr>
<tr>
<td>Building structure with aspect ratio (L/B)</td>
<td>8.942</td>
<td>--</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building structure with aspect ratio (L/B)</td>
<td>11.481</td>
<td>11.057</td>
</tr>
<tr>
<td>1.67</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The cracking of concrete is a dominant component in RCC buildings response. It is observed that substantial differences exist between the research recommendations for degrees of concrete cracking due to loadings and guidelines of different countries for incorporation of concrete cracking in the structural analysis and design. Significant differences also exist between different country codes recommendations for prime parameters related to concrete cracking viz., modulus of elasticity, modulus of rupture, and effective moment of inertia. The criteria of building structure for introducing the material non-linearity due to concrete cracking need to be elaborated and unified. More accurate guidelines for the flexural rigidity of concrete members after cracking are required for linear elastic structural analysis to enable better estimates of drifts. The present work has been carried out to study the quantitative effect of cracking and deflections amplification on the response of RCC building. The building with different aspect ratio and different relative height are analyzed. The lateral loads are generated as per the Indian code IS:1893-2002. The zone II of the code and medium soil has been assumed in the analysis. The ACI guidelines for effective flexural rigidity are followed to include the concrete cracking in absence of Indian standard recommendations for cracking. The significant results are summarized below.

1. The significant increase in deflections and drifts is observed with concrete cracking
considerations. An average 50% increase, as predictable, in top storey absolute deflections is computed whereas an increase of 40% in drifts is estimated.

2. The effect of cracking is slightly enlarged the percentage increase on drift for the higher aspect ratio of the building.

3. For high-rise structural system, the storey drifts after incorporation of cracking effect have enhanced appreciably. The increase in story drift is as high as 55%.

4. It is concluded that with the present guidelines of country codes with no mention of effective rigidity, the drift requirements may fail after incorporation of concrete cracking effect.

References

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American Concrete Institute, Michigan, 2000.