CURVATURE ANALYSIS OF HIGH STRENGTH CONCRETE BEAMS

G. Kaklauskas PhD & M. Hallgren PhD

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CURVATURE ANALYSIS OF HIGH STRENGTH CONCRETE BEAMS

G. Kaklauskas and M. Hallgren

1. Introduction

Concrete technology has developed rapidly during last decades. It is now quite common to use concrete with a compressive strength of 100 MPa or higher. High strength concrete seems to be an appropriate material to achieve higher, longer or more slender structures and to gain cost savings. However, current design codes for concrete structures are mainly based on tests where the concrete strengths have been below 60 MPa.

The shape of the stress-strain curve obtained from uniaxial compression tests of plain specimens is similar for concrete of normal, medium and high strength as shown in Fig 1. A high-strength concrete behaves in a linear fashion to a relatively higher stress level and has a higher strain at maximum stress than the low-strength concrete. On the descending portion of the stress-strain curve, higher strength concrete tends to behave in a more brittle manner, the stress dropping more sharply than it does for concrete with lower strength.

\[
\sigma_c = \frac{f_c k_1 \beta_c \left( \frac{\epsilon_c}{\epsilon_0} \right)}{k_1 \beta_c - 1 + \left( \frac{\epsilon_c}{\epsilon_0} \right)^2 \beta_c^2},
\]

(1)

where

\[
f_c = 0.94 f_c', \quad \epsilon_0 = 0.0005 (f_c')^{0.35}, \quad k_1 = (40/f_c')^2,
\]

\[
k_2 = (40/f_c')^{1.3}, \quad \beta_c = 1/(1-f_c'/\epsilon_0 E_c),
\]

\[
E_c = 10300 (f_c')^{0.33}
\]

Here \( \sigma_c \) and \( \epsilon_c \) are respectively the stress and strain of compressive concrete; \( f_c \) and \( \epsilon_0 \) are respectively the peak stress and strain for 100x100x200 mm prism; \( k_1 \) and \( k_2 \) are correction factors; \( \beta_c \) is a material parameter depending on the shape of the stress-strain diagram; and \( E_c \) is the initial tangent modulus.

Thorenfeldt et al. [3] proposed a similar expression to Eq 1 for both normal and high strength concrete with the only difference of assuming \( k_1 = 1 \).

Recently a new constitutive relationship for cracked tensile concrete based on smeared crack approach has been proposed [4] for deformational analysis of flexural reinforced concrete members. The relationship has been developed on a basis of a number of stress-strain curves for tensile concrete [4-6] obtained from beam tests reported in literature. Accuracy of the proposed constitutive relationship has been investigated [7] by calculating deflections for a large number of experimental reinforced concrete beams with moderate and small reinforcement ratios reported by several investigators.

The paper is aimed at investigating deformational behaviour of high strength concrete beams subjected to short-term bending. The present work includes both experimentation and analysis. The experimental part has involved a set of load test data for flexural high strength concrete elements. In the analytical contribution, comparison of experimental curvatures with curvatures predicted by four methods is carried out.
2. Tests of reinforced concrete beams from high strength concrete

General

The second author at the Royal Institute of Technology, Sweden, conducted flexural tests of 26 reinforced concrete beams of normal and high strength concrete [8]. The compressive cube (150 mm) strength of concrete ranged from about 40 to 100 MPa. The beams were simply supported and subjected to short-term four-point bending. Present research deploys experimental data of 26 beams divided into three series: B90, B91 and B92. All the beams had a rectangular cross-section and were singly reinforced in the pure bending zone. Beams of series B90 were nominally 4.0 m long, 140 mm high and 150 mm wide (in the pure bending zone) while the corresponding characteristics for beams of series B91 and B92 were 5.2 m, 150 mm and 180 mm. Measured cross-section dimensions and material strengths of the test beams are presented in Table 1.

Material properties

Concrete mix details are given in Table 2. The beams were cured covered with wet burlap sacks during the first five days and then in indoor climate in the laboratory with a relative humidity of about 70% and temperature of 20°C. Compressive strength of concrete (Table 1) was determined by tests on cylinders (300 mm height and 150 mm diameter) and cubes (150 mm). Number and diameter of deformed reinforcement bars as well as their yield stress are indicated in Table 1.

Testing arrangements

The test beams were supported on hinged roller supports which enabled free rotation and free horizontal displacement of the beams. The load was applied to the test beam with a servohydraulic actuator and transferred to the two loading points by a steel beam.

The longitudinal concrete strains in the mid section of the test beams were measured by five electrical resistance strain gauges glued to the beam surface. One of these gauges was placed centrally on the compressive surface and the other four at different levels on one side of the test beams with the extreme gauge distanced at 55 mm from the top. The strain in the tension reinforcement was measured in one bar in the mid section of the test beams. The bar was provided with two gauges glued to opposite sides. All gauges were of trade mark Showa and the lengths of the gauges for measuring concrete and steel strains were 30 and 8 mm, respectively.

The loading was controlled with a MTS 458.20 control console. The load was applied at a deformation rate of about 0.1 mm/s, measured on the movement of the piston rod, and in steps of 2.0 kN until the first crack was visually observed on the vertical side surfaces of the test beam. After the appearance of the first crack, the loading steps were increased to 4.0 kN. Between the loading steps, the piston rod was locked for about two minutes, during which the crack pattern was inspected and recorded. When the yield load of the beam was reached, the deformation rate was increased and the beam was loaded continuously until complete failure. The experimental results were presented in terms of moment-curvature (M - \( \kappa \)), diagrams for 26 test beams [8].

3. Strain and curvature analysis technique

The present curvature analysis method is based on classical principles of strength of materials extended to layered approach and use of full material diagrams. It is based on the following assumptions of behaviour of flexural reinforced concrete members: 1) the hypothesis of plane sections of beam bending and the resulting linear distribution of strain within the depth of the beam section is adopted; 2) perfect bond between reinforcement and concrete is assumed; 3) the constitutive model is based on the smeared crack approach, i.e. stresses and strains are averaged over representative lengths to span several cracks.

According to the layered approach, the beam's cross-section is divided into a number of horizontal layers corresponding to either concrete or reinforcement. Each layer may have different material properties assumed to be constant over the layer thickness. Thickness of the reinforcement layer is taken from the condition of the equivalent area. For reinforcement material idealisation, a bilinear, trilinear or more complex stress-strain relationship can be adopted. The stress-strain relationship for the compressive concrete has been assumed according to Eqs (1) and (2) assuming \( k_1 = 1 \). The present analysis employs a stress-strain relationship for tensile concrete proposed by the first author [4]. The descending part of the relationship shown in Fig 2 has the expression:

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\[ \sigma_l = 0.625 f'_t \left( 1 - \frac{\bar{\varepsilon}_t}{\beta} \right), \]  
(3)

where
\[ \bar{\varepsilon}_t = \frac{\varepsilon_t}{\varepsilon'_t}; \quad \varepsilon_t = \frac{f'_t}{E_c}. \]  
(4)

\[ \beta = 32.8 - 27.6 p + 7.12 p^2. \]  
(5)

where \( p \) is reinforcement percentage. Tensile strength of concrete was taken as
\[ f'_t = 0.233 \sqrt{R_{15}} \text{ [MPa]}, \]  
(6)

where \( R_{15} \) is 150 mm cube compression strength.

\[ \frac{f'_t}{\varepsilon'_t} = \frac{1}{\beta \varepsilon'_t} \]  

5. For the assumed material diagrams (eg, Fig 2), stress \( \sigma_l \) corresponding to strain \( \varepsilon_t \) is obtained. A secant deformation modulus \( E_i = \sigma_l / \varepsilon_t \) is determined.

6. Values of the obtained secant deformation modulus \( E_i \) for every layer are compared with the previously assumed or computed ones. If the agreement is not within the assumed error limits, a new iteration is started from step 2.

7. After convergence of deformation modulus \( E_i \) for all the layers, final values of strains, stresses and curvature are computed.

4. Comparison of curvatures assessed by different methods with test results

This section compares predicted and experimental curvatures of 26 beams described in section 2 (Table 1). Curvatures were assessed not only by the method discussed above, but also by ACI [9] Eurocode [10], and Russian Code [9] methods.

Curvatures for all the beams were calculated at five moment levels, ie 0.4, 0.55, 0.6, 0.7 and 0.8 of \( M_u \) which is the experimental ultimate moment. The experimental (dashed lines) and computed by the present analysis method (solid lines) moment-curvature diagrams for the three series are presented in Fig 3. Although good agreement has been achieved for most of the beams, some tendency of underestimation of curvatures with increasing discrepancy at higher moments can be noted. The reason for that could be due to the following: 1) the computation has not assessed any plastic strains of reinforcement; 2) since most of the specimens were highly reinforced members, numerical curvature results corresponding to higher loads were very sensitive to variation of such factors as concrete strength and the shape of the descending branch of the stress-strain relationship for compressive concrete.

Previous analysis [7] has shown that for moderately and lightly reinforced members neither concrete strength nor the shape of the descending branch of the compressive stress-strain relationship have significant influence on numerical results of deformations whereas the main factors are the modulus of elasticity of concrete as well as the stress-strain relationship for tensile concrete. For visualisation purposes, relative curvatures, \( \kappa / \kappa_{\text{exp}} \), versus relative moments are presented graphically in Fig. 4 where data points corresponding to different series are marked differently.
Accuracy of predictions has been assessed using basic statistical parameters such as mean value and standard deviation calculated for relative curvatures. These statistical parameters assessed for predictions by the method of present analysis and ACI [9], Eurocode [10], and Russian Code [11] methods are presented Table 3. It contains the statistical parameters not only for the total data, but also for moment levels corresponding to $0.4$, $0.6$, and $0.8$ of $M_u$.

An excellent agreement for the total data has been achieved for the present analysis, Eurocode and ACI methods with standard deviations for relative curvatures, $\kappa_{th}/\kappa_{exp}$, not exceeding 7.5% (Table 3). Even better results have been obtained for the moment level $0.4$ $M_u$, but greater variation corresponded to $0.8$ $M_u$. A tendency of the reduced mean value and its deviation from unity with increasing moments is clear for the ACI and Eurocode methods. Although predictions by the Russian Code method lead to a slightly greater standard deviation, the method gave a reasonable mean value.

Finally, it should be noted that better curvature predictions achieved in the present analysis by all the methods in comparison to the previous analysis [7] of reinforced concrete beams with low and moderate reinforcement ratios can be explained not only by high accuracy of the testing, but also by relatively insignificant role of tensile concrete due to high reinforcement ratio. When the influence of the tensile concrete (its strength) as a highly dispersed value is excluded, flexural deformability is mostly dependent on far more reliable characteristics such as modulus of elasticity of steel and concrete.
### Table 1. Main characteristics of test beams

<table>
<thead>
<tr>
<th>No</th>
<th>Beam</th>
<th>Depth [mm]</th>
<th>Width [mm]</th>
<th>Effective depth [mm]</th>
<th>Cylinder strength [MPa]</th>
<th>Tensile steel</th>
<th>Reinforcement ratio [%]</th>
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<td>116</td>
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<td>42.1</td>
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### Table 2. Concrete mix proportions of test beams

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<td>510</td>
<td>411</td>
<td>450</td>
<td>450</td>
<td>400</td>
<td>450</td>
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<tr>
<td>Silica fume, $s$</td>
<td>kg/m³</td>
<td>50</td>
<td>-</td>
<td>40</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>50</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Crushed aggreg. 8–18 mm</td>
<td>kg/m³</td>
<td>905</td>
<td>860</td>
<td>990</td>
<td>1000</td>
<td>1000</td>
<td>940</td>
<td>1100</td>
<td>1070</td>
<td>805</td>
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<td>Aggregate 0–8 mm</td>
<td>kg/m³</td>
<td>930</td>
<td>910</td>
<td>970</td>
<td>900</td>
<td>900</td>
<td>960</td>
<td>800</td>
<td>1030</td>
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<td>20</td>
<td>15</td>
<td>26</td>
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<td>$w/(c+s)$</td>
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<td>0.36</td>
<td>0.26</td>
<td>0.30</td>
<td>0.33</td>
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<td>0.31</td>
<td>0.41</td>
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<td>Age at beam test, $n$ days</td>
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<td>21</td>
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5. Concluding remarks

A simple iterative technique based on classical principles of strength of materials extended to layered approach and use of full material diagrams have been applied to curvature analysis of 26 high strength concrete beams. Comparison with the experimental curvatures at five load levels and with estimates of three other methods has been performed. Accuracy of predictions has been assessed using basic statistical parameters such as mean value and standard deviation calculated for relative curvatures. An excellent agreement for the total data has been achieved and use of full material diagrams have been applied to principles of strength of materials extended to layered approach.

The present analysis method as a universal, simple and accurate tool for deformation analysis of flexural reinforced concrete members can serve as an alternative to the code methods.

Table 3. Statistical parameters for relative curvatures, $\kappa_{th}/\kappa_{exp}$, estimated by different methods

<table>
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<tr>
<th>No.</th>
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<th>ACI</th>
<th>EC2</th>
<th>Russian Code</th>
<th>Present analysis</th>
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<tr>
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<td></td>
<td>Mean</td>
<td>Stan.</td>
<td>Mean</td>
<td>Stand.</td>
</tr>
<tr>
<td>1.</td>
<td>0.4 $M_u$ (26 points)</td>
<td>0.985</td>
<td>0.045</td>
<td>0.940</td>
<td>0.053</td>
</tr>
<tr>
<td>2.</td>
<td>0.6 $M_u$ (26 points)</td>
<td>0.938</td>
<td>0.053</td>
<td>0.904</td>
<td>0.066</td>
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<tr>
<td>3.</td>
<td>0.8 $M_u$ (26 points)</td>
<td>0.879</td>
<td>0.071</td>
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<td>0.085</td>
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<td>4.</td>
<td>Total (130 points)</td>
<td>0.935</td>
<td>0.066</td>
<td>0.900</td>
<td>0.075</td>
</tr>
</tbody>
</table>

References


Sijų gniuzdomo betono deformacijos grynojo lenkimo zo­
ñoje buvo matuojamos penkiais 30 mm ilgio elektriniais
tenzodavikliais, priklijuotais skirtinguose skerspjiivio
daliniuose. Skaičius

Armatūros strypų deformacijos buvo matuojamos 8 mm ilgio
tenzodavikliais.

Teorineje dalyje eksperimentinėms sijoms buvo apskai­
ciuoti kreiviai sluoksnių metodu ir palyginti su kitų žinomų
analtininių metodų apskaičiavimo rezultatais. Skaiciuojant
sluoksnių metodu, galiūniniu elemento skerspjiivis yra su­
dalijamas į horizontalius į betono ir armaturos sluoksnius. Skai­
ciuojama iteracijomis, taikant medžiagų atsparumo formulas bei

daliiams medžiagų diagramas. Gniuzdomam betonui taikoma
(1), o tempiamam betonui pirmojo autoriaus pasiūlyta (3) pri­
klausomybė.

Kiekvienai sijai penkiuose apkrovos lygiuose (0,4; 0,5;
0,6; 0,7 ir 0,8 eksperimento ardanciojo momento $M_u$ reikš­mes) buvo apskaičiuoti kreiviai ir palyginti su eksperi­
tenų rezultatais. Eksperimentines (punkturyne linija) ir teorinės (ištisa linija) momentų-kreivių diagramos visoms sijoms
pateiktos 3 pav. Nors gautas neblogas eksperimentinis atitikimas, daugeliui sijų, esant didesnėms apkrovoms, apskaičiuoti kreiviai yra kiek mažesni už eksperimentinius. Tai matyti 4 pav., kuriame pateikta

Be sluoksnų metodo, kreiviai dar buvo apskaičiuoti ame­
rikietiškų [9], Europenų [10] bei Lietuvoje galiojančių normų
metodais. Vertinant tikslumą, kiekvieno skaičiavimo metro­
du nustatytims santykiniams kreiviams buvo gauti tokių svar­
biausi statistiniai dydžiai, kaip vidutinis kvadratinis nuokrypis. Statistinio apskaičiavimo rezultatai pateikti 3 len­
tėje. Sluoksnų, Europenų, Amerikietiškų normų metodais
apskaičiuotiemis kreiviais vidutinis kvadratinis nuokrypis,
nustatytas visiems eksperimento taškams (visos sijos, 5 apkrovos
lygiai), neviršija 7,5%. Apkros kos $0,4 M_u$ vidutinis kvadr­

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