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On the Calculation of Crack Width in RC Linear Elements under Eccentric Load

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Abstract

Proof of controlling crack width is a basic condition for securing suitable performance in ser-viceability limit state. Most codes struggle with offering procedure for crack width calculation. So did the former Euro Code [ENV 1992-1-1:dec. 1991] and the present [BS EN 1992-1-1:2004]. Both contain a proce-dure, rendering almost identical calculation results, however aiming mainly to pure bending while eccentric load is practically out of the scope. A simplified procedure is offered here aiming to fill this gap via a very simple transformation leaving the principles of the Euro Code unchanged. Numerical examples demonstrate the application of the suggested procedure. Comparison with parallel analytical tools support the validity of the results thus obtained. The procedure is simple, user friendly and ready to be involved in code drafting.

Index terms— concrete structures, structural design, crack control, crack width calculation, steel reinforce-ment, consti-tutive laws, serviceability limit state.

1 I.

2 Notation

A s -the area of reinforcement close to the tension face of the section A s ' -the area of reinforcement close to the compres-sion face of the section d -effective height of the section d s -distance from the center of the tensile reinforcement As to the extreme fiber in tension d s ' -distance from the center of the compression reinforcement As' to the extreme fiber in com-pression e d -eccentricity of the normal force relative to sec-tion center E cm-concrete modulus of elasticity E s -reinforcing bars modulus of elasticity f ctm -the mean tensile strength of the concrete f yk -yield strength of reinforcing bars K 1 -k 2 -coefficients for calibration of S rm (bond and stress distribution) [ENV 1992-1-1:dec. 1991] M dser -service moment acting on the section result-ing from static analysis M sd,ser -moment acting on the section after normal force being transferred to A s N d,ser -service normal force acting on the section resulting from static analysis s rmaverage final crack spacing [ENV 1992-1-1:dec. 1991] w k -the design crack width y -distance from the extreme fiber in tension to the section center y' -distance from the extreme fiber in compression to the section center ? -coefficient relating the average crack width to the design crack width [ENV 1992-1-1:dec. 1991] ? sm -mean strain in the reinforcement at the crack allowing for tension stiffening ? -bar's diameter (or the average scaled bars diameters) ? r -reinforcement ratio relative to the effective concrete section in tension Ac,eff. ? sr -stress in the tensile reinforcement under the cracking moment Mcr [ENV 1992-1-1:dec. 1991] ? s -stress in the tensile reinforcement under the service moment including the axial force transferred to the tensile reinforcement II.

3 Introduction

imiting crack width is one of the two basic conditions (but not only) for securing suitable performance in serviceability limit state: deformation and cracking limitation. The later is no less important since crack width requirements are more relaxed than in the past, but the need of verification is essen-tial. Some codes, like the ACI [ACI 318M-05], have given up calculating crack width, assuming that con-trol may be attained indirectly.

The EN 2 in its for-mer [ENV 1992-1-1:dec. 1991] and present [BS EN 1992-1-1:2004] versions, has pursued in providing procedures for calculating the crack width, however, focusing on pure bending mainly. Considering ec-centrically loaded sections is important in both RC and PC elements. A simple procedure is offered here that allows a straightforward crack width calculation in linear concrete elements, eccentrically loaded. The results are compared with the limitations im-posed by EN2 **??**1992, **??**004] and with the stress state of sections eccentrically loaded obtained by nonli-near material analysis **??**Farhat, R., 1995] and found to be in very good agreement.

4 III.

Calculation of Crack Width According to En 2 [ENV 1992] EN 2 [ENV 1992] offered the following procedure for calculating crack width:

(1)

The average final crack spacing defined as:

(2) Note: k 2 = 0.5 for bending and 1.0 for pure tension with possible interpolation for intermediate cases according to: k 2 = (?1 + ?2)/2 ?1 with ?1 & ?2 being the greater and the lesser tensile strains at the boundaries of the sec-tion considered (quote).

Though this definition leaves the impression that ec-centric load is dealt with, it appears not to be the case, as eccentric compression is not included in this consideration and in a cracked section under eccen-tric tension there hardly is any possibility to calcu-late ? 1 , while undoubtedly ? 2 will be in compression.

The mean strain in the reinforcement defined as: Essentially there is difference in the cracks spacing and the strains, however the final calculation results according both renders almost identical results.

5 IV. Proposed Method for Calculation of Crack Width under Eccentric Load

The proposed herein method, follows the procedures as given in [ENV 1992-1-1:dec. 1991] (detailed above) or [BS EN 1992-1-1:2004], except for a transformation suggested that allows for easy and simple consideration of the eccentricity in loading. Only the procedure given in EN2 [ENV 1992-1-1:dec. 1991] is discussed in the following, however in the numerical examples that follow crack width is calculated according both EN2 versions.

A symmetrical with reference to vertical axis section is given in Figures 1a&2a (see notation). On the section acts a normal force in service N d,ser at eccentricity e d vs. the section center, as obtained from elastic In order to maintain equili-brium, after transfer, the moment will be:

(5)

for eccentric compression -see Fig. 2b (6)

for eccentric tensionsee Fig. 1b From here on the section analysis for cracking will be conducted under the action of M sd,ser and N d,ser. 2. The stress in the tensile face is to be checked assuming uncracked section. If it exceeds f ctm (the mean tensile strength of the concrete) the section is cracked. 3. The stress in the tensile reinforcement will be: sm rm k s w ? ? ? r 2 1 rm / k k 25 . 0 50 s ? ? ? ?]) (1 [E 2 s sr 2 1 s s sm ? ? ? ? ? ? ? ?) (s w cm sm max , r k ? ? ? ?

static analysis. The case of N d,ser in compres-sion with e d is given at Figure 2a and N d,ser in tension with e d is given in Figure 1a. 5. The average strain in the tensile reinforcement is calculated as given in (3) above. ? 1 and ? 2 remain as recommended there. 6. The average distance between cracks srm is calculated according to (2) above, with k1 = 0.8 for high bond bars and k 2 = 0.5 for pure bending. ? and ?r as defined in EN2 [ENV 1992]. 7. Finally the maximum crack width, according to EN2 **??**ENV 1992] is:

(10)

V.

6 Numerical Examples

The examples given in the following aim to cover a variety of problems that may rise applying the of-fered procedure. In all examples the concrete type is f ckcyl =25Mpa with mean concrete tensile strength -f ctm = 2.6 MPa and E cm = 31000 MPa. The reinforcement consists of ribbed single bars (?) with f yk = 400 MPa and/or welded mats of high strength welded bars ( ) with f yk = 500 MPa.

7 Example 1

A section of a wall, 300 mm thick, contains 2000 mm 2 /m tensile reinforcement in the form of ?16@100mm at a distance d s = 50 mm from the in-ner face of the wall, (See Figure 3). The section effective depth d is 250mm.

8 Solution:

The section is under tensile load with eccentricity e d = 75.3/115.9 = 0.65m

Transferring the load to the center of the tensile rein-forcement results in a moment:

The stress at service in the tensile reinforcement will be: With a cracking moment M cr = 39.0 kNm/m

The mean strain in the reinforcement is: An estimate of A c , eff gives 80000 mm 2 , therefore

The average distance between cracks will be: Therefore the calculated maximum crack width is:

The maximum crack width assessed according to EN2 [BS EN 1992-1-1:2004] is 0.196 mm.

The result was reviewed with the aid of: a. Nonlinear section analysis developed by Farhat **??**Farhat, 1995] wherefrom the stresses and strains in the cracked section are as follows:

The difference between the suggested here analysis and the nonlinear analysis for ? s is 3.3% -within very reasonable level of accuracy. b. According to Table **??**.2N [BS EN 1992-1-1:2004] for a maximum bar diameter of 16 mm and at a stress level of 200 MPa the crack width to be ex-pected will be approximately 0.2 mm. Also, accord-ing to Table **??**. A 400 mm thick section of a floor is given (Figure 4) where the tensile reinforcement at a distance 50 mm from the upper Any bottom floor reinforcement is ignored for the purpose of this analysis. The reinforcement placed in the form of a matt is not fully embedded in the support therefore one half of the amount is considered active, however scaling the amount in terms of strength to an equivalent of ribbed bars the total amount of reinforcement is 1760 mm 2 (1200+560).

Due to the most extreme load combination the fol-lowing was obtained: Solution:

The section is under tensile load with eccentricity Transferring the load to the center of the tensile rein-forcement results in a moment:

The stress at service in the tensile reinforcement will be :

The cracking moment is 69.33 kNm/m Therefore the mean strain in the reinforcement is: An estimate of A c,eff gives 113300 mm 2 , therefore

The average distance between cracks will be (with an average bars diameter -13mm):

Therefore the calculated maximum crack width is:w max calculated according to EN2 [BS EN 1992-1- 1:2004] is 0.160 mm.

Discussion of the results: a. Stresses and strains resulting from nonlinear section analysis **??**Farhat, 1995] produce:

Again the difference between ?s from the analysis offered and the nonlinear analysis **??**Farhat, 1995] is 4.1% -a very fair level of accuracy. b. According to table 7.2N [BS EN 1992-1-1:2004] for a stress level of 180 MPa in the reinforcement a maximum bar size of over 16 mm is allowed for limiting crack width to 0.2 mm. According to Table **??**.3N [BS EN 1992-1-1:2004] for the stress level of 180 MPa a maximum bar spac-ing exceeds 150 mm, but in the current example the distance is 125 mm, therefore it may be concluded that the max. crack width is lower than 0.2 mm (here -0.158 mm).

9 Example 3

A portion of the ceiling of a buried underground structure is given, 400 mm thick, having 2320 mm 2 /m at distance 50 mm from the bottom face and 1111 mm2/m at distance 50 mm from the upper face.

The effective depth d is 350 mm. See Figure 5. Addressing loading combination 1:

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The section is under compressive load with eccen-tricity e d = 120.3/123.7 = 0.973m

Transferring the load to the center of the tensile rein-forcement results in a moment:

The stress at service in the tensile reinforcement will be The cracking moment is 69.33 kNm/m Therefore the mean strain in the reinforcement is: With:

The average distance between cracks will be: Therefore the calculated maximum crack width is: w max according to EN2 [BS EN 1992-1-1:2004] is 0.109 mm Addressing load combination 2:

Checking stresses assuming uncracked state under eccentric tension proves that in the upper face the stress is 1.50 MPa and at the bottom face the stress is -0.82 MPa. Discussion of the results for load combination 1: a. The stresses and strains obtained in nonlinear analysis **??**Farhat, 1995] are:

The stress in the reinforcement for the proposed analysis is 143.

11 Conclusions

A simple procedure is presented; modifying slightly the proposed procedure in EN2 in it's both versions, allowing calculating directly crack width in linear concrete members, with sections under eccentric tensile or compressive normal force. Several exam-ples offered demonstrate the simplicity and practi-cality in application of the procedure. Nonlinear section analysis proves a very good cor-respondence with the results obtained with the sim-plified method offered. A good correspondence is obtained also with forecasts from EN2 [ENV 1992-1-1:dec. 1991] and EN2 [BS EN 1992-1-1:2004] based themselves on similar calculations.

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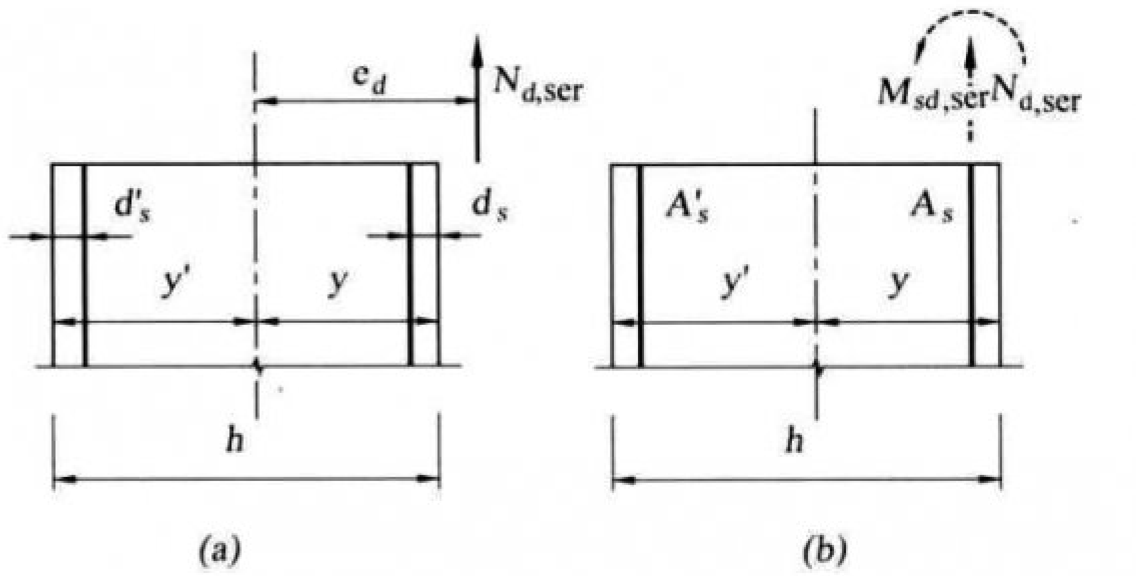
[1]

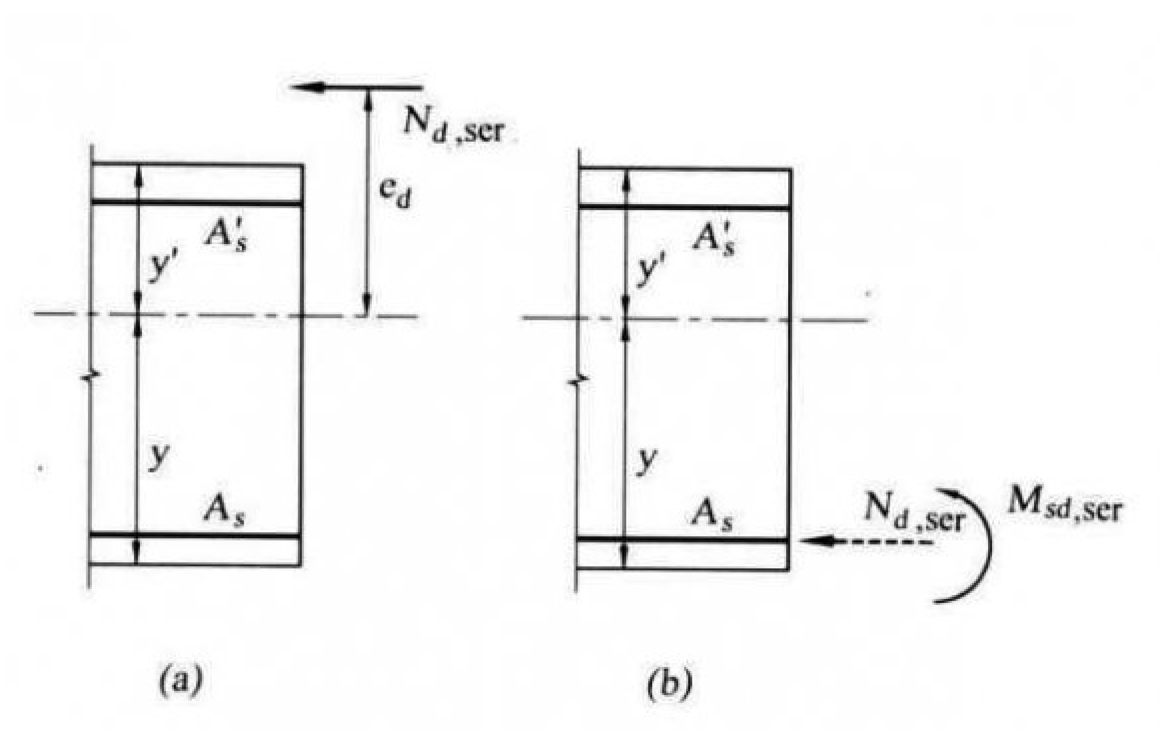
3

Figure 1: (3)



1

Figure 2: Figure 1 :



2

Figure 3: Figure 2 :

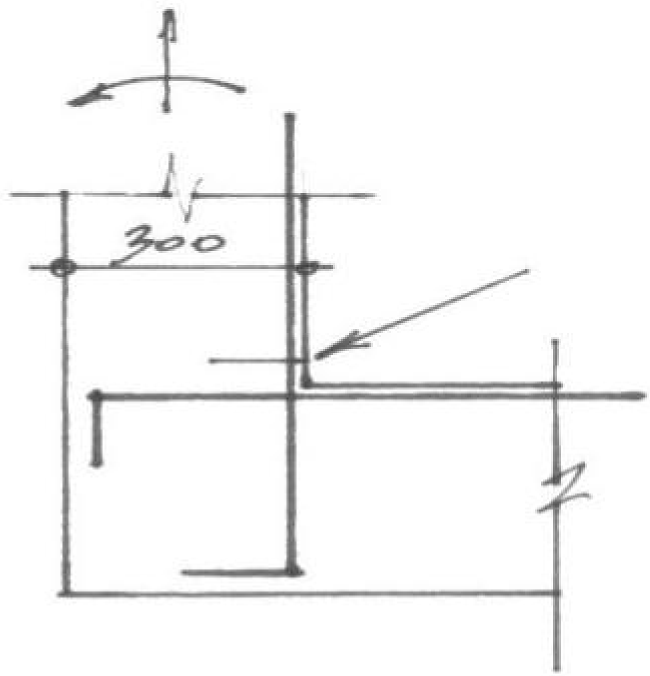
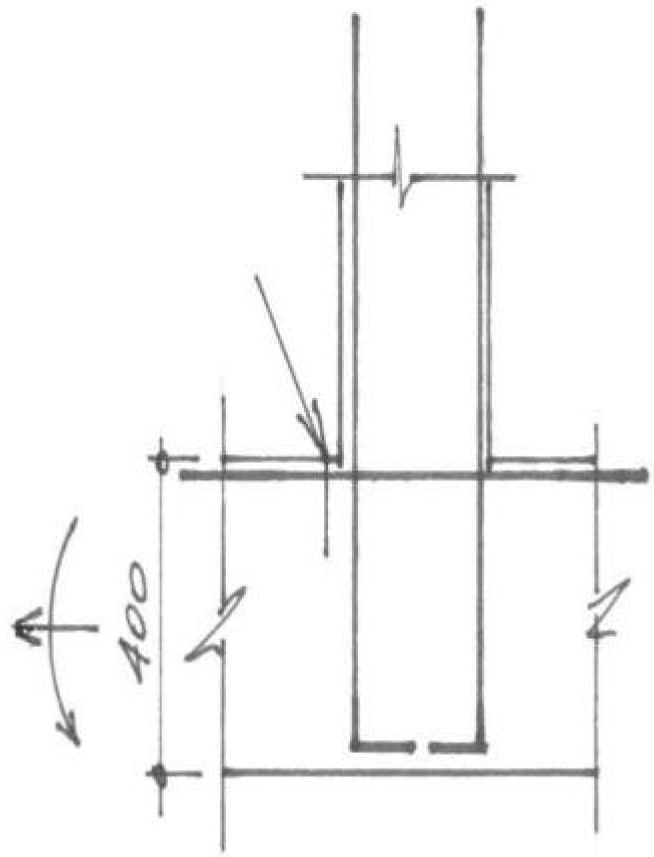


Figure 4:



3

Figure 5: Figure 3 :

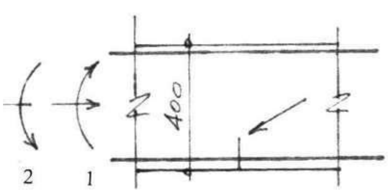


Figure 6:

? sr ? cr A d M 87 . 0 s M ser , ? 65 . 0 [9 . 115 ?
sd

s ? ? 2000 10 250 75 . 6 63 87 ?
. 0
sr ? ? 2000 10 250 0 . 6 39 87 . ?
0
w max ? 7 . 1 s rm ? sm
M ? kNm 3 . 75 / m N ser , d ? kN 9 . / m
ser 115
, d

Figure 7:

VI.

Figure 8:

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