CRACK PREDICTION FOR MEMBERS IN UNIAXIAL TENSION
AT ANY GIVEN LOADING STAGE

by

Rizkalla, S.H.¹, and Hwang, L.E.²

Abstract:

A methodology for predicting crack spacings and widths of reinforced concrete members in uniaxial tension at any given loading stage is presented. The method includes the proposal of a new expression for predicting the average gross strain of a member after the initiation of the first crack and accounting for the concrete contribution in the post-cracking range.

The proposed method is based on an extensive experimental program which involved testing of 34 specimens, to study the cracking behavior of reinforced concrete members subjected to membrane tensile stresses in the presence of transverse reinforcement. Major variables included ratio of reinforcement, concrete cover, concrete thickness, and spacing between transverse reinforcements. Based on the test results, the paper introduces a range within which the theoretical prediction of crack spacing and width is acceptable.

Using the proposed methodology, the prediction of the number of cracks was found to be within ±1 crack for most measurements of crack number. The ratio of the predicted crack width based on the proposed method to the measured crack widths is found to be 1.17, which indicates a high degree of predictive accuracy.

KEY WORDS: Cracking; crack spacing; crack widths; membrane load; reinforced concrete; strain; tension.

¹,² Associate Professor, Graduate Student, Department of Civil Engineering, The University of Manitoba, Winnipeg, Manitoba, Canada
Introduction

Many research reports exist on crack behavior of uniaxially tensioned reinforced concrete members. However, a widely accepted methodology for predicting crack spacing and width has not yet been developed. While the majority of concrete structures are reinforced in at least two directions, most research work, unfortunately, has involved testing of specimens reinforced only in the loading direction. In addition, most existing equations for predicting crack spacing and width are strictly limited to the state of stabilized crack pattern only, as illustrated in the typical load-average gross strain response shown in Figure 1, where specimen 2 is used as an example. To date no information is available for prediction of crack width and spacings between the initiation of the first crack and the final crack pattern stages.

An experimental program sponsored by the Natural Science and Engineering Research Council of Canada was recently conducted at the University of Manitoba to study the cracking behavior of reinforced concrete in tension in the presence of transverse reinforcements. Based on the experimental results, a constitutive relation for concrete in tension has been proposed [10]. The effect of various parameters, including the effect of the transverse reinforcement, on the proposed stress-strain curve has been discussed. The concrete cracking strength as related to the standard concrete strength was discussed and a relation between the cracking strength and ultimate compressive strength was proposed in the same paper.

Based on the same investigation, an expression for predicting the crack spacing and width at the stabilized crack pattern has been introduced [14]. A method to include the effect of transverse reinforcement on crack spacing was proposed at that time.
The main objective of this paper is to propose a methodology for predicting crack width and spacing of reinforced concrete members in tension at any given loading stage from the initiation of the first crack until the final crack pattern configuration. Based on the results of this experimental study, the nature of crack formation is discussed and the range within which the theoretical prediction of crack spacing and widths could be acceptable is recommended. The proposed method allows excellent prediction of the number of cracks and the average crack width as compared with measurements taken for segments subjected to uniaxial tensile membrane loading.

Experimental Program

A detailed description of the experimental program can be found in previous papers published by the authors [9, 10, 14]. However, for the reader's convenience, a brief summary is necessary.

Segments tested in the experimental program were reinforced in two directions with deformed bars. Longitudinal reinforcements were spaced at 3" (76 mm) centre to centre and extended 11" (280 mm) beyond each end of the specimen, as shown in Figure 2. The main variables considered in the test series were concrete cover, c, percentage of steel in the direction of the applied load, p, concrete thickness of the specimen, t, and spacing between transverse reinforcement, S_R, as given in Table 1.

All concrete used in the fabrication of the specimens were designed for a nominal ultimate strength of 5000 psi (34.5 MPa) and mixed in the laboratory. Six control cylinders 6" x 12" (152 mm x 305 mm) were cast at the same time as the specimens in order to relate specimen strength to standard material test results. The reinforcement used in the segments consisted of
hot rolled deformed bars graded 300 MPa and 400 MPa. For each specimen, samples of the steel bar were tested for tension to determine yield stress, ultimate stress and modulus of elasticity. After casting, the specimens were left to dry in open air for about one hour and then placed in a moist curing room for seven days. Following this seven day curing time, the specimens were removed from the curing room and covered with wet burlap and remained in this state for at least an additional three weeks before testing.

The load was applied using a 600,000-lb. (2670 kN) capacity universal testing machine. The load was transmitted from the loading machine to the specimen by specially designed end fittings as shown in Figure 3. The end fittings were very rigid, in order to achieve uniformity of loads from the machine to each load cell. Each reinforcing bar was connected to a separate, specially designed load cell, which was used to adjust the load.

During testing, a continuous record of deformation over a 30" (762 mm) gauge length was made using a linear variable differential transducer (LVDT) as shown in Figure 3. As well, readings from mechanical strain gauges were recorded. In addition, the number and width of cracks were measured at regular intervals with a travelling micrometer-microscope with an accuracy of 0.02 mm as shown in Figure 4. Two lines were marked on the segment surface to measure crack widths. One line was located directly over a longitudinal reinforcing bar and the other at the centerline of the specimen between two adjacent longitudinal bars. The widths of all cracks crossing these two lines were measured. Crack patterns were marked and numbered at the end of each increment. Testing was terminated when the load approached the yield point.
the segment surface. A detailed description of the instrumentation, testing procedure and test results has appeared elsewhere [9].

**Nature of Crack Formation**

The concept of random formation of cracks in reinforced concrete members had been discussed by Base [2], Beeby [3], Broms [4], Goto [7] and Hognestad [8], who have all indicated that, at final crack pattern, crack spacing can be expected to vary from a minimum crack spacing, $S_{\text{min}}$, to a maximum crack spacing, $S_{\text{max}}$, which can be up to twice the minimum crack spacing.

The relationships between minimum, maximum and average crack spacing, $S_{\text{ave}}$, can be mathematically expressed as follows:

$$\frac{S_{\text{min}}}{S_{\text{ave}}} = 0.67 ;$$

$$\frac{S_{\text{max}}}{S_{\text{ave}}} = 1.34 ;$$

where, $S_{\text{ave}}$ can be defined as the mean of the values of the maximum and minimum crack spacings for a given specimen at a given load.

Equations (1) and (2) emphasize the random nature of crack formation that has been observed in the past and suggest a range within which the theoretical prediction of crack spacing could be acceptable for reinforced concrete structures.

The measured minimum, $S_{\text{min}}$, maximum, $S_{\text{max}}$, and average crack spacing, $S_{\text{ave}}$, at final crack pattern, as illustrated in Figure 5 for a typical specimen, were measured for all specimens [9]. Based on the measured crack spacings, the ratios of $S_{\text{min}} / S_{\text{ave}}$ and $S_{\text{max}} / S_{\text{ave}}$ were computed for each
specimen and plotted as a function of the measured average crack spacing is
given in Figure 6. The average ratios of $S_{\text{min}}/S_{\text{ave}}$ and $S_{\text{max}}/S_{\text{ave}}$ for all
the tested specimen were found to be 0.70 and 1.34 respectively. These
values were in close agreement with the values indicated by Equations (1)
and (2). The ratios obtained experimentally clearly confirm the random
nature of crack distribution and the range within which theoretical
prediction is acceptable.

The relationship between maximum crack width, $W_{\text{max}}$, and average crack
width, $W_{\text{ave}}$, had been suggested by a number of studies [6, 8, 11, 5], but
the results reported have been quite varied. Maximum crack widths measured
on the surface of flexural members were reported by Clark [6], Hognestad [8]
and Kaar [11]. Clark found that the value of the ratio of maximum crack
width to average crack width at steel stresses varying from 15 ksi (103 MPa)
to 40 ksi (276 MPa) is

$$\frac{W_{\text{max}}}{W_{\text{ave}}} = 1.64$$

(3)

Hognestad [8] reported values for this ratio of 1.36, 1.50, 1.49, and 1.42
at steel stresses of 20 ksi, 30 ksi, 40 ksi, and 50 ksi (138, 207, 276, and
345 MPa) respectively. He also postulated that the theoretical ratio is
1.34, as given in Equation (3). Kaar [11] obtained a value of 1.50 while
CEB-FIB [5] recommended a value of 1.70 for flexural members. For tension
members Broms [4] obtained ratios between 1.50 and 2.0. The relationship
between minimum crack width, $W_{\text{min}}$, and average crack width, $W_{\text{ave}}$, had never
been mentioned in any studies or design codes mainly due to its irrelevance
for the design process.

The minimum, $W_{\text{min}}$, maximum, $W_{\text{max}}$, and average crack width, $W_{\text{ave}}$, at
steel stress levels of 30, 35, 40, 45, and 50 ksi (207, 241, 276, 310, and
345 MPa) were measured for all specimens tested in the program [9]. It was observed that the minimum crack width at low stress levels was not necessarily the minimum for the same specimen at higher stress level. The overall ratios of \( W_{\text{min}} / W_{\text{ave}} \) and \( W_{\text{max}} / W_{\text{ave}} \) for all specimens are plotted in figure 7 where average ratios of 0.67 and 1.55, respectively were obtained.

**Average Gross Strain**

The prediction of average width, according to Leonhardt [12], required the prediction of average gross strain, \( \varepsilon_{m} \), measured on the surface of the reinforced concrete members. If the cracking strain of the concrete, \( \varepsilon_{cr} \), is ignored, as being negligible, the average gross strain, \( \varepsilon_{m} \), can be approximated according to Leonhardt [12] as follows:

\[
\varepsilon_{m} = \varepsilon_{s2} \left[ 1 - \left( \frac{f_{s2, cr}}{f_{s2}} \right)^2 \right];
\]

where \( s_{2} \) is the steel strain at the cracked section; \( f_{s2, cr} \) is the steel stress at the crack immediately after cracking and \( f_{s2} \) is the steel stress at the crack.

Similarly, Beeby [3] suggested an expression for average gross strain, \( \varepsilon_{m} \), as

\[
\varepsilon_{m} = \varepsilon_{s2} - \frac{K f_{cr} f_{s2, cr}}{E_{s} p f_{s2}};
\]

where \( K \) is a constant depending on the type of bar; \( E_{s} \) is the modulus of elasticity of steel; \( p \) is the steel ratio and \( f_{cr} \) is the cracking strength of concrete. Values of the concrete cracking strength, \( f_{cr} \), could be obtained using one of the proposed expressions from an earlier paper [10]:

\[
f_{cr} = (f'_{c})^{2/3} \quad ; \quad (f'_{c} \text{ in psi})
\]

where \( f'_{c} \) is the ultimate compressive strength of concrete based on the cylinder test.
The average gross strain, $\varepsilon_m$, based on Leonhardt's expression, Equation (4), at steel stress levels, $f_{s2}$, of 30, 35, 40, 45, 50 and 55 ksi (207, 241, 276, 310, 345, and 380 MPa) were computed and compared to measured values as shown in Figure 8, using a typical specimen (2A). Similarly, using a value of 1.0 for the constant, $K$, in Beeby's Equation (5) for deformed bars, the average gross strain, $\varepsilon_m$, was also computed at these steel stress levels for the same specimen. Figure 8 indicates very clearly that both Leonhardt and Beeby underestimated the average gross strain. This behavior was also observed by MacGregor, et al. [13], using prestressed concrete segments loaded in tension.

An attempt is made herein to re-evaluate the constant, $K$, in Beeby's Equation (5). The proposed value of $K$ will be limited by the following conditions:

a) At the instant of first cracking, when $f_{s2} = f_{s2,cr}$ and $\varepsilon_m = \varepsilon_{cr}$, the value of $K$ is set at 1.0.

b) At the yield strength of reinforcement, when $f_{s2} = f_{sy}$, and $\varepsilon_m = \varepsilon_{sy}$, the value of $K$ is set at 0.0.

Where $f_{s2}$ and $\varepsilon_{s2}$ are the yield stress and strain of steel, respectively.

Using a linear relationship between the limits stated in (a) and (b), the expression of $K$ can be obtained as follows:

$$K = 1 - \frac{f_{s2} - f_{s2,cr}}{f_{sy} - f_{s2,cr}}$$

(7)

The average gross strains based on Beeby's Equation (5) were calculated using this proposed value of $K$ for the same specimen and given in Figure 9 which indicates an excellent comparison using this modification. The main feature of the proposed constant, $K$, is that it takes into account the
tension stiffening effect [10] which has a peak value at the initiation of
the first crack and diminishes as the reinforcing steel starts to yield.

Relationship of Crack Strain and Average Gross Strain

The average crack strain, $\varepsilon_w$, defined by the summation of the measured
crack widths divided by total gauge length within which cracks were
measured, is shown in relation to the average gross strain, $\varepsilon_m$, in Figure
10. The trend of the experimental data indicates that crack width increases
at a higher rate as the average gross strain, $\varepsilon_m$, is increased. This
phenomenon also illustrates the decrease in the overall stiffness of the
member as more cracks are formed. Based on the result of the 34 concrete
specimens, a best-fit curve for the data is

$$\varepsilon_w = 3.145 \varepsilon_m^{1.2} \quad (8)$$

The proposed equation was plotted and appears in Figure 10 as a solid
line.

Procedure for Computing Number of Cracks & Crack Widths at any Loading Stage

Based on experimental results and observations of crack behavior, a
procedure is developed to compute the number of cracks and crack widths at
any loading stage. The procedure may be summarized as follows:

1) The concrete cracking strength, $f_{cr}$, for a given compressive strength of
crushed, $f'_c$, can be found using Equation (6) from which the concrete
cracking strain can be obtained using

$$\varepsilon_{cr} = \frac{f_{cr}}{E_c}; \quad (9)$$

where $E_c$ is the modulus of elasticity of concrete suggested by ACI [1] as
For a given steel ratio, \( p \), the cracking load can be determined using the following expression:

\[
P_{cr} = f_{cr} A_c (1 + p n);
\]

where \( A_c \) = area of concrete;

\( n \) = modular ratio.

The steel stress at a crack immediately after cracking can be computed as follows:

\[
f_{s2,cr} = \frac{P_{cr}}{A_s};
\]

where \( A_s \) = area of steel.

3) Using Beeby's expression with the proposed value of constant, \( K \), from Equation (7), the average gross strain, \( \varepsilon_m \), can be computed for any given steel stress, \( f_{s2} \), using Equation (5), which is only valid when \( \varepsilon_m \) is greater than cracking strain, \( \varepsilon_{cr} \), computed from Equation (9).

4) The average crack spacing, \( S_m \), at the final crack patterns can be determined using one of the existing equations (Leonhardt's or Beeby's) or using the author's method

\[
S_m = 5 (d - 0.28) + K_l (a, c) + 0.08 d/p \quad (d \text{ in inches})
\]

or

\[
S_m = 5 (d - 7.2) + K_l (a, c) + 0.08 d/p \quad (d \text{ in mm})
\]

where \( K_l \) is a factor depending on the concrete cover of the bars, \( c \), and spacing between the longitudinal bars, \( a \); and \( d \) is the longitudinal bar diameter.

5) The average crack spacing, \( S_c \), in the presence of transverse
reinforcement, at the final crack pattern can be derived [14]:

\[ S_c = \beta S_m \]  \quad (14) \]

where \( \beta = \frac{0.96}{R 0.02} \); \n
\[ R = \frac{S_R}{S_m} \]

\( S \) = predicted average crack spacing based on Equation (13); \n
\( S_R \) = spacing between transverse reinforcement.

6) For a given length, \( L \), the final number of cracks, \( N_F \), is:

\[ N_F = \frac{L}{S_c} + 1 \]  \quad (15) \]

7) Using an expression proposed by MacGregor, et al. [13], and assumes the number of cracks will stabilize at an average gross strain, \( \varepsilon_m \), of 0.0010 [14]; for any average gross strain less than 0.0010, the number of cracks, \( N \), can be computed as:

\[ N = N_F \left[ \frac{\varepsilon_m - \varepsilon_{cr}}{0.0010 - \varepsilon_{cr}} \right] . \]  \quad (16) \]

8) For the average gross strain, \( \varepsilon_m \), determined from step (3), the crack strain, \( \varepsilon_w \), can be computed using Equation (8).

Consequently, the total crack width, \( \Sigma W \), for a given length, \( L \), can now be determined:

\[ \Sigma W = \varepsilon_w x L; \]  \quad (17) \]

and the average crack width, \( W_{ave} \), can be quantified:

\[ W_{ave} = \frac{\Sigma W}{N} \]  \quad (18) \]

from which the minimum \( (W_{min}) \) and maximum \( (W_{max}) \) crack widths can be derived:

\[ W_{min} = 0.67 W_{ave} ; \]  \quad (19) \]
Comparison of Computed Number of Cracks and Average Crack Widths with Measured Values

Using the outlined procedure, the number of cracks and average crack widths at the instant of first crack and various steel stresses, $f_{s2}$, of 30, 35, 40, 45, and 50 ksi (207, 241, 276, 310, and 345 MPa) were computed and compared to the measured values for all specimens as shown in Figure 11.

An average value of 1.01 was obtained for the ratio, $\frac{N(\text{predicted})}{N(\text{measured})}$. The figure also indicates that most of the predicted numbers of cracks are within an accuracy of ±1 as shown by the dotted lines.

Comparison between the predicted average crack width and measured values is shown in Figure 12. An overall average value of 1.17 is obtained with a coefficient of variation of 31.48%. The comparison shows quite a scatter in the average ratio. However, most of the predicted values are within the boundaries defined by minimum and maximum crack widths as previously indicated. Considering the random nature of crack formation, the results obtained are most gratifying.

Conclusions

The following conclusions were drawn as the result of this study.

1) The measured crack spacing and width are randomly distributed. However, the study has facilitated the establishment of ranges within which the theoretical predictions of crack spacing and width are acceptable for reinforced concrete members subjected to tension.
2) Beeby's and Leonhardt's expressions underestimate the average gross strain after cracking of concrete. A newly defined value for Beeby's constant, introduced in the present study, greatly enhances predictive accuracy.

3) A procedure for computing the number of cracks and crack widths at any loading stage has been proposed. Using the proposed methodology, predictive accuracy has been brought within ±1 crack for most measurements of crack number, and an overall average ratio for predicted to measured crack widths of 1.17 has been obtained.

Acknowledgments
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References
1. ACI 318-77, "Building Code Requirements for Reinforced Concrete", ACI Committee 318, American Concrete Institute, Detroit, 1977.


6. Clark, A.P., "Cracking in Reinforced Concrete Flexural Member", Journal of American Concrete Institute, Vol. 52, No. 8, April 1936, pp. 851-862.


Notation

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$A_c$</td>
<td>Area of concrete in cross-section</td>
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<td>$A_s$</td>
<td>Cross-sectional area of reinforcing steel</td>
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<td>$E_c$</td>
<td>Modulus of elasticity of concrete</td>
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<td>$E_s$</td>
<td>Modulus of elasticity of steel</td>
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<td>$f_{cr}$</td>
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<td>$f_{s2}$</td>
<td>Stress in reinforcement at a crack</td>
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<td>$f_{s2,cr}$</td>
<td>Stress in reinforcement at a crack immediately after cracking</td>
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<td>$f_{sy}$</td>
<td>Yield stress of steel</td>
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Compressive strength of concrete

Empirical constant

Distance between two outer most cracks

Modular ratio = \frac{E_s}{E_c}

Number of through cracks at a given load

Final number of through cracks in a given length, L

Steel ratio

Cracking load

\[ R = \frac{S_R}{S_m} \]

Measured average crack spacing

Average crack spacing in the presence of transverse reinforcement

Predicted average crack spacing

Maximum crack spacing

Minimum crack spacing

Spacing between transverse reinforcement

Crack width

Average crack width

Maximum crack width

Minimum crack width

\[ \beta = \frac{0.96}{R^{0.02}} \]

Cracking strain in concrete

Average gross strain measured over a gauge length which includes several cracks

Steel strain at a crack

Crack strain = \frac{\sum W}{L}

Yield strain of steel
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Fig. 1 Typical Load-Gross Strain Relationship (Specimen No. 2)
Fig. 2 Reinforcement Details of a Typical Specimen
Fig. 3 Test Set-up and Instrumentation
Fig. 4 Typical Specimen During Testing
Fig. 5 Maximum, Minimum and Average Crack Spacing for a Typical Specimen

\[ S_{\text{ave}} = \frac{L}{N-1} \]
Fig. 6 Comparison Between Maximum, Minimum and Average Measured Crack Spacing
Fig. 7 Comparison Between Maximum, Minimum and Average Measured Crack Width
Fig. 8 Comparison Between Measured and Predicted Average Strain Based on Leonhardt's and Beeby's Expressions
Fig. 9 Comparison Between Measured and Predicted Average Strains Based on Proposed K-value for Beeby's Expression

SPECIMEN NO: 2A

△ EXPERIMENTAL

PROPOSED
Fig. 10 Crack Strain Versus Average Strain
Fig. 11 Comparison Between Measured and Computed Number of Cracks Based on Equation (16)

- MEAN = 1.01
- STD. DEV. = 0.241
- C.O.V. = 23.71%
- PTS. = 198
Fig. 12 Comparison Between Measured and Computed Average Crack Widths Based on Proposed Method