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16MAR07-

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Response of Reinforced Concrete Members Under Uniaxial Tension

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Authors are responsible for all expenses incurred in preparing and presenting their papers, including time spent, costs for preparation of manuscripts and illustrations, travel to the conference, and conference registration fees.
Yours sincerely,

Er John S Y Tan Conference Director

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RESPONSE OF REINFORCED CONCRETE MEMBERS UNDER UNIAXIAL TENSION

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Abstract

Investigation of bond behaviour, crack pattern, crack spacing and ultimate bond strength for reinforced concrete members under uniaxial tension is very important in analysis and design of RC structures. This paper summarizes the result of an experimental project aimed at improving the current understanding of the response of cracked concrete. For this purpose a comprehensive experimental program including reinforced concrete cylanders with different concrete covers and reinforcement ratios is conducted.

All specimens tested under direct uniaxial tension. The axial forces were increased to reach yielding capacity of the steel reinforcements; by the onset of plastic deformations, the tests were creased and the number of transversal cracks and minimum and maximum crack spacing were recorded for each specimen. The bond stress between the reinforcing steel and the concrete were evaluated using equilibrium equations for a crack spacing portion.

Clear concrete cover, reinforcement diameter and reinforcement ratio are the main parameters considered in this investigation.

Key words: RC members, tensile force, crack pattern, crack spacing, bond stress.

1. Introduction

The main objective of this research is examination on bond behavior, assigning of crack spacing prediction for reinforced concrete members in uniaxial tension. When a reinforced concrete member is subjected to a sufficiently high tension force, the concrete cracks and at the crack section the total applied load subjects to steel bar. The tensile force is gradually transferred from the steel bar to the surrounding concrete by bond stresses at the interface of concrete and steel bar.

With an increase in tensile loading, the concrete tensile stress reaches the tensile strength of concrete and occurs a new crack at a distance from the previous cracked face. If the applied load increases, subsequent cracks reduce the distances between cracks. With the continuation of this mechanism, cracks will continue to form until average of the spacings between all cracks are less than or equal to S_m (ultimate average crack spacing). At this point, the final crack pattern has been reached and the tensile stress in concrete between the cracks will never reach the tensile strength. A typical specimen at final cracking state is illustrated in figure1. Figure 2 shows a portion of reinforced concrete member at a distance between two cracks. In this figure is shown the tensile stress that is transferred from the steel bar to the concrete by bond stress.

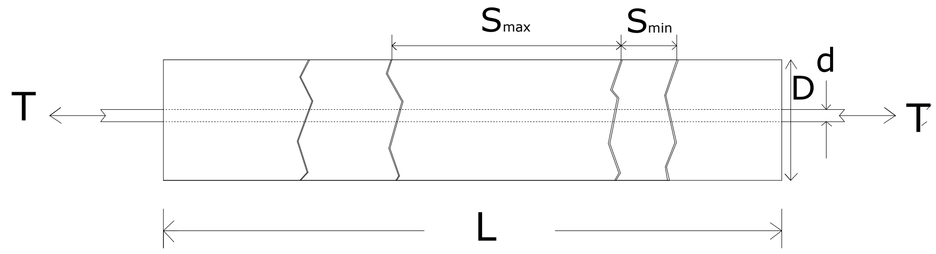

Figure 1. Maximum, minimum and average crack spacing for a typical specimen.

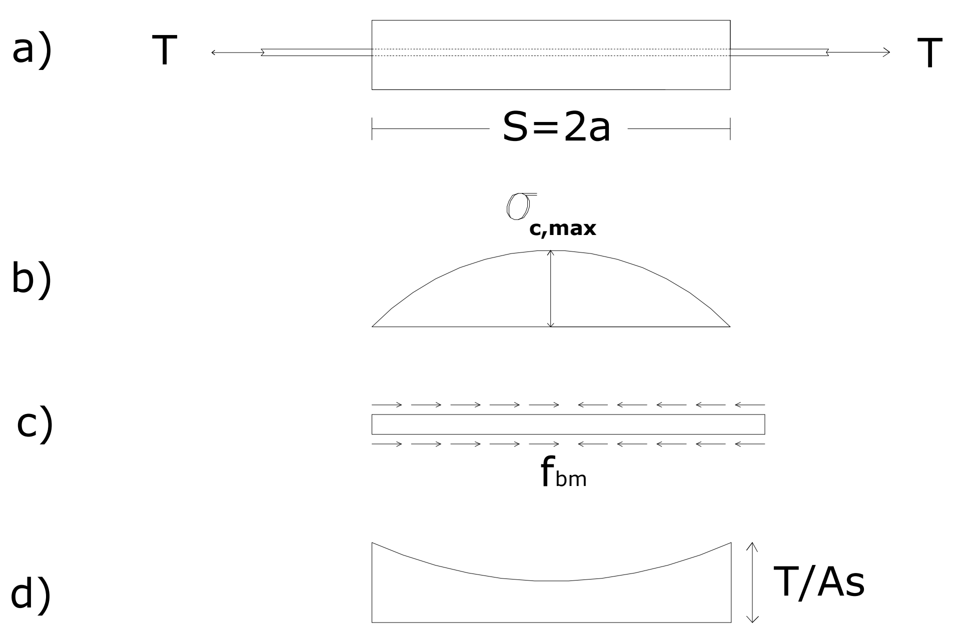

Figure 2. Distribution of concrete, steel bar and bond stress at a crack spacing.
a)Member between two cracks. b)Tensile stress transferred to the concrete.
c)Bond stress at the interface of concrete and steel bar. d)Distribution of reinforcement steel stress.

2. Experimental program

Medium strength concrete about 26 MPa was used in all spesimens. Physical and mechanical properties of concrete, which are result of adequate number of tests, are available from table 1. Three kinds deformed steel bars with diameter d (d=12,18,25 mm) were used. The yield stress and elasticity modulus of the steel bars, which are result of tensile tests, are available from table 2.

The reinforced concrete specimens were divided into seven types according to the rebar sizes and concrete covers. The geometry of the specimen, schematically, is represented in Fig.1. Concrete cylinder specimens had a constant 500 mm length (L=500 mm) and variabl diameter D (D=60,100,150 mm). One steel reinforcement with diameter d (d=12,18,25 mm) has been embeded in the middle of the concrete cylinder. This steel bar was extended adequately outside the two ends of the specimen. Specimens' specifications are represented in table 3.

The specimen diameter and reinforcement diameter have been considered in a manner to facilitate the feasible study of the effects of some important parameters such as clear concrete cover (*c*), ρ (reinforcement ratio), c/d and d/ρ. For construction of the specimens, 500 mm plastic molds have been used. The molds have been set on a special chassis, vertically. Steel reinforcement has been placed in the middle of the specimens to pass through the existing hole on an especial chassis at the end area. This set has been placed on a vibration table and the ready mixed concrete has been cast in mold layer by layer. After 24 hours, the molds have been opened and the specimens were curried in the room temperature for 28 days, then the direct tension tests were done for all spesimens.

Details of the tensile test setup are presented in Fig. 3. Two metal plates were attached to the top and the bottom of the specimens. A LVDT instrument was employed to measure axial deformations of the specimen. For this purpose, two gages were attached to the two ends of the specimen; by connecting them to the data logger apparatus, the value of axial deformation of the specimen in each stage of loading was recorded. Another LVDT has been utilized to measure reinforcing steel elongation and end slip in similar manner; for this purpose, two displacement gages were affixed to the reinforcing bar at the top and the bottom.

The axial load values were measured continuously by connecting a load cell to the data logger equipment.

Table 1. Material properties of concrete.

f_c (Mpa)	E_c (Mpa)	f_t (Mpa)
26	24400	1.62

Table 2. Material properties of steel bars.

d (mm)	f_y (Mpa)	E_s (Mpa)
12	515	205000
18	350	200000
25	369	202000

Table 3. Specifications of reinforced concrete specimens.

Specimen	d (mm)	D (mm)	c (mm)	ρ	c/d	d/ρ
S12-60	12	60	24	0.04	2	300
S12-100	12	100	44	0.0144	3.67	833
S18-60	18	60	21	0.09	1.167	200
S18-100	18	100	41	0.0324	2.278	555
S18-150	18	150	66	0.0144	3.67	1250
S25-100	25	100	37.5	0.0625	1.5	400
S25-150	25	150	62.5	0.0278	2.5	900

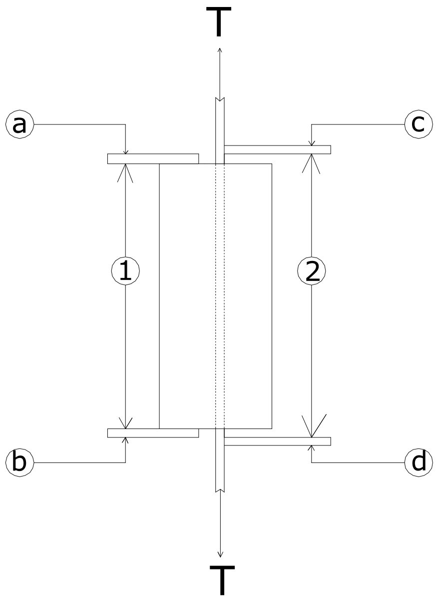

Figure 3. A schematic details of the tensile test setup and instrumentations' location.
(1),(2): LVDT for axial deformation of the specimen and reinforcing steel.
(a),(b),(c),(d): Displacement gages.

3. Experimental results

The axial forces were increased to reach yielding capacity of the steel reinforcements; by the onset of plastic deformations, the tests were ceased and the number of transversal cracks (N_{cr}) and minimum and maximum crack spacing ($S_{\min}$, $S_{\max}$) were recorded for each specimen. The results of all direct tension tests are represented in Table 4 and Photos of some of the specimens at the end of the tests are shown in figure 4.

The ultimate average crack spacing (S_m) was obtained by considering the specimen length (L=500 mm) and the number of transversal cracks(Ncr):

$$S_m = L/(N_{cr} + 1) \quad (1)$$

The results of above formula were inserted in table 4.

Table 4. The results of all direct tension tests.

No.	Specimen	N_{cr}	S_m (mm)	$S_{\min}$ (mm)	$S_{\max}$ (mm)	f_{bu} (Mpa)
1	S12-60a	6	71.4	60	110	3.29
2	S12-60b	6	71.4	65	90	3.29
3	S12-100a	4	100	70	180	6.65
4	S12-100b	4	100	85	150	6.65
5	S18-60a	9	50	35	60	2.95
6	S18-60b	8	55.5	35	80	2.66
7	S18-100a	5	83.3	50	120	5.23
8	S18-100b	4	100	60	140	4.35
9	S18-150a	2	166.7	135	210	5.98
10	S18-150b	2	166.7	135	200	5.98
11	S25-100a	5	83.3	60	90	3.66
12	S25-100b	5	83.3	60	100	3.66
13	S25-150a	3	125	80	150	5.67
14	S25-150b	3	125	90	160	5.67

Figure 4. Photos of some of the specimens at the end of the tests.
{(S18-60a,b), (S18-100a,b), (S18-150a,b)}

4. Analysis of experimental results

4.1. Minimum and maximum crack spacing

At the end of the direct tension tests, it was observed that the original specimens have been converted into several pieces with the arbitrary sizes in length. It was clearly evident that the crack spacing has a random nature. Maximum and minimum crack spacings were recorded for each specimen at end of the each direct tension test; accordingly, the average ultimate crack spacing was calculated. By the means of the least square curve fitting technique applied to the experimental results (see Fig. 5), the ultimate average crack spacing, S_m, for specimens were related to the minimum and maximum crack spacing as below:

$$S_{\min} = 0.72 S_m , \quad S_{\max} = 1.35 S_m \tag{2}$$

the ratios obtained experimentally clearly confirm the random nature of crack distribution and the range within which theoretical prediction is acceptable for reinforced concrete structures.

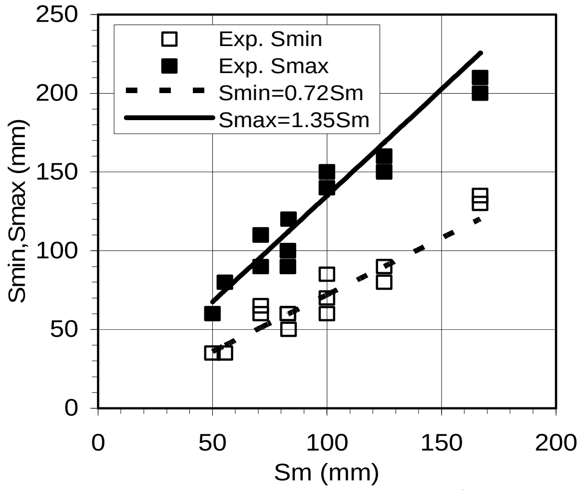

Figure 5. Relationship of the ultimate average crack spacing (S_m), and the minimum, maximum crack spacing

4.2. the ultimate average crack spacing

The experimental results for reinforced concrete specimens were presented in Table 4; according to these results, these remarks could be made about the parameter S_m :

1. Concrete specimen diameter or in other word reinforcing steel concrete cover (c) has a direct relationship with the ultimate average crack spacing;
2. reinforcement ratio (ρ) has an inverse relationship with the ultimate average crack spacing.
3. Increasing in the ratio of d/ρ and the concrete cover result in increasing the average crack spacing in the specimen.

Review of some researches (CEB-FIP 1990, Rizkalla and Hwang 1984) show that the average crack spacing, S_m, could be expressed as a function of the rebar diameter, d, concrete cover, c, and ratios of c/d and d/ρ; current research results agree with the results of the past researches. By the means of the least square curve fitting techniques, these two formulas were proposed:

$$S_m = 0.6(d+40) + 0.21c + 0.09\frac{d}{\rho} \tag{3a}$$

$$S_m = 2.35c \tag{3b}$$

The comparison between predictions of these formulas with the ones proposed by Rizkalla and Hwang (1984) and CEB-FIB (1990) is illustrated in Fig. 6. The comparison shows that equations (3a), (3b) have better agreement with experimental results. These results; specially simple equation (3b) and equations (2), would be useful to be employed in the practical design codes for assigning of crack pattern and crack spacing prediction for reinforced concrete members.

4.3. bond stress

In a reinforced concrete member after formation of the first tensile crack, by increasing the applied tensile loads, concrete cracks, successively until the ultimate crack pattern is achieved. In the post cracking state, slip happens between reinforcing steel and concrete. The values of the mean bond stresses are not constant in this state and increases by slips, accordingly.

Consider tact concrete between two adjacent cracks as shown in figure 2; the average traction forces on the concrete and the reinforcement steel interface is equal to $f_{bm}\pi da$. For developing a new crack in tact concrete, maximum concrete stress contribution has to reach to its maximum value (f_t); utilizing equilibrium of the forces for concrete as shown in Fig. 2 and results in:

$$f_{bm} = \frac{f_t A_c}{\pi da} \tag{4}$$

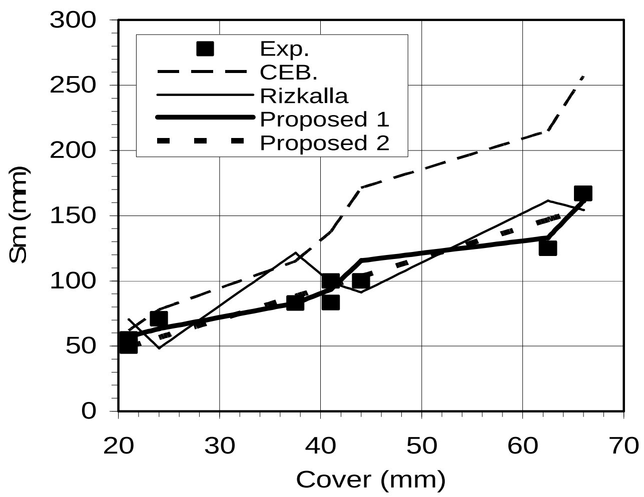

Figure 6. Crack spacing, a view over the predictions of experimental data and analytical formulas

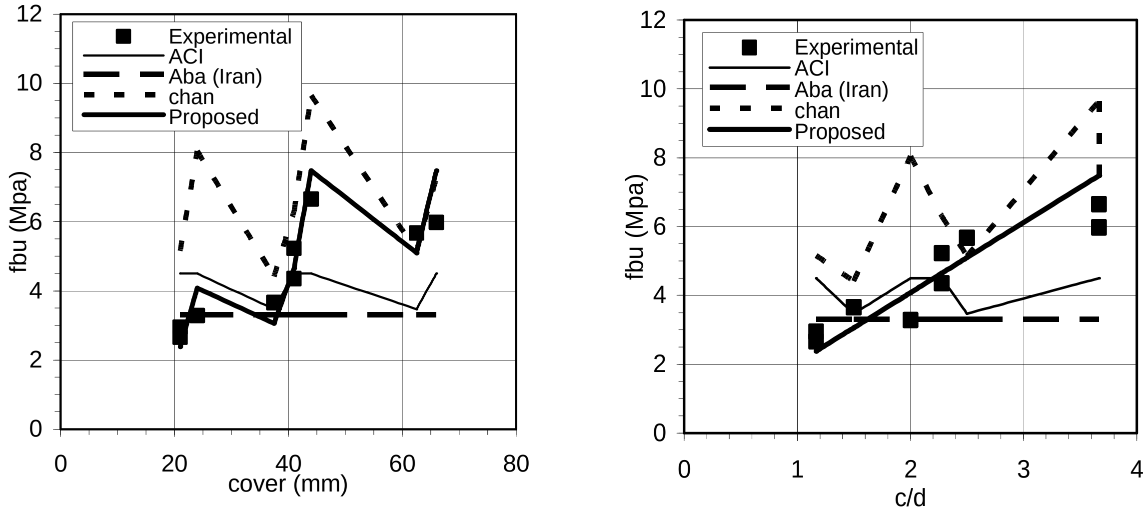

Figure 7. Comparisons between analytical and experimental ultimate bond strength.

After the last tensile cracks appear, the numbers of the tensile cracks remain constant until reinforcement yielding and the value of the average bond stress reaches to its maximum which is almost constant and equal to f_{bu}. At this stage, Eq. (4) can be rewritten in the following form ($S_m = 2a$):

$$f_{bu} = \frac{2 f_t A_c}{\pi d S_m} \quad (5)$$

The values of f_{bu} calculated by above formula and inserted in table 4. As it is observed from table 4, c/d ratio plays a key role in the ultimate bond strength of the specimens. By utilizing least square curve fitting technique, this formula was proposed:

$$f_{bu} = 0.4\frac{c}{d}\sqrt{f_c}\,(MPa) \quad (6)$$

In Fig. 7, the predictions of the proposed formula were compared with the similar ones (Chan, *et al.* 1992, ACI 318-99, ABA-99) and experimental results. The comparison shows that equation (6) has better agreement with experimental results.

5. Conclusions and summary

The bond strength, crack pattern and average ultimate crack spacing were studied experimentally herein. The specimens properties were chosen in a manner to reflect the effects of the governing parameters in the tensile behavior of the reinforced concrete specimens; namely, clear concrete cover (c), reinforcement diameter (d), reinforcement ratio (ρ), c/d and d/ρ ratios. This research was not restricted to the qualitative representations; some empirical formulas are proposed to predict tensile characteristic parameters of reinforced concrete. The proposed formulas are almost unique in the literature [1-10] and suitable for application in the codes or related analytical models.

For this purpose a comprehensive experimental program including reinforced concrete cylanders with different concrete covers and reinforcement ratios is conducted. All specimens tested under direct uniaxial tension. At the end of the direct tension tests, it was observed that the crack spacing has a random nature and was obtained the relationship of the ultimate average crack spacing (S_m), and the minimum, maximum crack spacing. Two formulas were proposed for determining the ultimate average crack spacing. These results would be useful for assigning of crack pattern and crack spacing prediction for reinforced concrete members.

The bond stress between the reinforcing steel and the concrete were evaluated using equilibrium equations for a crack spacing portion. A formula was proposed for determining the ultimate bond strength. The comparison between predictions of this formula with the ones proposed by et al, shows that the proposed equation in this paper has better agreement with experimental results.

Notations

T =applied tensile load
l = specimen length
c = clear concrete cover
d = reinforcement diameter
D = specimen diameter
ρ =reinforcement ratio
f_c = concrete compressive strength
f_t = concrete tensile strength
f_y = yielding stress of the steel reinforcement
E_c = concrete intial modulus of elasticity
E_s = steel renforcement intial modulus of elasticity
N_{cr} = final number of cracks after the tensile test
S_m =ultimate average crack spacing between two adjacent cracks
$S_{\max}$ =ultimate maximum crack spacing between two adjacent cracks
$S_{\min}$ =ultimate minimum crack spacing between two adjacent cracks
A_c = net concrete cross-section
a = half of spacing between two subsequent cracks
f_{bu} = ultimate bond strength

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