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ORIGINAL ARTICLE

Crack width evaluation for flexural RC members

Said M. Allam*, **Mohie S. Shoukry**, **Gehad E. Rashad**, **Amal S. Hassan**

Structural Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

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Abstract Some building code equations and equations developed by researchers are used for the calculation of the crack width in reinforced concrete flexural members. To investigate codes' provisions beside some equations found in the literature concerning the crack width calculation of reinforced concrete members subjected to flexure, five reinforced concrete rectangular models were investigated theoretically. The models include different parameters such as reinforcement steel ratio, steel rebar arrangement and reinforcement grade. Also, to verify the accuracy of the building code equations and the equations developed by researchers a comparison against some experimental data available in the literature was carried out. The experimental data include some variables affecting the crack width such as steel stress, concrete cover, flexural reinforcement ratio and rebar arrangement. The study showed a large scatter among the different code equations, however, most of the code equations overestimate the effect of concrete cover on the calculated values of the crack width. Also, the Egyptian code equation should limit the value of the mean steel stress as given by Eurocode equation to overcome the underestimated values obtained in the case of sections having low steel ratio. Moreover, the reinforcement detailing (bars distribution) is an important factor affecting the crack width.

1. Introduction

Crack width calculation is one of the serviceability requirements in the structural concrete elements. The occurrence of cracks in reinforced concrete elements is expected under service loads, due to the low tensile strength of concrete. Control of cracking is important for obtaining acceptable appearance and for long-term durability of concrete structures, especially those subjected to aggressive environments. Excessive crack width may reduce the service life of the structure by permitting more rapid penetration of corrosive factors such as high humidity, repeated saturation with moisture, vapor, salt-water spray and gases with chemicals, to reach the reinforcement. Generally, cracking should not induce reinforcement steel corrosion or spoil the appearance of the structure. In addition, cracking in reinforced concrete structures has an effect on structural performance including stiffness, energy absorption, capacity, and ductility. Consequently, there is an increased interest in the control of cracking by building codes and scientific organizations. With the use of ultimate strength

* Corresponding author. Tel.: +20 01112244066.
E-mail address: Sa_allam@yahoo.com

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methodology and high strength reinforcement steel, researchers and designers recognized the need for providing a mechanism by which crack width would be minimized. Therefore, researches were undertaken in 1960s to quantify the above concept and develop design tools [1].

The crack width of a flexural member is obtained by multiplying the maximum crack spacing by the mean strain of the flexural steel reinforcement. Therefore, the crack width depends on the nature and the arrangement of the reinforcing steel crossing the cracks and the bond between the steel bars found in the tension zone of concrete. Many research work found in the literature predicted the crack width of a flexural member based on theoretical models and experimental data. Saliger [2] and Tomas [3] used Bond-Slip model, Borms [4] and Base et al. [5] used No-Slip model, however Welch and Janjua [6] and Leonhardt [7] used Localized Bond-Slip model to predict the crack width. Gergely and Lutz [8] used the results of experimental data to formulate an equation to calculate the crack width. Based on the experimental work, Oh and Kang [9] proposed a formulation for predicting the maximum crack width. Frosch [10] developed a simple theoretical equation to predict the crack width based on a physical model. Besides the research work carried out for crack width formulation, other research work experimentally investigated the factors affecting the crack width. Makhlouf and Malhas [11] investigated the effect of thick concrete cover on the maximum flexural crack width under service load. Beeby [12] and Nawy and Blair [13] showed that the transverse reinforcement had a strong influence on the crack spacing. Gilbert and Nejadi [14] tested six beams and six one-way slabs with different flexural reinforcement ratio and bar arrangement including various concrete cover.

In this paper, a study is carried out to investigate several formulas suggested by different building codes for the calculation of the crack width in reinforced concrete flexural members. Also, the formulas proposed by other researchers were also investigated and compared with codes' equations. In addition, the most prevalent building codes' equations are examined and tested against some experimental data available in the literature. Moreover, a comparison was carried out among the equations to discuss the various factors and parameters affecting the crack width.

2. Crack width prediction according to some building codes provisions

2.1. Eurocode2 1992-1 (2001)

Eurocode2 [15] gives the following equation for predicting the crack width of flexural members

$$W_k = S_{r,max}(\varepsilon_{sm} - \varepsilon_{cm}) \tag{1}$$

where W_k = the design crack width, mm.

The mean tensile strain $\varepsilon_{sm} - \varepsilon_{cm}$) is given by the following equation:

$$(\varepsilon_{sm} - \varepsilon_{cm}) = \frac{\left(f_s - K_t\left(\frac{f_{cteff}(1+n\rho_{eff})}{\rho_{eff}}\right)\right)}{E_s} \geqslant 0.6\frac{f_s}{E_s} \tag{2}$$

where ε_{sm} is the mean strain in the reinforcement under the relevant combination of loads, including the effect of imposed deformations and taking into account the effects of tensioning stiffening. Only the additional tensile strain beyond zero strain in the concrete is considered; ε_{cm} is the mean strain in concrete between cracks. K_t = factor expressing the duration of loading: K_t = 0.6 for short term loading and K_t = 0.4 for long term loading, f_s = the stress in the tension reinforcement computed on the basis of a cracked section, n = the modular ratio $\frac{E_s}{E_{cm}}$, f_{cteff} = the mean value of tensile strength of the concrete effective at the time when the cracks may first be expected to occur,

$$\rho_{eff} = \frac{A_s}{A_{ceff}}$$

A_{ceff} = effective tension area, is the area of concrete surrounding the tension reinforcement. $S_{r,max}$ = the maximum crack spacing, mm and is given by the following equation

$$S_{r,max} = 3.4c + 0.425k_1k_2\phi/\rho_{eff} \tag{3}$$

where c = concrete clear cover, k_1 = coefficient that takes into account the bond properties of the bonded reinforcement and equals to 0.8 for high bond reinforcing bars, and equals to 1.6 for plain reinforcing bars, ϕ = the bar diameter, mm; in case of using various diameters, the average diameter shall be used, k_2 = coefficient that takes into account the strain distribution and is equal to 0.5 for sections subjected to pure bending and equals to 1.0 for sections subjected to pure axial tension.

2.2. Egyptian code; ECP 203-2007

The Egyptian code ECP 203-2007 [16] gives the crack width by the following equation:

$$W_k = \beta\varepsilon_{sm}S_{rm} \tag{4}$$

where W_k = coefficient for checking crack width condition, mm; S_{rm} = average stabilized crack spacing, mm; ε_{sm} = mean steel strain under relevant combination of loads and allowing for the effect such as tension stiffening or shrinkage; β = coefficient relating the average crack width to the design value: β = 1.7 for cracks induced by loading and for cracking induced by restraining the deformation for cross section having width or depth (whichever smaller) in excess of 800 mm, and β = 1.3 for cracking induced by restraining the deformation for cross section having width or depth (whichever smaller) less than 300 mm.

The mean steel strain ε_{sm} is given as

$$\varepsilon_{sm} = \frac{f_s}{E_s}\left(1 - \beta_1\beta_2\left(\frac{f_{scr2}}{f_s}\right)^2\right) \tag{5}$$

where f_s = stress in the tension reinforcement calculated on the basis of a cracked section, N/mm^2; f_{scr2} = stress in the tension longitudinal reinforcement computed on the basis of a cracked section under loading conditions that cause the first crack, N/mm^2; β_1 = a coefficient accounting for bar bond characteristics, and is equal to 0.8 for deformed bars and 0.5 for plain smooth bars, β_2 = a coefficient accounting for load duration; is equal to 1.0 for single short-term loading and 0.5 for sustained or cyclic loading; E_s = Modulus of elasticity of the reinforcement, N/mm^2.

The Egyptian code gives the average stabilized mean crack spacing by the following equation:

$$S_{rm} = 50 + 0.25k_1k_2\phi/\rho_{eff} \tag{6}$$