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Cracking localization in tensile conventionally reinforced fibrous concrete bars

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HIGHLIGHTS

- The paper presents a study of cracking localization (CL) in R/SFRS tensile bars.
- The tests included specimens with two contents of fibers and control, plain specimens.
- For each type of mixture, the conventional reinforcement ranged from 0.79 to 4.91%.
- Results show effects of fibers and reinforcement contents on CL.
- A theoretical model that quantifies CL has been experimentally verified.

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ABSTRACT

This paper presents an experimental verification and quantification of the cracking localization phenomenon in reinforced concrete (RC) tensile prismatic bars with steel fibers. The phenomenon is characterized by significant widening of single or few cracks out of the total number of cracks that develop under tension (as opposed to nearly uniform widening in plain RC members). The experimental program included specimens with two contents of hooked-end fibers (30 and 60 kg/m^3 that correspond to 0.38 and 0.76% in volume), as well as control specimens without fibers. For each type of mixture, the conventional reinforcement consisted of centrally located deformed rebars at reinforcement ratios of 0.79–4.91%. Results of the tests further support the existence of the cracking localization phenomenon and the trend of its decrease with increasing reinforcement ratio. A quantitative measure of this phenomenon is represented by a ratio between the number of the significantly wide cracks and the total number of cracks in the specimen. Furthermore, the results show that for a given conventional reinforcement ratio, cracking localization is more pronounced for larger amounts of fiber content (and vice versa). A previously developed and presently enhanced theoretical model has been calibrated and it shows good agreement with the experimental results.

1. Introduction

This paper describes part of a study that focuses on the effect of the relative fibers content on the ductility of the structural members, made of concrete with steel fibers and conventional reinforcement. The purpose of adding steel fibers to concrete mixtures is to increase the material toughness [1–4], where the action of the fibers is manifested in bridging the cracks after cracking load is exceeded [5,6]. It is therefore expected that fibers would improve structural ductility and crack control in elements made of fiber reinforced concrete [5–7,21,22]. It is well-known that structural ductility is an important property that refers to the ultimate limit state of a building structure (e.g., to provide ample warning before failure or in seismic design). It is measured by the ability of the structure to develop deformations at the ultimate limit state. Yet, it was also found that reinforced concrete (RC) beams that included both conventional reinforcement and steel fibers (R/SFRC beams) with low amounts of conventional reinforcement had reduced ductility, compared with similar, but plain, RC beams [8–10,23]. This phenomenon was characterized by significant widening of a single or few cracks (compared with the other ones) at increased loads (beyond yielding of the rebars) and it was diminished at higher reinforcement ratios. A similar observation, denoted as "crack localization", was made in tensile R/SFRC specimens [11,12]. These results lead to an understanding that in order to prevent crack localization, the amount of conventional reinforcement in the presence of fibers should be larger than some

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given value, as suggested in [11]. In R/SFRC beams, these findings suggest that a new criterion that ensures sufficient ductility may be needed to set a minimum reinforcement ratio [9].

The cracking localization observed in R/SFRC members may be related to the fibers scatter along the member, which has been investigated by several researchers (e.g., [13–16,20]). Deluce and Vecchio [12] refer to the scatter of the fibers by describing a localization effect, which is caused at "the weakest section", leading to local yielding of the rebar. Therefore, analysis of crack localization needs to be based on a proper theoretical model of the fibers distribution. Such probabilistic model has been proposed by Dancygier and Karinski [17]. The model is based on the hypothesis that the non-uniform distribution of the fibers leads to formation of "weak sections". Thus, based on a probability function of the fibers distribution, the model is able to predict, out of a given number of cracks, how many are expected to widen more than the others do. The model shows that as the conventional reinforcement ratio increases this phenomenon diminishes, which conforms to the above-mentioned experimental observations. Yet, the model includes several parameters that need to be calibrated empirically.

The paper describes results of an experimental study, which aimed to quantify the cracking localization phenomenon and to further verify and calibrate the above-mentioned probabilistic model.

2. Theoretical model

The crack localization phenomenon can be quantified by the ratio m/n, where n is the number of cracks that develop in a member and m is the number of dominantly wide cracks (out of n; hence, it is clear that $m/n \leq 1.0$). Increased values of this ratio indicate elimination of the crack localization. For the case of a tensile R/SFRC bar (i.e., a bar that includes both conventional reinforcement and steel fibers), Dancygier and Karinski [17] have proposed a cumulative function for the fibers distribution, which allows the development of a model that predicts the ratio m/n, depending on the amounts of the volumetric contents of the conventional steel and fibers. For clarity of presentation, a short description of the model, with a further modification (which is introduced in this paper), is presented in the following text. Note that derivations of all formulas presented in this section are given in [17].

The model refers to an R/SFRC bar of length L, subjected to tensile load. The fibers distribution is represented by a random variable, ξ, which is defined as the ratio between the actual volumes of steel (reinforcement and fibers) in a typical segment and their average value (in the bar), as follows:

$$\xi = \frac{actual\ volume\ of\ ALL\ steel\ in\ a\ segment\ (fibers\ \&\ rebars)}{average\ volume\ of\ ALL\ steel\ in\ a\ segment\ (fibers\ \&\ rebars)} = \frac{\rho + \rho'_f(1-\rho)}{\rho + \rho_f(1-\rho)} \tag{1}$$

where ρ'_f is the actual fibers ratio in a specific segment, ρ_f is its mean value and ρ is the conventional reinforcement ratio. While ρ is deterministic, ρ'_f is a random variable. It can be seen from Eq. (1) that the variable ξ ranges between two limits:

$$\xi_{min} = \frac{\rho}{\rho + \rho_f(1-\rho)} \quad \text{and} \quad \xi_{max} = \frac{\rho + \rho_f\frac{(1-\rho)}{\lambda}}{\rho + \rho_f(1-\rho)}, \tag{2}$$

where the lower limit corresponds to a theoretical case of no fibers in a specific segment ($\rho'_f = 0$ in Eq. (1)) and the upper limit corresponds to a theoretical state in which, for the common case of $\rho_f < \lambda = 0.5L_f/L$, all fibers are allocated in one segment (where L_f is the fiber's length).

The proposed cumulative distribution function has the following form:

$$P(\xi) = \begin{cases} f\left(\frac{\xi-\xi_{min}}{1-\xi_{min}}\right)^{\frac{p_0(1-\xi_{min})}{f}} & \xi_{min} \leqslant \xi \leqslant 1.0 \\ 1-(1-f)\left(\frac{\xi_{max}-\xi}{\xi_{max}-1}\right)^{\frac{p_0(\xi_{max}-1)}{1-f}} & 1.0 \leqslant \xi \leqslant \xi_{max} \end{cases}, \tag{3}$$

where $p_0 = \frac{f(1-f)\left[\frac{(1-f)}{\lambda}-1\right]}{(1-\xi_{min})(2f-1)\left(\frac{1}{\lambda}-1\right)}$ and f is equal to $P(\xi)$ at the mean value $\xi = 1$. This parameter is obtained by solving the following algebraic equation:

$$\sigma^2 = \frac{2\left[(1-\xi_{min})(2f-1)\left(\frac{1}{\lambda}-1\right)\right]^2\left(3\frac{f}{\lambda}-1-\frac{1}{\lambda}\right)}{\left[\left(\frac{1}{\lambda}\right)^2 f^3 + \frac{2}{\lambda}\left(\frac{1}{\lambda}-2\right)f^2 - \left(\left(\frac{1}{\lambda}\right)^2+\frac{1}{\lambda}-3\right)f + \frac{1}{\lambda}-1\right]\left[\left(\frac{1}{\lambda}+3\right)f - \frac{f^2}{\lambda}-2\right]}, \tag{4}$$

where σ is the standard deviation of the of ξ. Based on the standard deviation σ_{mix} of a fibrous concrete mix (without rebars), the standard deviation σ in the presence of conventional reinforcement, is calculated as follows [18]:

$$\sigma = (1-\xi_{min})\sigma_{mix} \tag{5}$$

σ_{mix} in this equation has to be obtained experimentally (for each fibers volumetric ratio).

A segment along the bar, which includes a significantly wide crack, is defined here 'a weak segment'. Quantitatively, this is a segment in which the ratio ξ (Eq. (1)) is less or equal to a certain critical ratio, denoted ξ_w, whose value should be generally determined experimentally. Alternatively, this parameter can be formulated, as proposed in [17]. However, the experiments presented in this paper have shown that the formulation given in [17] is not suitable for relatively long bars that allow development of more than 1–2 wide cracks (as those that were used for calibration of ξ_w in the referred paper). Therefore, the following revised empirical expression for ξ_w is proposed:

$$\xi_w = exp\left(\alpha \cdot \frac{\sigma_{mix}-\sigma}{\sigma_{mix,max}}\right), \tag{6}$$

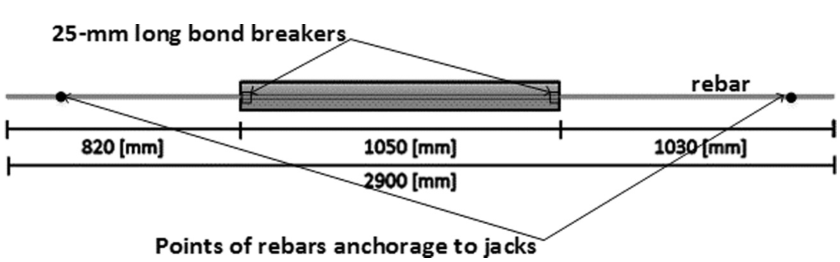

Fig. 1. Schematic description of a typical specimen.