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Performance evaluation of corrugated steel fiber in cementitious matrix

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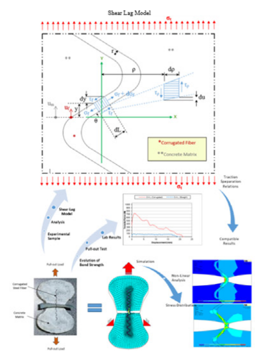
HIGHLIGHTS

- Enhancing in interfacial bond strength due to the corrugation.
- Shear lag model and relations of traction separation for fiber in corrugated shape.
- Greater bond strength might be obtained by setting larger inclination in corrugation.
- Recognized evolution in bond strength allows the fiber to reach its yield strength before the failure in bond strength.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasing the adhesion efficiency between the fiber and the concrete, in fiber reinforced concrete members, might be obtained by enhancing the properties of the concrete mixture using several parameters such as cement weight, water to cement ratio, grading curve of aggregates and admixtures, or by apply some changes on the fiber parameters such as the aspect ratio (l/d) or the outer roughness or the embedded length and the diameter value. Laboratory experiments lead to the fact that the use of smooth and straight steel fiber, in fiber reinforced concrete, produces weak bond strength between the fiber and the concrete. Therefore, to obtain better bond strength it is necessary to increase the total length of the fiber, which may cause unacceptable workability. Accordingly, it could be developed a new form of fiber has larger supporting region using the corrugated fiber shape. In this paper, the performance of this corrugated form will be monitored through new shear lag model to extract the traction separation relations between the corrugated fiber and the concrete matrix, as well as an experimental study using different values of embedded length of the fiber, in addition to several computer simulations which will be created using a finite element model and applying same dimensions and forces which are used in the laboratory experimental procedure. Through the results of nonlinear analysis of the computer simulations, the distribution of stresses in different directions for each of the concrete and the fiber can be shown, then the evolution of the bond strength between the fiber and the concrete can be monitored as an actual result of applying the corrugated shape.

1. Introduction

Since the idea of using fiber reinforced concrete is desirable widespread worldwide, and design guidelines of steel fiber reinforced concrete are still unavailable, the relevant scientific researches are still going forward to understand precisely the mechanical behavior of this structural composite material. Usually pull-out test is used to monitor the development of the mechanical behavior of the fiber in concrete matrix.

In Steel Fiber Reinforced Concrete (SFRC) many types of steel fiber are generally used, and these different types might be

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classified into three main types (straight form, hooked ends form and corrugated form) depending on its external manufacturing form [1–3]. Last time twisted non-round crosssection fibers were successfully used for concrete reinforcement.

Generally, all different types of steel fiber have to work to increase the internal resistance of the SFRC composite against the phenomenon of the occurrence of cracks under the influence of any external applied loads such as axial tensile forces, compressive forces and bending moments [4–6].

The occurrence of cracks in a hardened structural member from Fiber Reinforced Concrete (FRC) is resisted through three internal mechanisms between the fiber and the concrete, where full bonding stresses work at the interface between the two materials to prevent cracks from happening until reach the maximum fully bond strength at the interface, then some surrounding cracks around the fiber start to appear gradually along the depond length, and this depond length becomes equal to the whole embedded length of the fiber, then frictional sliding movement is started as a final attempt to prevent the fiber from pulling out of the concrete [7,8].

Many factors affect the fictional stresses such as fiber end shape [1,9], water to cement ratio [10], curing method [10,19], sand to coarse aggregate ratio [11], fiber dimensions and its embedded length in the concrete matrix [12]. Test results have shown that pullout behavior of different steel fiber reinforced VHSC composites is influenced by the matrix strength and fiber end condition (smooth, flat end, or hooked). Results reveal that both maximum pull-out load and total pullout energy increases as matrix strength increases for all deformed fibers that did not rupture. The test results also indicated that the increase in total pullout energy is more significant than that in peak load [11,13], where high complementary energy is found for both lowest and highest water to cement ratio due to the higher area under the curve of stress-strain of the composite which is considered until the peak load and achieved due to absence of load for the first crack in the case of lowest w/c, and higher area due to true delay in peak strain in the case of highest water to cement ratio. Therefore both the energy and complementary energy are to be taken into consideration for the ductile behavior of fiber reinforced concrete.

Debonding of the fiber/matrix interface led to interfacial failure where only friction resisted fiber extraction [14]. A single fiber embedded in various off-axis directions for the cruciform specimen test creates various combined stress states [15]. In (pull-out) test which offers a reliable estimation of compressive strength, the developed stress field is quite complicated and researchers have argued about the nature of the fracture mechanism [16], results show that the stress intensity factor at the fiber tip extracted from the angular deflections agreed with the results calculated by the finite element method [17,18].

Test results indicated that fiber type, embedded length of fiber, curing conditions, fiber end condition, and matrix strength has a considerable effect on fiber–matrix bond [19,20].

Considered bond strength between the fiber and the concrete matrix is necessary to increase the performance of fiber reinforced concrete, where pull-out tests are usually used to evaluate this bond strength of the composite [21–23]. Pull out behavior of steel fibers which are not straight and not circular in shape have received little attention compared to the straight steel fibers. Flat corrugated steel fibers are proved to be very effective at interface during pull out, which results into strain hardening and dissipation of significant amount of cold work energy [24].

The fiber pull-out behavior can be affected with the durability related factors, where the fiber pullout strength in cracked SCC, after 10 days of immersion in 3.5% NaCl solution, increased with the crack width due to the increase of fiber surface roughness caused by corrosion products, which improved the interfacial bond fiber/cementitious matrix. The relatively high residual pullout strength in the final phase of the fiber pullout test is caused by the pullout bending character of the adopted test that increases the fiber/matrix shear friction with the crack opening process (snubbing effect) [25]. The effect of alkali solution on pull-out behavior of control specimens is three fold. First of all, the bond performance of the alkali exposed specimens is a bit higher than those of water cured ones at early ages. The pull-out peak load and debonding toughness of control mixture were reduced at 28 days due to the ASR. At later ages (90 and 150 days), the bond strength of the specimens exposed to 80 °C NaOH solution significantly increased. This finding can be explained by the ASR gel congestion phenomenon. SEM analysis after pull-out test showed that the fiber–matrix interface filled by noticeable volume of ASR gel. Reduced or no gel formation around steel fiber was observed in mixtures containing mineral admixtures due to mitigation effect of these admixtures on ASR [10]. Curing at a low temperature of 2 °C was not found to adversely affect the pull-out resistance even after one year of continuous marine exposure [26].

From the above review through the literature, it can be concluded that the adhesion efficiency between the fiber and the concrete in fiber reinforced concrete members might be increased by enhancing the properties of the concrete mixture using several parameters such as (cement weight, water to cement ratio, grading curve of aggregates and admixtures) or by doing some changes on the fiber parameters such as increasing the contact surface roughness of the fiber to increase the contribution of the frictional forces, the use of longer fiber embedded length as well as larger diameter.

During this research the impact of using the corrugated shape on the bond strength between the steel fiber and the concrete will be monitored and analyzed using a new suggested shear lag model, as well as various pull-out experiments of single steel fiber in two shapes (straight and corrugated) will be set using different values of embedded lengths. On other side, computer simulations will be created according to finite element model, where same dimensions and forces will be used comparison the laboratory experimental study, and therefore the impact of using the corrugated shape will be monitored to observe the evolution of the bond strength between the fiber and the concrete.

2. Research significance

Since the bond strength between the concrete and the steel fiber is generated and measured at the contacted surfaces between these two materials, the laboratory experiments of this study have demonstrated that only weak bond strength can be produced when using straight steel fiber with smooth external surface. Thus, to obtain better bonding strength, it is necessary to increase the manufacturing length of the fiber, which may cause an unacceptable workability in the freshly fiber-concrete mixes. Usage of non-straight fibers such as fibers with hooked ends or corrugated shape might lead to avoid that mixing problems, also these non-straight fibers may lead to obtain greater bond strength at the interface without extra production cost. The significance of this research is beyond to determine the modalities of performance evaluation for these sophisticated shapes of steel fibers, where this study will introduce theoretical and practical methods in addition to numerical simulations which can be used to evaluate the performance of the steel fibers with corrugated shape.

3. Materials and methods

3.1. Creation of shear lag model

It is known that applying tensile force on a member of plain concrete will cause different shapes of cracks due to the weak