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Predicting the shear strength of steel fiber reinforced concrete beams

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ABSTRACT

This study predicts the shear strength of steel fiber reinforced concrete (SFRC) beams based on existing experimental results. A large database containing 222 shear strength tests of SFRC beams without stirrups was divided into six different groups based on their span-depth ratio ($a/d \geqslant 3$ or $a/d < 3$), concrete compressive strength ($f_c' \geqslant 50$ or $f_c' < 50$) and steel fiber shapes (hooked, crimped and plain) and was used to develop separate equations for predicting their respective shear strength. The proposed equations were obtained by performing both linear and non-linear regression analysis on each database. A statistical analysis was then performed to compare the proposed equations to those of the previously developed equations by other researchers for predicting the shear strength of SFRC beams. Overall, it was observed that the linear regression equations developed from this research for SFRC database could accurately predict the shear strength compared to the other previously proposed models.

1. Introduction

The use of fibers for the reinforcement of brittle building materials is not a new concept. In the ancient civilizations of West Asia, Africa and South America, straw fibers were often used to reinforce deteriorating adobe bricks [1]. Over the past 100 years, the use of fibers as reinforcement in concrete has been growing. At present, four primary fiber types are being placed in concrete: natural, synthetic, glass and steel. Natural fibers such as sisal, coconut, jute, sugar cane, bamboo, and flax are the oldest type of fiber reinforcement in building materials. Their low cost and local origins make them a popular concrete reinforcement option in developing countries [1]. Presently, natural fibers are being used primarily in the African construction industry for concrete pipes, tanks and houses [1]. Although the use of natural fibers increases the flexural, shear and tensile strength of concrete, they are less durable in concrete than the other fiber types [2]. The high alkalinity of concrete pore water makes the natural fibers more prone to degradation [1]. Solutions such as natural fiber coatings have been developed to solve this durability issue; however, further research on the durability of natural fiber reinforced concrete under severe environmental conditions is needed for its implementation in developed countries [1].

Synthetic fibers such as acrylic, aramid, carbon, nylon, polyester and polyethylene fibers are man-made and were first introduced as a possible concrete component in 1965 [1]. Initially, they were not able to obtain similar performance results in concrete to that of glass and steel fibers. With more recent research on the behavior of different synthetic fibers in concrete, synthetic fibers are able to successfully reinforce concrete [1]. Small amounts of synthetic fibers can increase concrete failure resistance and strength, however, studies performed by Majdzadeh et al. [3] and Greenough and Nehdi [4] still indicate that synthetic fibers do not perform as well as steel fibers in increasing the shear strength of concrete beams. More research is necessary to understand the distribution of synthetic fibers through the concrete matrix and improve their mechanical properties [5]. Furthermore, standardized testing procedures have not yet been fully developed, which is limiting the commercial use of synthetic fibers in concrete [1].

In the 1960s, glass fiber was introduced as a potential source of reinforcement in concrete. Due to the effect of concrete alkalinity on glass fibers, glass fiber concrete was prone to durability issues. Eventually, British researchers were able to develop alkali resistant glasses, which allow producing much durable and strong concrete containing glass fibers. However, due to its lightweight and ability to be formed vertically, glass fiber reinforced concrete is primarily being used for architectural applications such as façade and cladding panels [1]. Presently, steel fibers are the most commonly researched fiber type concrete. In the 1910s steel elements such as nails and metal chips, were considered as possible sources of reinforcement in concrete [1]. Through both research and experimental work, steel fibers were eventually introduced as an effective concrete reinforcement in the 1960s. Steel fibers ranging from approx. 6.4 mm to 76 mm in length allow them to be uniformly distributed throughout a concrete mixture [1,6]. Since its introduction, the use of steel fiber reinforced concrete (SFRC) has received much

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Nomenclature

a	shear span, mm
a/d	shear span/effective depth ratio
A_{sw}	cross-sectional area of the shear reinforcement, mm^2
b	beam width, mm
d	effective beam depth, mm
d_a	maximum aggregate size, mm
d_f	fiber diameter, mm
D_f	bond factor
F	fiber factor
F_y	yield strength of shear reinforcement, MPa
f'_c	concrete compressive strength, MPa
f_f	flexural strength of plain concrete, MPa
f_{sp}	split cylinder strength of plain concrete, MPa
h	beam height, mm
l_f	fiber length, mm
l_f/d_f	fiber aspect ratio
η_o	fiber orientation factor
N	number of tests in database
ρ	tensile reinforcement ratio
S	spacing between shear reinforcement measured along the longitudinal axis, mm
τ	fiber–matrix interfacial bond strength, MPa
τ_{FRC}	fiber reinforced concrete shear strength, MPa
τ_{plain}	shear strength of plain concrete, MPa
σ_{tu}	residual stress of fibrous concrete in tension, MPa
V/M	external shear to moment ratio
V_c	shear resistance of the concrete, MPa
V_f	volume percentage of fibers
V_{test}	experimental shear strength, MPa
V_{calc}	predicted shear strength, MPa
V_u	ultimate shear strength, MPa

attention in concrete industry as more research is being performed and more is being understood about its material properties and behavior. Presently, SFRC is primarily being used in applications where the placement of reinforcing bars is difficult, such as in hydraulic structures (dams, spillways), large industrial slabs, tunnel linings, and in bridge decks [7].Other applications of SFRC are still being researched and are yet to be fully implemented in the construction industry. SFRC can be used for strengthening beam-column joints of reinforced concrete (RC) frames in seismic regions. Wang and Lee [8] experimentally demonstrated that SFRC jacketing significantly improves the ductility and flexural and shear strength of interior beam-column joints compared to that of regular concrete jacketing. Filiatrault et al. [9] performed full-scale testing of interior beam–column joints where SFRC was used particularly at the joint region, which is often highly congested with reinforcements and makes concreting works difficult. The test results indicated that SFRC joint could provide adequate ductility under seismic loading and could substantially improve its joint shear strength, and therefore, proves to be a potential alternative to conventional confining reinforcement. Fattuhi and Hughues [10] used SFRC as a secondary reinforcement in concrete corbels to increase their strength and ductility. The use of steel fibers in shotcrete has also been proven to increase its cohesion on the repaired surface as well as its crack resistance, ductility, energy absorption and impact resistance. SFRC shotcrete is currently being used primarily in slope stabilization applications [11].

Accurate design procedures and codes are required for the shear strength prediction of SFRC beams to allow for its wider application in the construction industry. The objective of this study is to develop numerical tools/equations for accurately predicting the shear strength of SFRC beams that can be implemented in design codes. The research presented in this paper involves the collection of all experimental data available on SFRC without stirrups, the sorting of the collected data and a regression analysis of the data to develop more accurate equations for the prediction of SFRC beam shear strength. The equations developed through this research have been statistically evaluated and compared to those developed previously by other researchers.

2. Research significance

In general, concrete is considered as a brittle material with a low tensile strength and shear capacity. The shear failure of reinforced concrete beams is a common concern for structural engineers as it often occurs with little or no notice [12]. The addition of steel fibers to a concrete mixture enhances the shear and toughness of concrete members. The steel fibers help to form bridges through developing cracks in the concrete and provide more resistance to the crack growth [12]. This eliminates the possibility of a sudden failure in concrete and allows for a more progressive failure. It is well established from many previous studies that the addition of steel fibers in concrete significantly increases its shear strength. It is difficult, however, to accurately predict the increase in shear strength as the interaction between the steal fibers and the concrete matrix is complex [7]. The development of an accurate model/equation for predicting the shear strength of SFRC is needed for the development of valid design codes, which will enable SFRC to be used as a common building material.

3. Parameters affecting shear strength

In order to produce accurate equations for modeling the shear behavior of SFRC beams, the most important parameters affecting their shear strength of SFRC must be investigated. The parameters chosen in this study for the development of shear strength equations were those observed from the previous studies on the shear strength of SFRC. These parameters are the concrete compressive strength (f'_c), tensile reinforcement ratio (ρ), span-depth ratio ($\frac{a}{d}$), fiber aspect ratio $\left(\frac{l_f}{d_f}\right)$ and the amount of fiber in concrete (V_f) [6]. The influence of each parameter on the shear strength of SFRC beams has been observed from previous studies conducted by Narayanan and Darwish [6], Ahn et al. [13], Khuntia et al. [14], Khaloo and Kim [15] Swamy and Bahia [16], Li et al. [17],

Khuntia et al. [14] observed that an increase in concrete compressive strength increases the shear strength of SFRC beams exponentially. This is due to the stronger bonds developed between fibers and concrete matrix when high strength concrete is used [15]. Contrarily, an increase in the shear span-depth ratio of an SFRC beam causes an exponential decrease in the beam shear strength due to the arching action of the beam [6]. Swamy and Bahia [16] observed that with the increase in the tensile reinforcement ratio of SFRC beam, its rate of increase in shear strength increases up to a certain limit beyond which it declines. The rate of increase in shear strength is larger at lower reinforcement ratios, which is due to the larger dowel forces in concrete [17]. At larger reinforcement ratios the rate of increase in shear strength decreases due to reduced dowel resistance, however, the shear strength value does not decrease in SFRC concrete beams [16].