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ORIGINAL RESEARCH

Experimental and numerical modeling for shear strength of hybrid fiber reinforced concrete beams with stirrups

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Abstract

The use of hybrid fibers in concrete has attracted wide attention in recent years. Using hybrid fibers with different elasticity moduli increases the strength and ductility of fiber reinforced concrete (FRC). In addition, hybrid fibers improve the shear strength of FRC beams significantly. The previous studies have shown that the hybrid use of fibers leads to a phenomenon, called synergy. However, the effect of combining hybrid fibers with stirrups is scantly studied and continues to main unknown. In this study, the effects of stirrups, concrete compressive strength, polypropylene fibers, steel fibers, and their hybrids on the shear strength of FRC beams are investigated. For this purpose, 24 FRC beams were tested in an experimental program. Experimental results show that samples with hybrid fiber have the highest shear performance. Additionally, a new model for simulating these beams' shear strength is presented, using genetic programming technique. The proposed model precisely predicts sample performance. The R^2 for this model was 0.868, which is a suitable value due to the complexity of the problem.

Keywords: Hybrid fibers; Genetic Programming; Concrete shear strength; Stirrup

The use of concrete with various fibers has been accompanied by significant benefits [1]. Compared with ordinary concrete, fiber-reinforced concrete (FRC) has better ductility, shear strength, tensile strength, toughness, and durability [2, 3]. Increasing the shear strength of concrete is one of the significant advantages of using fibers, which has even been considered in ACI-318 [4]. The minimum shear reinforcement required can be avoided in members made of FRC containing 0.75% volume fraction of steel fibers [4]. Improvements in the mechanical properties of FRC depend on several factors. The most important of them are the type and geometry of fibers, fiber content, and compressive strength of concrete [5, 6]. Researchers have shown that fibers with a high elastic modulus, such as steel fibers, improve the behavior of FRC in its first crack strength and final strength [1]. However, fibers with a low elastic modulus, such as polypropylene fibers, improve post-cracking behavior and FRC ductility [1]. Fiber geometry also has a significant role in the behavior of fiber concrete. Micro and macro fibers have been proposed, respectively, to prevent the propagation of micro-scale and large-scale cracks [7]. According to these results, concrete with hybrid fibers is recommended to achieve all the advantages of FRC.

The use of hybrid fibers with low and high young modulus improves concrete's ductility and strength properties, respectively. In addition to the benefits of using hybrid fiber reinforced concrete, numerous studies have shown that using hybrid fibers leads to a phenomenon, called synergy [8]. In the synergy phenomenon, the use of several types of fibers together leads to better performance than the total effect of each of them separately [8]. The hybrid use of polypropylene and steel fibers improves concrete's toughness and strain capacity [9, 10]. Banthia and Gupta [7] investigated the effect of hybrid fibers in terms of performance and synergy (micro, macro, and fibrillating polypropylene fiber, steel fiber, carbon fiber) to determine the best hybrid fibers. Based on the synergy criterion, samples including macro steel fibers and micro polypropylene fibers had the best performance. These results were consistent with the findings of similar studies, such as the studies by Abou El-Mal [10]. In addition to achieving proper mechanical performance, the cost and density of fibrous concrete can be reduced by replacing some macro steel fibers with micro polypropylene fibers, which

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can be attributed to the lower density and cost of polypropylene fibers [11]. Moreover, this hybrid fiber with better crack control leads to better durability of FRC [11].

As mentioned, according to the regulation of ACI-318 [4], the minimum stirrups required can be replaced by a 0.75% steel fibers volumetric ratio. Therefore, FRC is very suitable for structural members, such as concrete slabs or shallow foundations, where it is impossible or difficult to consider stirrups. However, due to the wide advantages of this material, its use in other structural members is also common. Structural members are usually not in the conditions of minimum shear reinforcement. To consider the effect of fibers on these members, it is necessary to reduce shear reinforcement using an appropriate equation. This work reduces the complexity of the structural reinforcement bars and casting problems while creating an economic advantage [12]. For the shear design of steel fiber reinforced concrete (SFRC) beams, a method was proposed by RILEM TC 162-TDF [13]. In this method, the effects of fibers, stirrups, and concrete are used as separate components for the shear design. However, recent studies have shown that calculating the effect of fibers as a separate factor is not appropriate [12, 14]. This is because fibers affect the shear bearing mechanism, particularly aggregate interlock [14]. FRC should be considered a composite material with specific bearing patterns and mechanical properties [14]. In the shear design of SFRC beams, Moradi et al. [12] showed that the effects of fibers, concrete, and shear reinforcement are unretractable. Therefore, the experimental analysis of FRC beams is needed to present shear design models. **1-Introduction**

Most experimental studies have focused on the shear strength of FRC beams containing steel fibers, and there are scant studies on polypropylene fibers reinforced concrete. Based on the result of 11 beams without stirrups, Arslan et al. [15] investigated the effect of polypropylene fibers on the shear behavior. In their samples, the shear-span to the effective-depth ratio (shear-span-ratio) was 2.5, 3.5, and 4.5. Arslan et al. [15] showed that samples that failed in the shear mode had the shear-span-ratio less than 3.5. Therefore, only eight samples were failed with shear mode. Navas et al. [16] prepared and tested 16 large-scale beams to investigate the effect of compressive strength of concrete, stirrups, and polypropylene fibers on the shear capacity of FRC beams. Their findings indicated that polypropylene fibers have a notable effect on FRC beams' shear capacity. Their results also showed a synergy effect for fibers and shear reinforcement, improving the FRC beams' shear capacity. In similar studies, Navas et al. [17] investigated the effect of stirrups and steel fibers on eight large-scale specimens. The sum of Navas et al. [16, 17] results provides a suitable database for researchers to continue research in this field. By investigating the effect of polypropylene fiber and stirrups on the shear behavior of FRC beams, Zhang et al. [18] concluded that ductility and strength improved by adding fibers. Moreover, the improving effect of polypropylene fibers on the shear strength of samples is reduced by increasing the number of stirrups. They concluded that sliding on the critical crack surface of the samples with a higher shear reinforcement ratio causes more damage to the fibers and their bridging effect. Gali and Subramaniam [19] investigated the effect of steel and polypropylene fibers hybrid on the FRC beams' shear strength. However, their studies included four samples, of which only one sample contained polypropylene fibers. For analyzing the factors affecting the shear strength of FRC beams, Gali and Subramaniam [19] presented an analytical model. However, no practical relation was provided to predict the shear strength of these beams.

In this article, 24 FRC samples were prepared. Based on these samples, the effect of polypropylene and steel fibers and their combination on the shear strength of FRC beams was investigated. The concrete compressive strength and the stirrups effects were also investigated based on these samples. However, many other factors affect the shear behavior of FRC beams. These factors include the strength and geometry of the fibers, size effects, and compressive and tensile rebars. Numerous samples are needed to consider the effect of these factors, which is beyond the scope of any scientific research. Therefore, to complete the database and investigate these factors, 100 samples from the literature were used. In the second part of this research, based on experimental and collected samples, by using genetic programming technique a comprehensive equation was presented to determine the shear strength of FRC beams. The proposed equation can be used in the design of FRC beams and the study of factors affecting them.

2- Experimental Program (Experimental Setup)

2-1- Specifications of Materials, Concrete Composition, and Samples

As mentioned earlier, 24 FRC samples with and without stirrups were experimentally examined. The fibers used in this study included steel fibers and polypropylene fibers with a volumetric ratio of 0.375%, 0.75%, and 1.5%. These fibers were used separately or in combination. Table 1 shows the characteristics of the fibers used in this research. Based on reinforcement layup and geometry, three groups of samples were used (Fig. 1). The geometries of samples and the longitudinal rebars were constant in all samples (length, width, and height were 1100, 100, and 125 mm, respectively). Only the arrangement of shear rebars was different (without stirrups, Φ3@ 50 mm, and Φ3@ 40 mm). Fig. 1 shows the three geometries used in this study.

These geometries are taken from the Moradi et al. [12] studies. Table 2 shows the specifications of all samples.

According to the research objectives, eight concrete compositions with different amounts and types of fibers were considered (Table 3). Five standard cylindrical samples (length 30 and diameter 15 cm) for each composition were prepared. Two samples were used to determine the splitting tensile strength as per ASTM C496 [20] and three cylindrical samples used to determine the compressive strength of the concrete compositions according to ASTM C39 [21] (Fig. 2). Table 3 presents the mean splitting tensile strength and compressive strength of concrete compositions.

According to Table 2, three rebars with diameters of 14, 8, and 3 mm were used to withstand tensile, compressive, and shear forces, respectively. According to ASTM A370 [22], the strength characteristics of these rebars are shown in Table 4. Fig. 3 presents the stress-strain diagram of these rebars.

2-2- Test Setup of Shear Sample

The most appropriate test to determine the shear strength of FRC beams is the 4-point bending test. In this test, the shear force in the middle part of the beam is zero, and it is in the maximum in the area between the loading and support points. If the final crack of the beam is located in the middle of the beam, the specimen has flexural failure mode. Subsequently, if this crack is located in the area between the loading and support points, the specimen has shear failure mode.

The samples were designed to be used for determining the shear strength. This is possible by providing sufficient flexural reinforcement and limiting the shear span to an effective-depth ratio of less than 3.5 [15]. Samples were made and cast based on the specifications presented in Table 2 (Fig. 4). As mentioned, to evaluate the compressive and splitting tensile strength of concrete, five cylindrical samples were prepared from each concrete composition. All samples were demolded after 24 hours and cured under standard conditions for 28 days. All beams at the age of 28 days were subjected to a 4-point bending test, according to ASTM C1609 [23] (Fig. 5-a). The universal testing machine had a loading capacity of 2000 kN, and all samples were loaded up to failure monotonically (Figure 5b).

2-3- Results of Experimental Samples

All samples had shear failure mode, as discussed in the next section. The results of the samples are presented in Table 5. To complete the results of the samples, samples with/without steel fibers were added to the sample set from the author's previous studies (Table 5). The experimental conditions, geometry, and characteristics of these samples were similar to the samples of this study. For better evaluation of the results, the result of samples with low and high compressive strength of concrete (about 28 and 40 MPa) are shown in two separate diagrams (Fig. 6). In this figure, the effect of fiber volume ratio, hybrid ratio, and stirrups can be easily investigated. The most important conclusion drawn from Fig. 6 is that the hybridization of fibers leads to the highest shear performance of FRC beams. The effect of fiber hybridization and their synergy are more effective in higher compressive strengths, and the results are significantly different from the shear strength of samples containing steel fibers. The lowest performance of FRC samples was observed when polypropylene fibers were used alone. This low performance can be due to the low Young's modulus and tensile strength of these fibers. The performance of polypropylene fibers improves with increasing the compressive strength of concrete (Fig. 6). As shown in Fig. 6-b, the large difference in concrete compressive strength does not change the effect pattern of stirrups and fibers. Based on this result, it can be concluded that the effect of stirrups and fibers is higher than the concrete compressive strength. However, due to the limited samples, this issue needs further investigation. In the next section, more accurate comparisons are provided using a comprehensive equation.

The addition of stirrups with a spacing of 50 mm increased the shear strength by 24% and 57% in the C40 and C28 specimens, respectively. This improvement decreased with increasing the volume ratio of fibers. In the samples with a 0.75% total volumetric ratio of fibers, stirrups addition increased the shear strength by 19%, on average. This increase reached 9% in the samples with a 1.5% total volume ratio of fibers, on average. Therefore, it can be concluded that the performance of stirrups decreased with using fibers. In fact, the combination of stirrups and fibers had a negative effect, which can be due to the restriction created by the stirrups for the fibers to pass through them. In other words, the uniform distribution of fibers may be affected by stirrups. This result has been observed in similar studies [12, 18]. Moreover, sliding on the critical crack surface in samples with a higher shear reinforcement ratio may cause more damage to the fibers and their bridging effect [18]. According to the results, micro polypropylene fibers and stirrups combination has a slightly better performance. This performance can be due to their easier passage through the stirrups and their uniform distribution.

2-4- Observed Cracks in Samples

Fig. 7 shows the crack propagation pattern of the samples. According to the design prediction, all samples had shear failure mode (Fig. 7). Comparing samples 1-6 and 7-12 shows that increasing the volumetric percentage of hybrid fibers significantly reduces the crack width. The presence of stirrups also helps to reduce the crack width as well as create multiple cracks (Fig. 8). Samples with hybrid fibers (0.75%-0.75%) had the highest shear strength among all samples (samples 7-12). It can also be inferred from the figure 7 that the crack width reduces with increasing the compressive strength. High strength concrete, along with low crack width will lead to higher durability. These results indicate the optimal design of these samples (samples 7-12). Fig. 9 shows the crack propagation pattern of RC and SFRC samples. Comparing the results of Fig. 7 and Fig. 9 indicates that the most significant advantage of using polypropylene fibers is crack width reduction. Samples without these fibers show a much wider crack at failure.

3- New Shear Model for FRC Beams

As was mentioned, based on the results of this study and other similar studies, a new shear model is presented to predict the shear strength of the FRC beam. The proposed model was developed by the Genetic Programming (GP) method. This method is introduced in the next section.

3-1- Genetic Programming (GP) Method

The GP is a branch of artificial intelligence. The idea of this method is inspired by Darwin's theory and is based on the principles of natural inheritance. This method starts with a large number of random populations (relations), which are then developed by applying Darwin's theory of natural selection, including crossover, mutation, and other biological mechanisms. Therefore, after a few generations, a better population is produced. Each individual (relation) in the initial GP population is a combination of input and random numbers linked together by mathematical operations (addition, subtraction, power, etc.). The selection of mathematical operators and input variables in the GP is done automatically. Therefore, the best result is produced based on the nature of the problem (polynomial, exponential, etc.). Relations in the GP method are defined as trees branch. Two examples for crossover and mutation operators are presented in Fig. 10. Fig. 10a shows the mutation operator, in which Subtree 4 is selected and replaced by a new relation. No new subtree is produced in the crossover process, and the two-parent subtrees are swapped (Fig. 10b).

The GP process includes producing the initial population based on the problem variables, evaluating the individuals (relations) by the objective function, selecting the next generation's parents, applying the biological operators, and finally producing the new generation. This process continues in a loop until it reaches the number of generations specified by the user. Finally, the best relations are reported as the response of the problem.

3-2- Proposed Model

The GP method should be fed by a set of input and output parameters. Extensive variables affect the shear strength of hybrid fibers reinforced concrete beams. For this purpose, instead of directly defining inputs, some combinations of them were used. These combinations included polypropylene fiber ratio (R_{fp}), steel fiber ratio (R_{fs}), shear reinforcement ratio (R_V), compression reinforcement ratio (R_c), and tensile reinforcement ratio (R_t), which were defined in equations 1-5, respectively. In Equations 1 and 2, $F_p.L_p.D_p$ are polypropylene fibers' tensile strength, length, and diameter, respectively. Moreover, $F_s.L_s.D_s$ are steel fibers' tensile strength, length, and diameter, respectively. In Equations 3 to 5, $A_V.A_C.A_t$ are the areas of shear, compressive and tensile reinforcement, respectively, and $f_{yv}.f_{yc}.f_{yt}$ are corresponding to yield stresses of these reinforcements. In Equations 3 to 5, S, d, and b are the stirrups spacing, the effective depth, and the width of the beam, respectively. Effective depth, concrete compressive strength (f_c), the volumetric ratio of polypropylene fibers (V_{fp}), and volumetric ratio of steel fibers (V_{fs}) were also used as input data. Instead of shear strength (V), the shear strength ratio $(V_{sc} = V/bd)$ was chosen as the GP relation output to eliminate the effect of size.

$$R_{fp} = \frac{F_p L_p}{100 D_p} \quad (1)$$

$$R_{fs} = \frac{F_s L_s}{100 D_s} \quad (2)$$

$$R_V = \frac{A_V}{Sb} f_{yv} \quad (3)$$

$$R_C = \frac{A_C}{bd} f_{yc} \quad (4)$$

$$R_t = \frac{A_t}{bd} f_{yt} \quad (5)$$

The input and output data of 124 samples were presented in Table 6. These data were collected based on the results of this study and ten similar studies [12, 15-19, 24 and 26-28]. Twenty-four samples from this table were randomly selected and used to evaluate the relations (these data were marked with an asterisk). The rest of the samples were used for relation discovery using the GP. The GP code used in this study was prepared by Silva et al. [29] in MATLAB. In addition to the input data, a set of random and fixed numbers were used. Moreover, the operators used in this model were plus, minus, multiplication, and sine. These operators resulted in a more accurate response in GP executions. The initial population was 1,500 individuals, and the maximum generation was 1,000. Similar to Moradi et al.'s study, Equation 6 was considered the GP objective function [12]. This objective function represents the sum of differences between the experimental results and results of the proposed relation by GP. A relation with lower $F_{objective}$ is more accurate.

$$F_{objective} = \sum_{i=1}^{100} |V_{sc}(\text{predicted}) - V_{sc}(\text{experimental})| \quad (6)$$

The GP output tree is shown in Fig. 11. Eq. 7 is its corresponding mathematical relation. By simplifying this relation, we reach Eq. 8, where the unit of d is meter, and sin angles are in radians. There were many variables in this equation. Therefore, a long equation is expected. Fig. 12 shows the scatter plot of the experimental results and the results predicted by the proposed relation. The midline is the location of the results without error. Based on Fig. 12, it can be said that the proposed relation's results comply with the experimental result.

$$\mathrm{V}_{\mathrm{sc}} = 0.53166 + \left(\frac{f_c}{10}\right)^{sin(d+(\sin(d(0.83273\sin((R_t+0.00081931)^{(d-}} + ((0.28795\,(V_{fp}\,((V_{fs}+R_V) + sin(R_{fp}+0.65598^{R_c})) + R_{fs}) + \sin(R_{fp})) - (-1\times\sin(V_{fs}))) \tag{7}$$

$$\mathrm{V}_{\mathrm{sc}} = 0.5 + \left(\frac{f_c}{10}\right)^{sin(d+\sin(d(0.83\sin(R_t{}^{(d-0.7^{R_c})}\sin(R_c)+0.96}} + R_V + sin(R_{fp}+0.7^{R_c})) + 0.3R_{fs} + \sin(R_{fp}) + \sin(V_{fs}) \tag{8}$$

3-3- Assessment of Proposed Model and Guide Diagrams

Various statistical criteria have been used to evaluate the results of the model. Equations 9 and 10 show the calculation of the SAD and ASAD indices. The SAD index is equal to $\mathrm{F}_{\mathrm{objective}}$. Table 7 presents the statistical index values for the samples used in equation discovery and the evaluation samples. R^2 is an important index that shows the correlation of the samples. In an equation without any error, R^2 is equal to one. In Table 7, the value of this index for the proposed equation is very close to one, even for data not in the relation discovery process. This result indicates the high accuracy of the proposed equation. The confidence interval of 95% of $(\mathrm{V}_{\mathrm{SC}})_{\mathrm{Exp.}}/(\mathrm{V}_{\mathrm{SC}})_{\mathrm{predict}}$ predicted for all samples based on the proposed equation is 1.011±0.025. The confidence of 0.95 suggests that only five out of 100 samples were outside of the declared range. Accordingly, the proposed relation had high accuracy.

As mentioned earlier, there is no similar equation to compare with the proposed equation. However, for the results of RC and SFRC beams with/without stirrup, we can use Eq. 11 proposed by Moradi et al. [12]. This equation was accurate and comprehensive compared to similar equations [12]. In Equation 11, V_f and A are the volumetric percentage of steel fibers and their dimensional ratio (L_s/D_s), respectively. Other variables were defined in Section 3.2. The statistical indices of Eq. 11 and the proposed equation for RC and SFRC samples are shown in Table 7. These equations are almost have equal accuracy. However, it should be noted that Eq. 11 is not useable for samples containing polypropylene and hybrid fibers.

$$\text{Sum of Absolute Differences (SAD)} = \sum |\mathrm{V}_{\mathrm{sc}}(\text{predicted}) - \mathrm{V}_{\mathrm{sc}}(\text{experimental})| \tag{9}$$

$$\text{Average Sum of Absolute Differences (A} = \frac{\text{Absolute Error}}{number\ of\ test} \tag{10}$$

$$\mathrm{V}_{sc} = V_f + R_v + \frac{f_c{}^{0.6833}}{5.687} - (AR_v+0.001)^{\frac{f_c R_c}{10}}\left(\frac{f_c}{82} + R_c{}^{0.81}\right) + d^{(0.7R_t)\left(0.284-d+R_c{}^{\frac{f_c}{10}}\right)} + 0.72^{R_t(0.4+d)^{(R_c+A)}} - d^{\left((R_v+0.06)^{\left(d+\frac{f_c}{104}\right)}+A^{d^{(0.7-V_f)}}\right)} \tag{11}$$

Based on the proposed equation, some diagrams were presented to evaluate the shear behavior of FRC beams (Fig. 13). Fig. 13a shows the effect of fiber hybridization on the shear strength of FRC beams without stirrups. The total fiber volume fraction is assumed to be 2%, and these fibers are supplied with different ratios of steel and polypropylene fibers. The synergy effect of the fibers is evident. The hybrid beams with any ratio have higher shear strength than single fiber beams. According to this diagram, the optimum ratio for the hybrid fiber is 0.5% of polypropylene fibers and 1.5% of steel fibers (for the compressive strength range of 20 to 60 MPa). This hybrid ratio increases the scaled shear strength by 27% compared to the sample containing 2% steel fibers. As shown in Fig.13-a, concrete compressive strength has a uniform direct impact on the shear strength of beams. In Fig. 13-b, the effects of stirrups and fibers combination and the size effect are investigated. According to ACI-318 [4], we can replace the required minimum stirrups with 0.75% steel fibers. However, this replacement by polypropylene fibers may not be suitable (Fig. 13-b).

As shown in Fig. 13-b, shear strength increases with increasing the sample size. This effect may be due to the uniform distribution of fibers in the samples and the homogeneity of materials. Adding stirrups to RC samples increases the mean shear strength by 0.64 MPa, on average. This increase also applies to SFRC, but the samples containing polypropylene fibers show a 0.74 MPa increase in shear strength.

Therefore, polypropylene fibers have a better performance in combination with stirrups. This effect is due to their more uniform distribution and failure mechanism at the cracks [18].

4- Conclusion

In this study, the effects of stirrups, concrete compressive strength, polypropylene fibers, steel fibers, and their hybrids on the FRC beams shear strength are investigated. To this end, 24 FRC beams were experimentally examined. Moreover, a model for simulating these beams' shear strength was presented based on experimental samples. The results of this study can be summarized as follows:

- Samples with hybrid fiber result in the best shear performance. The improvement in results was significantly higher than samples containing steel fibers (27% increase in shear strength compared to the sample containing 2% steel fibers). In addition, polypropylene fibers have better performance with stirrups compared to other fiber-reinforced samples.
- The proposed model accurately simulated experimental results that were not used in equation discovery. The value of R^2 of this model was 0.868 for all samples, which is a suitable value due to the complexity of the problem.
- According to the results obtained from the analysis of the proposed model, a hybrid of 1.5% steel fiber and 0.5% polypropylene fiber is the optimal volume fraction to achieve the highest shear strength. This combination is proposed for a total of 2% of fiber volume fraction, and for other values, the proposed model can be used to determine the optimal ratio.

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