Evaluation of Shear Strength for Steel Fiber Reinforced Concrete Beams

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Abstract— In this paper, shear strength of steel fiber reinforced concrete (SFRC) beams without stirrups is predicted using a rational and unified mechanical approach. Based on forces equilibrium conditions of the shear transfer mechanisms through the diagonal shear crack, the design equations have been developed. Relation for the shear resistance of steel fibers is proposed as a function of the post-cracking strength based on: 1) ultimate crack opening limit-based geometrical condition, 2) crack width-based constitutive tension softening law and 3) the 45-degree truss model. Based on a semi-empirical mixture rule, the post-cracking strength of SFRC is estimated which accounts for fiber content, fiber aspect ratio and the fiber efficiency factors of length, orientation and shape. Using an empirical equation, the concrete contribution to shear is obtained as a function of compressive strength. The shear strength predictions have been validated with 253 experimental results from 22 different investigations and showed a good agreement which strongly support the proposed analytical approach. Compared to the other models from the literature, the proposed method can be used in design practice for predicting the shear strength of SFRC beams without stirrups where most of the predictions agree conservatively with the experimental results. Accordingly, the proposed approach can be applied across a practical range of concrete strengths, shear span/depth ratios, fiber factors and types and steel ratios. Additionally, a parametric study is reported for the factors affecting the shear strength of SFRC beams.

Keywords— Concrete beams; ultimate shear capacity; fiber volume; fiber aspect ratio; steel fibers.

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1 INTRODUCTION

The contribution of steel fibers parameters has been studied on the structural behaviour of the reinforced concrete beams over many years [1]. It was found that steel fibers could replace partially or fully the stirrups. When principal tensile stresses within the shear span of a concrete beam without stirrups exceed the tensile strength of concrete, diagonal cracks develop in the web, eventually causing shear failure. The addition of randomly oriented short discrete steel fibers to concrete matrix, improves the post-cracking tensile strength of concrete and the resistance to cracks growth [1,2], and, hence significantly enhances the shear strength of reinforced concrete beams. To confirm the effectiveness of steel fibers as shear reinforcement, many experimental programs [3-15] have been conducted on steel fiber reinforced concrete (SFRC) beams. Fibers are used to boost the shear capacity of concrete or to replace, partially, the vertical stirrups in structural members which will avoid the congestion of shear reinforcement at high shear zones.

There are limited approaches to predict the shear strength of SFRC beams under different fiber and reinforcement conditions although some limited semi-empirical relations have been suggested to determine the ultimate shear capacity of SFRC beams [6,10]. In this paper, a general analytical method is proposed for predicting the shear strength of SFRC beams without stirrups. The method is applicable across practical ranges of concrete strengths, shear span ratios and fiber volume contents and aspect ratios. The analytical predictions of the proposed method are validated by the available experimental results in the literature and found to agree conservatively with the experimental results of several previous investigations.

2 CONTRIBUTION OF STEEL FIBERS IN THE SHEAR CARRYING CAPACITY

In this section, the shear carrying capacity of the steel fibers is derived as a function of the different fiber parameters: fiber volume, fiber aspect ratio and fiber shape.

2.1 Post-cracking response and shear resistance of steel fibers

After the appearance of diagonal cracking, the available experimental results [3-15] confirm that there is a substantial reserve strength in SFRC beams failing in shear. This trend is attributed to the significant post-cracking tensile strength of SFRC. After composite cracking, the load is transformed to the fibers at the crack interface as observed in direct tension tests [1,2]. Due to fibers debonding, the tensile stress response abruptly drops and is arrested at a certain level by the pullout resistance of the fibers. This stress level is defined as the post-cracking tensile strength (σ_{pc}) [2]. As the crack width increases, the pullout resistance decreases and accordingly vanishes at the maximum pullout length where the maximum crack width (W_{max}) is half the fiber length. For fiber content less than 3.0% that is practically used, the post-cracking strength is smaller than the tensile strength of SFRC. Fibers intercepted by the crack, augment shear resistance in SFRC beams through the dowel action mechanism of steel fibers.

Based on that and on the diagonal crack geometry relative to the shear behavior of SFRC beam as shown in Fig. 1, the following items have been considered in the derivation of the predictive equations of shear carrying capacity of steel fibers:

1. Similar to the conventional stirrups, the contribution of steel fibers to shear resistance after the formation of shear cracks is evaluated by the traditional truss model

where a crack inclination of 45-degree is assumed in the web as shown in Fig. 1.

2. To account for the variation of post-cracking tensile stress with the crack width (W) and hence, the change in the average shear resistance of steel fibers along the diagonal crack, the principal tensile stress $\sigma_{sf}(w)$ is expressed by the following tension softening law [2]:

$$\sigma_{sf}(w) = \sigma_{pc}\left[1 - \frac{W}{W_{max}}\right]^2 \qquad (1)$$

3. As shown in Fig. 1, the width of main diagonal crack is supposed to vary linearly from a maximum value Wm at the tension steel level to zero at the bottom of compression zone.

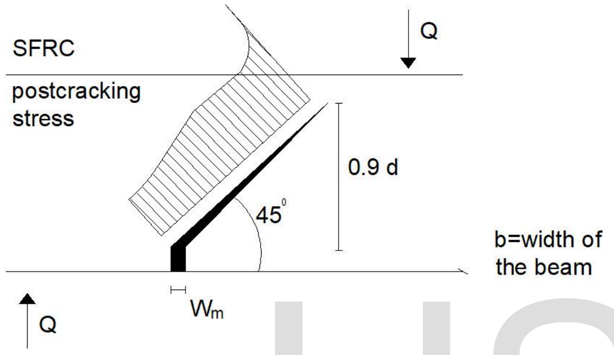

Fig. 1. Crack Geometry Relative to Fibers Shear Resistance in SFRC Beam.

2.2 Post-cracking tensile strength of SFRC

To evaluate the post-cracking strength for different types of concrete and steel fibers, the simple rule of mixture is not valid. Based on the experimental results [2, 16-18], semi-empirical relation is proposed here to modify the composite mixture rule for the following reasons:

1. Due to the fact that the short discrete steel fibers are placed in a randomly oriented and distributed manner, the fiber volume fraction v_f, fiber aspect ratio (l_f/ϕ_f) and fiber efficiency factors for length (η_l) and orientation (η_o) are introduced in the governing relation.
2. Due to frictional effects, the randomly oriented steel fibers bridging a crack plane provide a pull-out resistance higher than predicted from a pure micromechanics analysis or mixture rule.
3. The deformed fibers provide more anchorage and better pull-out resistance and toughness than that of straight or plain fibers. As a result, the proposed relation accounts for the effect of fiber shape and concrete matrix type using a fiber shape efficiency factor (η_s).
4. Depending on the micro-failure mechanism of steel fibers, the basic relation of (σ_{pc}) considers the effect of fiber fracture stress (σ_{fu}) and the fiber-matrix interfacial bond strength (τ_u).

The post-cracking strength is expressed by the modified composite mixture rule as:

$$\sigma_{pc} = \mu\ \eta_o\ \eta_l\ \eta_s\ v_f\ \sigma_{fu} \qquad (2)$$

where μ is an empirical dimensionless factor. For fibers to be randomly oriented in the space, the fiber length should be smaller than the dimensions of beam section which leads [6, 15] to $\eta_o = 0.41$.

An approach has been suggested [19] and used here for predicting the post-cracking tensile strength (σ_{pc}) of SFRC beams, which depends, among other factors, on the volume fraction, shape, aspect ratio, and surface characteristics of the fiber and on the properties of the concrete matrix:

$$\sigma_{pc} = 0.28\ F\ \sqrt{f_c'} \qquad (3)$$

where f'_c is the cylindrical compressive strength of concrete and F is the fiber factor expressed as the following equation:

$$F = \beta\ v_f\ (\frac{l_f}{\phi_f}) \qquad (4)$$

where β is the factor for fiber shape and concrete type and considered as 1.0 for hooked or crimped steel fibers, 2/3 for plain or round steel fibers with normal-weight concrete and 3/4 for hooked or crimped steel fibers with light-weight concrete.

2.3 Proposed equation for shear resistance of steel fiber

Due the linear variation of diagonal crack width in the SFRC beam, shown in Fig. 1, the pull-out resisting stress is not constant. Consequently, the shear carrying capacity of steel fibers V_{sf} is calculated by integrating the post-cracking remaining stress of SFRC along the crack and projecting vertically to equilibrate a part of the beam shear load Q. The crack geometrical condition and the constitutive tension softening law of Section 2.1 are used in joint with the 45-degree truss model to develop the proposed relation for the shear carrying capacity of steel fibers. At distance S along the diagonal crack, the crack width W is given from the crack geometry by:

$$W = (5/0.9d\sqrt{2})W_m \qquad (5)$$

Then, the incremental distance dS is expressed as:

$$dS = (0.9d\sqrt{2}/W_m)dW \qquad (6)$$

The incremental dowel force of steel fibers is given as a function of the post-cracking stress $\sigma_{sf}(w)$ and incremental distance dS in the form:

$$dp = \sigma_{sf}(w)bdS \qquad (7)$$

The vertical component of shear force of fiber resistance along the diagonal crack is derived from integration of Eq. (7) as:

$$V_{sf} = \int_0^{0.9d\sqrt{2}} \sigma_{sf}(w)\,\frac{b}{\sqrt{2}}\,dS \qquad (8)$$

From Eqs. (6) and (8), the value of V_{sf} is obtained as:

$$V_{sf} = \frac{0.9bd}{W_m}\int_0^{W_m} \sigma_{sf}(w)dW \tag{9}$$

Introducing Eq. (l) for the tensile stress-crack width relation leads to:

$$V_{sf} = \frac{0.9db}{W_m}\int_0^{W_m}\left[1-\frac{W}{W_{max}}\right]^2 dW \tag{10}$$

$$V_{sf} = 0.9bd\sigma_{pc}\left[1-\frac{W_m}{W_{max}}+\frac{1}{3}\left(\frac{W_m}{W_{max}}\right)^2\right] \tag{11}$$

From available test results [9, 16], the following ultimate crack opening limit at the failure of SFRC beams in shear is established here and related to the maximum pull-out length by:

$$W_m = W_{max}/8 \tag{12}$$

From Eqs. (11) and (12), the shear stress carried by steel fibers, Q_{sf} is expressed in terms of the post-cracking tensile strength as:

$$V_{sf} = 0.792\ \sigma_{pc} \tag{13}$$

Using Eq. (3) for σpc in Eq. (13), the shear resistance of fibers is evaluated as:

$$V_{sf} = 0.23\ \beta\ v_f\ \left(\frac{l_f}{\phi_f}\right)\sqrt{f_c{}'} \tag{14}$$

3 SHEAR STRENGTH OF SFRC BEAMS

Shear in reinforced concrete is a complex phenomenon that has so far defied purely analytical prediction. The concepts that underline current design practice [1] are based partly on test evidence and partly on successful long-term experience with satisfactory structural performance. Even more rational analyses, such as the softened truss approach [20], contain important semi-empirical relationships of cracked concrete in tension, compression and shear. The differences between the shear strength equations are the result of considerable scatter of the experimentally observed shear strengths. Consequently, the acceptance of conservative lower limits for design code equations of concrete shear resistance is valid.

3.1 Shear equilibrium requirements in SFRC beam

To formulate the equilibrium requirements for a loaded SFRC beam with web reinforcement, it is necessary to all external and internal actions that may be present. The free body diagram of a part of the shear span of a simply supported SFRC beam, subjected to point loads is examined in Fig. 2. The external shearing force Q is considered to be resisted by:

1. The shear resistance of un-cracked SFRC across the compression zone which sum up to Q_{cy}.
2. The frictional shear force Q_a due to aggregate interlock action along the crack surfaces.
3. The transverse shear force induced in the main flexural steel by dowel action Q_d; and
4. The shear reinforcement resistance Q_s due to stirrups and discrete steel fibers.

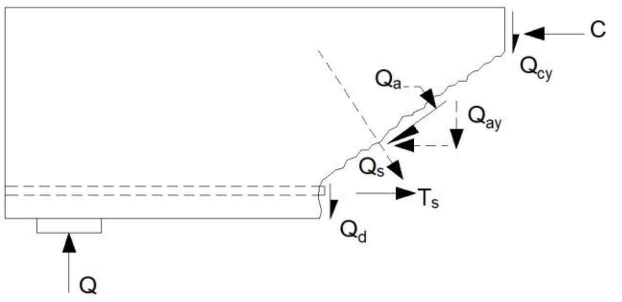

Fig. 2. Forces at Diagonal Crack of SFRC Beam.

The equilibrium of shear forces in the vertical direction, y gives:

$$Q = Q_{cy} + Q_{ay} + Q_d + Q_{sy} \tag{15}$$

Since the individual contributions from each of the first three internal shear components are difficult to estimate, they are commonly lumped together and denoted by Q_c, the concrete contribution to shear. The component Q_{sy} in SFRC beams is given by the sum of the vertical component of the fiber pull-out forces along the inclined crack Q_{sf} and the vertical component of stirrups shear resistance Q_{st}. Thus, Eq. (19) may be rewritten as:

$$Q = Q_c + Q_{sf} + Q_{st} \tag{16}$$

3.2 Contribution of concrete in shear

The concrete contribution to shear Q_c is assumed to equal to the shear strength of a beam without stirrups, which in turn, is taken equal to the first inclined crack shear load. However, the application of existing non-fibrous concrete code equations [1,21] for computing the fiber concrete contribution to shear is not valid because of the following experimental observations [3-15] of fibers inclusion effect on the concrete shear resistance in SFRC beams without stirrups:

1. For the same concrete strength, the cracking shear load was seen to increase with the increase of fiber factor. The improvement in the composite compressive strength with the fiber factor increase, enhances the shear resistance of un-cracked SFRC across the compression zone.
2. For the same steel ratio, a steady increase in the cracking shear strength was observed with the fiber factor increase. The presence of fibers improves the effectiveness of dowel resistance of main steel by enhancing the tensile strength of concrete in the splitting plane along steel bars.
3. The shear friction strength is increased due the fiber dowel action and the aggregate interlock.

The diagonal crack shear strength of SFRC beam is reached when the principal tensile stress in the shear span equals SFRC tensile strength, which is proportional to the square root of

SFRC compressive strength $f'c$ [1,2]. The contribution of concrete in shear can be expressed by the provided equation in the ACI318M-14 [21] as:

$$Q_c = (0.16\lambda \sqrt{f_c}' + 17\rho)\ bd \quad \leq 0.29\lambda\sqrt{f_c}'\ bd \tag{17}$$

Where λ is the light-weight concrete modification factor with value of 1.0 for normal-weight concrete and 0.75 for light-weight concrete and ρ is the ratio of the longitudinal steel.

3.3 Proposed design equation for ultimate shear strength

A suitable design equation may be obtained by considering the ultimate shear strength to consist of two terms. The first term is given by Eq. (17) and accounts for the contribution of concrete. The second term consider the shear resistance of steel fibers and is given by Eq. (14). The following formula is proposed for predicting the shear carrying capacity Q_u of SFRC beams:

$$Q_u = e\ (Q_c + Q_{sf}) \tag{18}$$

$$e = 1.0 \qquad a/d > 2.8 \tag{19-a}$$

$$e = 2.8d/a \qquad a/d \leq 2.8 \tag{19-b}$$

where e is a non-dimensional factor that takes into account the effect of arch action. For reinforced concrete deep beams [21], the value of e is (2.5d/a). But as the inclusion of fibers improves the arch action, through enhancing the compressive strength of concrete, a higher value of e is not unreasonable. Similar finding is given elsewhere [10, 12]. The value of e was based on an elaborate statistical study of available testing results of deep beams. Using suitable substitutions in Eq. (18) from Sections 2.3, 3.2 and 3.3, Q_u is predicted by:

$$Q_u = e\ [0.16\lambda \sqrt{f_c}' + 17\rho + 0.23\ \beta\ v_f\ (\frac{l_f}{\phi_f})\ \sqrt{f_c}']\ bd$$

$$(0.16\lambda \sqrt{f_c}' + 17\rho) \quad \leq 0.29\lambda\sqrt{f_c}' \tag{20}$$

4 COMPARISON WITH EXPERIMENTAL RESULTS

A comparison of the predicted shear strength Q_{up} of SFRC beams using the proposed general analytical equation and the experimental measured failure shear stress Q_{ue} as reported in twenty-two different investigations [3, 4, 10, 15, 22-39] is reported. The analytical predictions of two hundred and fifty-three tests are presented for a wide range of variables:

- Compressive strength of concrete ranging between 20.0 to 80.0 Mpa,
- Shear span-to-effective depth ratio ranging between 1.5 to 5.0,
- Fiber factor ranging between 0.25 and 2.0,
- Steel fiber types including hooked, crimped, plain or round fibers,
- Fiber volume content ranging between 0.25 to 2.0%,
- Fiber aspect ratio ranging between 19 and 133.

Compared with experimental shear strength data, the predicted values of shear strength are quite acceptable under different conditions. For 253 tests of SFRC beams with hooked, crimped and plain fibers, the mean value of experimental to predicted shear strength ratio (Q_{ue}/Q_{up}) is 1.11 with a standard deviation (SD) as 0.16. The same comparison between analytical and test results is shown in Fig. 3 where most of the predictions agree conservatively with the experimental results. The proposed approach for computing shear strength of SFRC beams without stirrups can be used with confidence in design practice for all practical ranges of concrete strength, steel fiber factor and types and shear span-to-depth ratio.

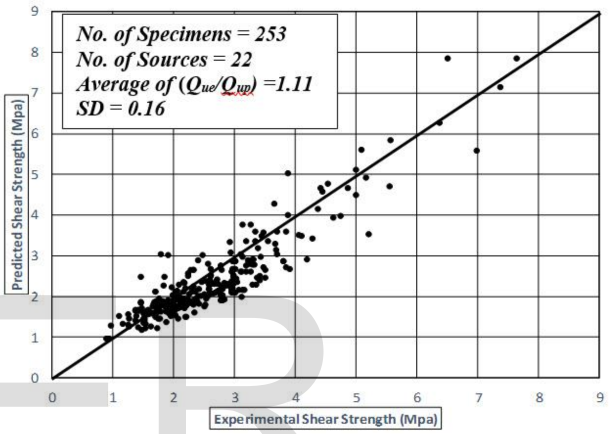

Fig. 3. Comparison of Experimental and Predicted Shear Strength of SFRC Beams.

5 COMPARATIVE STUDIES WITH OTHER SHEAR STRENGTH EQUATIONS

Comparative studies between the proposed shear model with similar existing models from the literature, have been performed to show the effectiveness of the proposed model in computing the shear strength of SFRC beams. Four models from the literature [15, 19, 40 and 41] have been applied to the same two hundred and eighty-seven tests. The governing strength equations for shear models given in [15, 19, 40 and 41] are respectively expressed by the following equations:

$$Q_u = [0.167 \sqrt{f_c}' + 0.37\ \tau\ v_f\ (\frac{l_f}{\phi_f})]\ bd \tag{21}$$

$$Q_u = [(0.167 + 0.25F)\ \sqrt{f_c}']\ bd \tag{22}$$

$$Q_u = [0.35\ (1 + \sqrt{\frac{400}{d}})\ (f_c')^{0.18}\ ((1+F)\ \rho\ \frac{d}{a})^{0.4} + 0.9\eta_o\tau F]\ bd \tag{23}$$

$$Q_u = [\rho + \frac{\rho}{\upsilon} + \frac{d}{a}\ (\frac{\rho\ ft'(\rho+2)(\frac{ft'a}{d} - \frac{3}{\upsilon})}{a/d} + ft') + \upsilon\ ]\ bd \tag{24}$$

Consequently, the comparison between analytical and test results for these models are shown in Figs. 4 through 7.

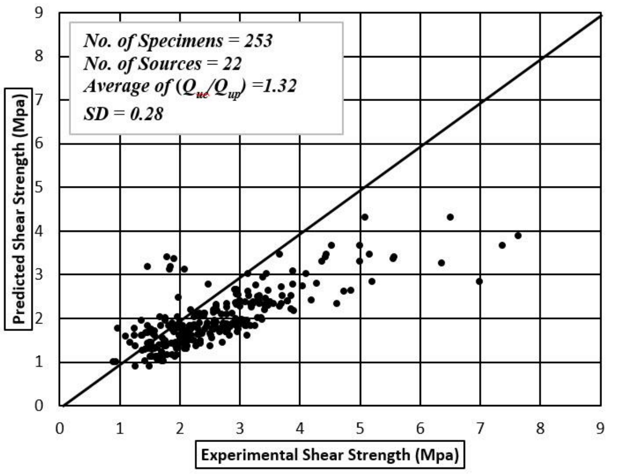

Fig. 4. Comparison of Experimental and Predicted Shear Strength of SFRC Beams [15].

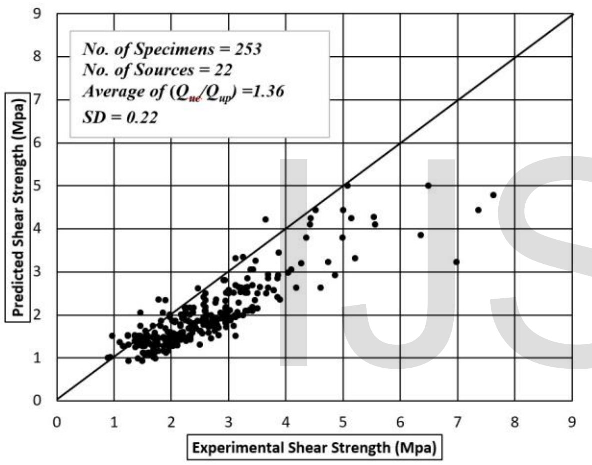

Fig. 5. Comparison of Experimental and Predicted Shear Strength of SFRC Beams [19].

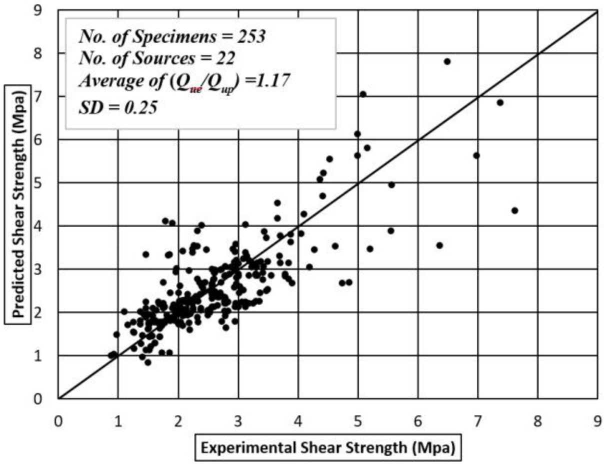

Fig. 6. Comparison of Experimental and Predicted Shear Strength of SFRC Beams [40].

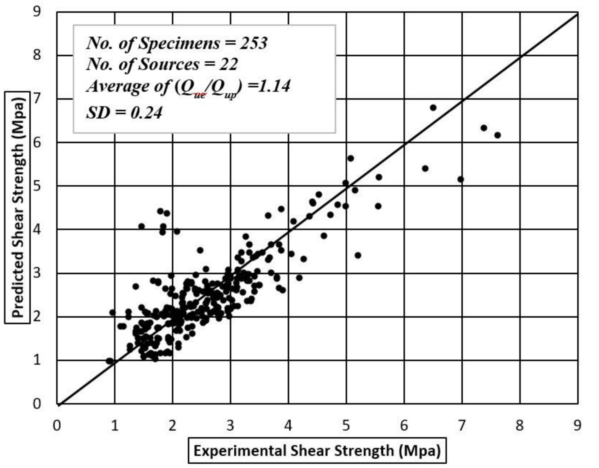

Fig. 7. Comparison of Experimental and Predicted Shear Strength of SFRC Beams [41].

For the whole comparative study, the mean values of (Q_{ue}/Q_{up}) are 1.32, 1.36, 1.17 and 1.14 with Standard deviations of values 0.28, 0.22, 0.25 and 0.24 respectively for the models from [15], [19], [40] and [41]. Compared to the proposed model, the shear strength predictions of other four models are more conservative. It is clear that the proposed approach for computing shear strength of SFRC beams can be used with confidence and economy in the design.

6 PARAMETRIC STUDIES FOR THE PREDICTED SHEAR STRENGTH

Parametric studies are presented for the factors affecting the predicted shear capacity of SFRC beams. The influence of concrete strength $f'c$, fiber factor F, shear span ratio (a/d) and longitudinal reinforcement ratio on the predicted shear strength Q_{up} are shown respectively in Figs 8, 9, 10 and 11. The study of these figures highlights the following facts:

1. The shear strength of SFRC beams increases with the increase in concrete compressive strength or fiber factor. Also, it increases significantly with the decrease of (a/d) ratio. The change in f'_c from 20 to 60 Mpa increases Q_{up} by 64.3%. The change in F from 0.5 to 2 leads to 109.7% increase in Q_{up}. Decreasing (a/d) ratio from 3.0 to 1.0 increases Q_{up} by 125.3%. Also, 24.23% increase in Q_{up} is obtained for the change in ρ from 1.0 to 3.0%.
2. The shear capacity tends to show greater sensitivity to the combined change in the four governing parameters. Due to the combined increase in f'_c (20 to 60 Mpa) and F (0.5 to 2), Q_{up} increases by 254.3%. Due the same increase in f'_c and the decrease in (a/d) ratio (3 to 1), the increase in Q_{up} is 360.1%. The same increase in F and the decrease in (a/d) ratio (3 to 1) leads to 372.6% increase in Q_{up}. The increase of both f'_c (20 to 60 Mpa) and ρ (1.0 to 3.0%) increases Q_{up} by 88.56%. The combined increase in F (0.5 to 2) and ρ (1.0 to 3.0%) increases Q_{up} by 133.9%. Decreasing (a/d) ratio (3 to 1)

and increasing ρ (1.0 to 3.0%), increases Q_{up} by 247.8%.

3. The shear strength increase is mainly due to the enhancement of concrete shear resistance and the improvement of dowel resistance of steel fibers. Also, fiber reinforcement improves the arch action in short beams (a/d < 2.8) as effectively as it improves the beam action in shallow beams (a/d > 2.8).

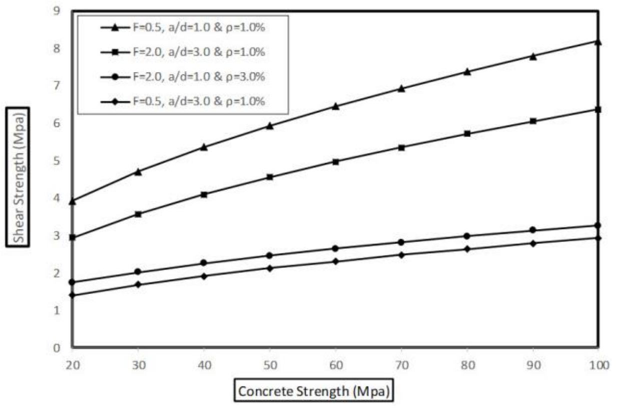

Fig. 8. Effect of Concrete Strength on Predicted Shear Strength of SFRC Beams.

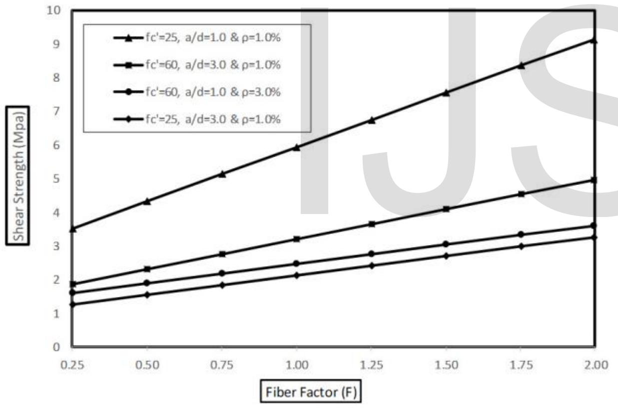

Fig. 9. Effect of Fiber Factor on Predicted Shear Strength of SFRC Beams.

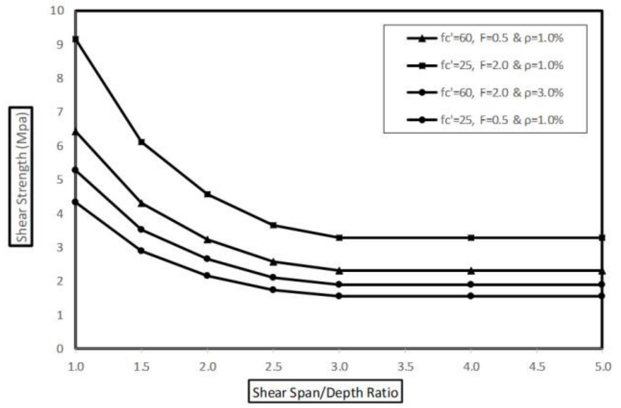

Fig. 10. Effect of Shear Span/Depth Ratio on Predicted Shear Strength of SFRC Beams.

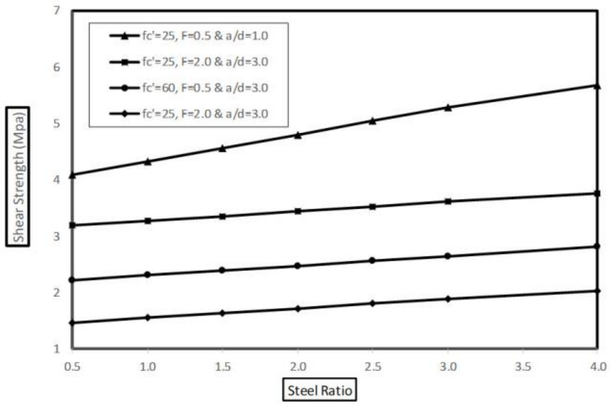

Fig. 11. Effect of Steel Ratio on Predicted Shear Strength of SFRC Beams.

7 CONCLUSION

A general and rational procedure is developed to predict the shear strength of SFRC beams without stirrups. From the analytical, validation, parametric and comparative studies presented in this paper, the following conclusions are drawn:

1. The comparison of the analytical predictions with two hundred and fifty-three experimental data, presented for a wide range of variables in twenty-two different investigations, confirms that the ultimate shear strength of SFRC beams without stirrups can be conservatively evaluated using the proposed analytical approach. Compared with the proposed model, the existing approaches overestimate the predicted shear strength of SFRC beams.
2. The parametric study indicates that the shear strength increases with an increase in concrete strength, fiber factor and tensile steel ratio. For short beams (a/d <2.8), it also increases with a decrease in (a/d) ratio due to the presence of arch action. A steady increase in the shear strength ratio is observed with the fiber factor increase. For the same fiber factor, the strength ratio is seen to increase with concrete strength and steel ratio.
3. The good agreement between the experimental and analytical results supports the reliability of the proposed crack opening limit-based geometrical condition and crack width-based postcracking constitutive law along with the 45-degree truss approach in the modelling of the shear resistance of steel fibers. It accounts for the fiber efficiency factors of length, orientation and shape, fiber content and aspect ratio, post-cracking stress-crack width variation and interfacial bond strength.
4. The proposed empirically modified mixture rule can be applied for hooked, crimped, plain and round steel fibers used in SFRC beams. Also, the proposed empirical relation for predicting the concrete contribution in shear is validated for a wide range of concrete strengths, shear span-to-depth ratio and steel ratios. It

can be used with confidence in design purposes for all practical ranges of concrete strength, steel fiber factor and types, fiber volume fraction and aspect ratio, shear span-to effective beam depth ratio and longitudinal reinforcement percentages.

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