Shear Strength Models for Steel Fibre Reinforced Concrete Beams: Current Scenario

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Abstract

This review paper presents a comprehensive comparative analysis of various studies conducted on the shear strength of Self-compacting Concrete (SCC) and Normally Vibrated Concrete (NVC) in order to determine the sustainability and affordability of SCC as a construction material. Compaction is the main factor in concrete production. NVC needs compaction and vibration to remove the entrapped air which is both expensive and time-consuming. But SCC has flow ability and passing ability. Although SCC takes a greater amount of paste content, thereby raising the cost of building material, yet the use of such waste material as fly ash, silica, etc. comes in handy as paste content. Thus, the advantages offered by SCC in terms of increased strength as well as cost reduction makes it a highly desirable construction material. The review has selected the works of some eminent scholars on concrete and has analyzed them through individual as well as comparative perspective. A close analysis has helped filter out relevant works for the current study. This process of selection has proved helpful to include most standard works available in the review. Major findings have been enlisted at the end and ways to improve concrete behaviour have been suggested.

Keywords: Self-Compacting Concrete; Shear Models; Shear Strength; Steel Fibers; Workability; Beams.

1. Introduction

It is a well-known fact that shear capacity is one of determining factors in robust building construction. This capacity is generated by beams having longitudinal structure aided by stirrups which produces a high compression force and tension reinforcement [1-3]. However, the structure alone cannot protect beams from cracks; it requires the right kind of concrete. With the advancement in civil engineering technology, extensive research has been carried out on shear capacity of concrete structures, proposing various models/designs [4-5]. Of these, Self-Compacting Concrete (SCC) has emerged as a promising building material considering its low cost and high performance. It is the latest generation concrete having both low and high grades. It has high deformability and resistance against segregation and bleeding. However, the lack of knowledge and practice of casting SCC and its structural maintenance services pose a serious challenge in its practical utilization in construction concrete industry. Secondly, some experts and designers have a concern that SCC is probably not strong enough in shear and torsional strengths because of some hesitation in mechanisms resisting shear, notably the interlocking mechanism of aggregates [6-8].

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Further, most of the research till date has shown that shear strength is obtained by the contributions of the un-cracked conventionally vibrated concrete (CVC) in the compression zone which ranges from 20 to 40%, interlocking of aggregate ranges from 35% to 50%, and dowel action of the longitudinal steel ranges from 15 to 25% [9-10]. Needless to say, SCC has become a potential area of research globally, producing a substantial body of models and designs vis-à-vis concrete preparation. The present paper attempts to document some of the prominent models and designs in order to select the best out of them.

2. Shear Strength of SCC: History

Over the last three decades a large scale work has been done on the shear strength of concrete with different fibre ratio. Binary and ternary blends of SCC have been reported to have the standard ratio, chiefly due to their environmental impact assessment and cost deduction. Somehow ternary and quaternary blends are not found sufficiently useful. Various experiments have been performed to find out fresh and hard properties of different SCC with mineral admixtures. These primarily include samples having a constant water/binder ratio varying from 0.44 to 0.58 and a total binder/cement content of 450 kg/m³ [11]. It is observed that the ternary use of cement when added with silica fumes provides the best result.

Similarly an experimental study was conducted to evaluate the suitability and ease of various workability test methods of SCC by Soo-Duck et al. (2006) [12]. The findings suggested that SCC is workable when its water binder ratio varies between 0.35 to 0.42. It was clear that SCC used in structural concrete industry should have slump flow values between 620 to 720 mm and L-box test ratio (h2/ h1) ≥ 0.7, J-Ring flow from 600 to 700 mm, slump minus J-Ring flow dia. ≤ 50 mm, or V-funnel test time ≤ 8 sec.

Further, The Taguchi method is applied to determine the outcome of an analytical approach consisting of variable factors. It can predict the combination of standard factors for optimal factor level by measuring the significant variance in factor level. Taguchi’s experiment design theory for optimum design was used by Gesoğlu et al. (2009) [13] to study mix proportions of high strength self-compacting concrete (HSSCC). Best mix proportions were obtained by conducting ultra-Sonic Pulse Velocity Test, Compressive strength and Tensile strength and minimization of Air, Water and permeability.

El-Sayed et al. (2010) [14] derived the equation for designing the shear capacity of the concrete beams reinforced with FRP. Equation 1 was derived from a model and was simplified to provide the design formulae. The designing equation for it is as shown below:

\[ V_{cf} = \left( \frac{\rho_f E_f}{90 \beta_1 f_c^2} \right) \left( \sqrt{f_c^3} \frac{b_w d}{6} \right) \leq \sqrt{f_c^3} \frac{b_w d}{6} \]  

(1)

Fibre, as pointed out above, has a great impact on the shear strength of SCC. Fibre enhances the strength and workability properties of concrete. Fibres used in mix are available in different size distribution of skeletal structure and they are defined on the basis of specific surface area. Iqbal et al. (2016) [15] studied the strength properties of SCC beams using steel fibre. They concluded that steel fibre concrete improved the strength of existing structure. There was about 14 to 58% improvement in cracking load when reinforced with 40mm, 50mm, 60mm diameter bars reinforced in tension side. Voo et al. (2010) [16] calculated the shear value characteristics of beams with fibre-reinforced high performance concrete having no stirrups. They reported that the HPSCRC beams with different testing variables like l/d ratio, i.e. shear span and effective depth value, the type and the volumes of the fibres, etc. It was noted that there was a significant and specific distribution in cracking produced through the web. This cracking was prior to the direction and formation of crack failure. Gao et al. (2020) [17] proposed a shear strength calculation model of polymer fibre reinforced beams without stirrups. He presented a linear Equation 2 to determine shear strength:

\[ \frac{V^e_c}{\sqrt{f_c bd}} = 0.4(k + 0.1) \]  

(2)

The previous models of shear, i.e. ISIS M03-07, ACI 440.1R-15, CSA S806-12, CSA S6-14, JSCE-97, AASHTO LRFD-17, BISE-99, and CNR DT203-06 were unable to reflect the reinforcement ratio properly.

López et al. (2020) [18] calculated the shear strength of continuous and cantilever beams with shear reinforcement ratios varying from 0 to 20%. The results so obtained were checked and validated against Eurocode 2, ACI 318-19 [4], and Model Code 2010. Some other scholars put forward equations to calculate shear strength of concrete beams depending on various parameters. Ruiz et al. (2015) [19] gave his review on shear transfer action in RC beams with rectangular cross section. The governing parameters were also discussed which were a) Shear transfer across reinforced concrete b) Contribution of shear transfer action in slender beams c) Contribution of top part on shear transfer d) Contribution of bottom part on shear transfer. Singh (2017) [20] predicted the ultimate shear strength
capacity of SCC flexural beam members. For it a design model showing the influence of shear strength capacity of SCC beams was presented. Also Singh (2017) proposed a closed forum solution to calculate shear strength capacity of Steel Fibre Reinforced Concrete (SFRC) rectangular beams having no web reinforcement. A theoretical formulation was presented herein for this purpose. Its efficacy was checked with available design guidelines, empirical relations, and experimental test data.

Moving on, some other notable works on shear strength maximization are credited to Yacob et al. (2019) and Mohammed et al. (2019) [21, 22]. Yacob et al. (2019) evaluated the shear strength of geopolymer concrete beams. The test variables were shear span to effective depth ratio with different transverse ratios. All of the beams failed in shear aside from two beams; one had higher a/d proportion and one had small size. These beams failed in flexural-shear mode. All the GC beams showed their high shear strength. Mohammed et al. (2019) evaluated the shear strength of RCC beams prepared with recycled brick aggregates. The main parameters were steel ratio variation (0.82 to 1.23%) and shear span to effective depth ratio.

The authors of this review paper used following five methods of shear design and reviewed them.

i. Compression Field Theory
ii. Truss Approaches with Concrete Contributions
iii. Shear Friction Theory
iv. Strut and Tie Model.
v. Some latest research work on the shear design of reinforced concrete beams.

Figure 1. Flow Chart Showing the Research Methodology

Searching for shear strength data base

Category clustering

Filtering based on category clustering

Analyzing abstracts and filtering irrelevant papers

Filtering based on full text reading

Scanning of References

Analysis of Literature review
These theories have included the American Concrete design guidelines ACI 440.1R-06 [23], the Canada Standard Association, CAN/CSAS806-02, ISIS Canada manual, ISIS-M03-07, the British Institution of Structure Engineer’s guidelines, and the design recommendations provided in the society of the Japan’s Civil Engineers. In addition to this, Modified Compression Field Theory (MCFT) was reviewed and compared with the results obtained experimentally (see Table 1). Moreover Asteris et al. (2017) [24] derived the comparison of the results with the experimental findings demonstrates the ability of artificial neural networks to approximate the compressive strength of self-compacting concrete in a reliable and robust manner. The table given below records some of the universally-acknowledged shear equations. The purpose of presenting them together is to understand their individual as well as relative value.

### Table 1. Different Available Shear Strength Models

<table>
<thead>
<tr>
<th>Design code</th>
<th>Shear strength</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurocode 2 (2004) [25]</td>
<td>$V_{max} = 0.5bd'f_c'v$</td>
<td>$b=$Beam width, $d'=$Effective depth, $f_c'=$Compressive strength of concrete</td>
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<tr>
<td></td>
<td>$v = 0.6 \left(1 - \frac{f_c'}{250}\right)$. $f_c'$ in MPa</td>
<td></td>
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<tr>
<td>Eurocode 2 (2004) [25]</td>
<td>$V_c = \min{(0.9 \cdot 0.6(1 - \frac{f_c'}{250})) \cdot \frac{f_c'}{Y_c} \cdot \frac{1}{\cot \theta + \tan \theta} \cdot \frac{p_{sw}}{Y_c} \cdot \cot g \theta } : 0.90p_{sw}f_{yw} \cdot \cot g \theta$</td>
<td>$p_{sw} = area\ of\ steel\ reinforcement$</td>
</tr>
<tr>
<td></td>
<td>$p_{sw} = f_{yw} \cdot Y_c$ : $0.5 \left(1 - \frac{f_c'}{250}\right)$. $f_c'$ in MPa, $0.4 \leq \cot g \theta \leq 2.5$</td>
<td>$\cot g \theta \leq 2.5$</td>
</tr>
<tr>
<td>ACI Committee 318-95 (1996) [26]</td>
<td>$V_{max} = \frac{5}{6} \sqrt{f_c'b_wC}$. $f_c' \leq 70$ MPa</td>
<td></td>
</tr>
<tr>
<td>CSA A23.3-M04 Committee. [27]</td>
<td>$V_{max} = 0.25f_{bd}$</td>
<td></td>
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<tr>
<td>ACI Committee 318 (2014) [28]</td>
<td>$V_{max} = 0.2f_{bd}$</td>
<td></td>
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<tr>
<td>ACI 440.1R-06 [28]</td>
<td>$V_c = \frac{2}{\sqrt{\pi}} \sqrt{f_c'b_wC}$. $C = kd$</td>
<td>$b'$ = Beam width, $d' =$ Effective depth, $f_c'$ =Compressive strength of concrete</td>
</tr>
<tr>
<td></td>
<td>$K = \sqrt{2p_{n1} + (p_{n1})^2}$</td>
<td>$p_{n1} = reinforcement\ ratio\ in\ flexure$</td>
</tr>
<tr>
<td>CAN/CSA-S806 [29]</td>
<td>$V_c = 0.035\beta_d\beta_v\left(\frac{f_c'}{M_f}\right)^{1/2}b_w'\sqrt{d}$</td>
<td>$\beta_d$ =Inclination of Concrete; $\lambda_d$ =Factor to account for Light weight concrete; $E$, $V$ and $M$ Fibre factors, i.e. elasticity, volume</td>
</tr>
<tr>
<td>JSCE [30]</td>
<td>$V_c = \beta_d\beta_v\beta_c\beta_n\alpha_v\beta_s\beta_m\beta_f\beta_y$</td>
<td>$\beta_s$ = Strength reducing factor of concrete.</td>
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<td></td>
<td>$(V_c)_c = V_c + V_v$</td>
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<tr>
<td></td>
<td>$V_v = \frac{\alpha\beta_d\beta_v\beta_c\beta_n\alpha_v\beta_s\beta_m\beta_f\beta_y}{\sqrt{f_c'b_w}} \leq 0.67\sqrt{f_c'b_w}$</td>
<td></td>
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<tr>
<td>ACI Building Code (1999) [31]</td>
<td>$V_c = 0.17\sqrt{f_c'b_w}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Member sub to Shear &amp; bending)</td>
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<tr>
<td></td>
<td>$V_c = 0.17 \left(1 + 0.07 \frac{K}{k}\right)\sqrt{f_c'b_w}$</td>
<td></td>
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<tr>
<td></td>
<td>(Shear, Bending &amp; axial compression)</td>
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</tr>
<tr>
<td></td>
<td>$V_c = 0.17 \left(1 + 0.29 \frac{K}{k}\right)\sqrt{f_c'b_w}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Shear, Bending &amp; axial tension)</td>
<td></td>
</tr>
<tr>
<td>ACI Building Code (1962) [32]</td>
<td>$V_{uc} = \left(0.157 \cdot \sqrt{f_c'} + 17.2 \cdot \frac{d}{b} \right) &lt; 0.30 \cdot \sqrt{f_c'}$</td>
<td>$\sqrt{f_c'} = a\ measure\ of\ a\ measure\ of\ concrete\ tensile\ strength$</td>
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<tr>
<td></td>
<td>$V_{uc} = \frac{A_{sw}}{bS} \cdot f_{yw} = p_{sw} \cdot f_{yw}$</td>
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<tr>
<td></td>
<td>$V_u = V_{uc} + V_{vi}$</td>
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<tr>
<td>CAN3 (2004) [33]</td>
<td>$V_u = \phi \cdot \beta \cdot \left(\sqrt{f_c'} + \phi \cdot p_{sw} \cdot f_{yw} \cdot \cot \theta \right) \leq 0.25 \cdot \phi \cdot f_c'$</td>
<td></td>
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<tr>
<td></td>
<td>$\beta = \frac{0.4}{b_s}$. $S$ + $1500$ $\frac{f_s}{E_s}$. $\phi = 29^\circ$ + $700 \frac{f_c'}{E_s}$</td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Design Expressions</td>
<td></td>
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<tr>
<td>Zararis (2003) [34]</td>
<td>$V_u = \xi \cdot f_c'^{a_{na}} \frac{X_c}{d} + \left[0.5 + 0.25 \cdot \frac{a}{d}\right] p_{sw} \cdot f_{yw}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\xi = 0.3 \cdot (1.2 - 0.2 \cdot \frac{a}{d})$</td>
<td></td>
</tr>
<tr>
<td>Arslan (2007) [35]</td>
<td>$V_u = 0.12 \cdot \sqrt{f_c'} + 0.02 \cdot \phi \cdot f_c'^{a_{na}} + p_{sw} \cdot f_{yw}$</td>
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</table>
For the above table, it can be deduced that the Eurocode 2 model has a remarkable degree of accuracy to calculate shear strength. ACI 318-2005 model predicts the underestimated shear strength capacity. Comparatively, the ACI model is not as precise as the Eurocode 2 model because the former has normal standard deviation value 0.33 for lower grades and 0.44 for higher grades. Similarly, the deviation values in the CSA A23.3M04 model are 0.76 for lower grades and 0.83 for higher grades which is considered overestimated and can lead to unsafe design. It is noted that these models apply the modified compression field theory to calculate shear value still. However, the model proposed by Singh (2015) yields more accurate results [42]. This is because unlike CSA A23.3-14, which is the result of merging the modified compression field theory with a sectional based approach, the proposed model incorporates the modified compression field theory into a strut and tie based approach. Also the results shown in Euro 2 code 2004 [43] are comparable. Results showed that the characteristics of shear strength of RC beams without shear reinforcement compared well to other codal provisions. Comparing the codes, it was realized that the prediction uniformity of the low strength RC beams was significantly enhanced by SFRSCC. In contrast to those without shear reinforcement, more cracks of larger widths were found in the beams with shear reinforcement. In contrast to the corresponding b, beams subject to cyclic loads exhibited wider crack widths. The first diagonal shear crack load of beams without shear reinforcement was between 42-92% of the failure load, while 42-58% of the failure loads ranged from those of beams with shear connections. There was lower post-diagonal shear resistance to the SFRSCC concrete beams without shear connections. It is proposed that the reinforcing bar anchorage in SFRSCC RC beams should be adequately constructed to ensure that no premature failure occurs under cyclic loads.

3. Conclusions

The review of the various models to calculate the shear strength of Self-Compacting Concrete (SCC) gives out some significant results. SCC is more cost-effective and environment-friendly as it uses fly ash, silica, etc. as ingredients. It has another peculiar advantage over normal concrete in that it does not need vibrator to settle the paste content, thereby saving time in the preparation of concrete. Some concrete specialists have experimented with the impact of different types of fibre on concrete and have concluded that by and large, the fibre increases the shear capacity of SCC. Further, binary, ternary and quaternary blends made by mixing concrete with fly ash, limestone powder, granite filler, and micro silica give different results. Of these, the binary has the standard ratio. Further, Contrasting information and different codes and conditions, the conversation might be finished up as follows:

- ACI code thinks little of the shear limit of concrete beams with no shear reinforcement. It gives lower shear estimations of RCC beams as contrasted with the test Specimens. ACI Code emphasizes the importance of boundaries like shear length to profundity proportion, compressive strength of concrete only, without considering the impact of longitudinal steel proportion;

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Equation</th>
<th>Shear Capacity of Composite Member</th>
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<tbody>
<tr>
<td>Russo et al. (2013)</td>
<td>$V_u = \frac{1 + \frac{4.58}{d}}{\sqrt{T + \frac{d}{25 - d^2}}} \cdot [0.4 - f'<em>c + 0.5 \cdot \rho_t \cdot f'</em>{yc} \cdot f_y'(a - 0.45)^{\frac{2}{3}}] + 0.36 \cdot p^2 \cdot f'<em>{yc} \cdot (p</em>{aw} - f_{yw})^{0.66}$</td>
<td></td>
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<tr>
<td>Campione et al. (2014)</td>
<td>$V_c = \left(0.886 \cdot j_0 \cdot \sqrt{\frac{d}{b}} \sqrt{\frac{d}{b}} + \frac{1.168 + j_0 \cdot s_m}{\sqrt{b \cdot d \cdot p}} \cdot \rho_t \cdot \sqrt{f'_{yc}}\right) \cdot \frac{d}{b}$</td>
<td></td>
</tr>
<tr>
<td>Weng et al. (2001)</td>
<td>$(V_{n,comp}) = (V_{n,0}) \cdot (V_{n,1})$</td>
<td></td>
</tr>
<tr>
<td>Liu et al. (2012)</td>
<td>$(V_{n,0}) = 0.6 \cdot f'<em>{yc} \cdot A</em>{sw}$</td>
<td>$(V_{n,1}) = \min [(V_{n,RC1}) \cdot (V_{n,RC2})]$</td>
</tr>
<tr>
<td>Choi et al. (2015)</td>
<td>$V_{max} = \frac{1}{2} f_c' \cdot c_p \cdot b \leq V_f$</td>
<td>$V_f = \text{shear corresponding to the flexural strength of the Member, } c_p = \text{depth of the concrete compression zone determined by using the force-equilibrium and the compressive strain } \alpha_{eq}=0.003$</td>
</tr>
<tr>
<td>Singh (2016)</td>
<td>$\tau_c = 0.87 (\mu) + 0.67 (f_c) - 0.64 + (0.3 f_c') \alpha_{eq}$</td>
<td></td>
</tr>
</tbody>
</table>
• Canadian code does not consider the impact of shear span to effective depth ratio and longitudinal steel proportion. It chiefly focuses on the compressive strength of concrete;

• The model presented by Singh (2016) [41] is quite conservative in estimating the shear strength of concrete with steel fibers. There is a scope to improve the presented formulae to enhance compressive strength and save shear reinforcement by deriving it for higher grades.

4. Declarations

4.1. Author Contributions

Conceptualization, R.S. and H.S.; investigation, R.S. and H.S.; resources, R.S. and H.S.;; writing—original draft preparation, R.S. and H.S.; writing—review and editing, R.S. and H.S.; visualization, R.S. and H.S. All authors have read and agreed to the published version of the manuscript.

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4.4. Conflicts of Interest

The authors declare no conflict of interest.

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