INVESTIGATION OF THE SIZE EFFECT IN SHEAR OF STEEL FIBER REINFORCED CONCRETE (SFRC) SLENDER BEAMS

M. Zarrinpour (1), J.-S. Cho (2) and S.-H. Chao (1)

(1) University of Texas at Arlington, USA
(2) Engineer at Stueve Construction Co. Algona, Iowa, USA

Abstract

Significant shear strength reduction with the increase of the height of slender plain concrete beams with no web reinforcement is a well-known phenomenon called size effect. The American Concrete Institute’s ACI 318 Building Code allows steel fiber reinforced concrete (SFRC) to replace conventional minimum shear reinforcement in slender beams; however, the beam’s height is limited to 610 mm (24 in.) This is due to the fact that, except for a very few tests, the majority of test results on shear behavior of SFRC beams has been evaluated on specimens with an effective depth of 178 mm (7 in.) to 572 mm (22.5 in.). The object of this research was to investigate the size effect of SFRC beams in shear as well as the long-term shear performance (up to 33 months after casting) of SFRC beams by experimentally testing four pairs of SFRC slender beams with an extended observance time after casting. These beams had total heights of 457 mm (18 in.), 610 mm (24 in.), 915 mm (36 in.), and 1220 mm (48 in.), and one pair of beams was 457 mm (18 in.) high companion beams made of plain concrete. The only variable parameter was the overall depth, while the remaining key factors were held constant including shear span to effective depth ratio of 3.5, longitudinal reinforcement ratio (approximately 2.7%), compressive strength of concrete (targeted at 42 MPa), steel fiber volume fraction (0.75%), and types of steel fiber (hooked-end fibers conformed to ACI requirements). Test results indicate that the normalized shear stress at failure is substantially increased for all SFRC specimens as a result of fiber inclusion. In spite of the various effective depths of the specimens, the discrepancy in normalized shear strengths was relatively marginal. Also, even though the specimens were tested at a quite high age ranging from 502 to 1005 days and exposed to weather, no degradation was observed in terms of their shear behavior.

1. INTRODUCTION

A large body of research conducted on shear behavior of reinforced concrete (RC) slender beams with no shear reinforcement has demonstrated the existence of size effect on ultimate shear stress [1-4], in which shear strength (in terms of stress) decreases as the beam depth increases. Therefore, the test results from rather small beams are not applicable to large-scale
beams. Size effect on ultimate shear stress for plain concrete is explained by the increased inclined crack spacing when the slender beam becomes deeper. If the strain in concrete between two consecutive cracks is neglected, the average width of the inclined cracks can be approximately represented by the product of the average crack spacing and the strain of the reinforcement. Therefore, at a given longitudinal bar strain, an increase in crack spacing causes wider cracks, thereby reducing aggregate interlock capacity in resisting the shear [2].

Based on this assumption, any factor causing an increase of either crack spacing or tensile strain in longitudinal reinforcement can lead to an increase in crack width and subsequent reduction of the aggregate interlock capacity, thus exacerbating the size effect. This can happen when using reinforcement with smaller modulus of elasticity or an insufficient reinforcement ratio [5-7]. On the other hand, any factor which enhances aggregate interlock such as using larger aggregate size or placing layers of longitudinal reinforcement along the depth of the beam or using stirrups can minimize the size effect [4, 5].

It is well-established that addition of discrete steel fibers into concrete can considerably increase the shear strength. [8-14]. While using steel fiber-reinforced concrete (SFRC) to replace conventional mild steel shear reinforcement has been permitted by design code [15], it is unclear if size effect is also a concern in SFRC slender beams. This concern is reflected in the ACI code where the maximum beam overall depth, $h$, is not allowed to be more than 610 mm (24 in.). Nevertheless, some researchers have suggested that size effect on ultimate shear stress shall be less serious for SFRC beams [16]. Information collected in Figure 1 illustrates the relation between normalized shear strength and effective depth for the SFRC beams with 0.75% fiber volume fraction [14, 17]. Note that the steel fiber volume fraction of 0.75% is the minimum amount of steel fiber specified by [15] used to replace the conventional minimum shear reinforcement (stirrup). As noticed, all the test beams had an effective depth ranging from 178 mm (7 in.) to 572 mm (22.5 in.) and an average strength of approximately $0.33 \sqrt{f'_c}$ MPa ($4.0 \sqrt{f'_c}$ psi) with no obvious size effect. Additional research is needed to investigate the size effect in deeper SFRC beams with depths greater than 610 mm (24 in.).

![Figure 1](image.png)

Figure 1: Normalized shear stress at failure versus beam effective depth, $V_f = 0.75\%$
2. EXPERIMENT PROGRAM

2.1. Specimen description and reinforcement detailing

A total of 10 beams including four pairs of SFRC and one pair of 457 mm (18 in.) deep RC beams were tested. To reduce the potential uncertainty of the test results, the beams in each pair were identical. For all the specimens, shear span to effective depth ratio, $a/d$, longitudinal reinforcement ratio, $\rho$, steel fiber volume fraction, $V_f$, fiber type, and concrete compressive strength were held constant. For SFRC beams, overall depth was considered as the only variable parameter ranging from 457 mm (18 in.) to 1220 mm (48 in.). Steel fibers used in this research were hooked-end fibers ($l/d = 67, l = 51$ mm (2.0 in.), $d = 0.76$ mm (0.03 in.), $f_t = 1096$ MPa (159 ksi)) conforming to ASTM A820. The fiber content was fixed at 0.75% by volume, which is the minimum amount as specified by ACI 318 building code [15]. The design compressive strength of concrete was 42 MPa (6000 psi) in compliance with the maximum allowable compressive strength for SFRC [15]. Table 1 lists the design properties of beams used in this experimental program.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Width mm (in.)</th>
<th>Overall depth (h) mm (in.)</th>
<th>Effective depth (d) mm (in.)</th>
<th>$a/d$</th>
<th>$\rho$ (%)</th>
<th>$V_f$ (%)</th>
<th>Targeted $f'_c$ MPa (psi)</th>
<th>Measured $f'_c$ MPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRC18a,b</td>
<td>152 (6)</td>
<td>457 (18)</td>
<td>394 (15.5)</td>
<td>3.6</td>
<td>2.82</td>
<td>0.75</td>
<td>42 (6000)</td>
<td>39 (5707)</td>
</tr>
<tr>
<td>SFRC24a,b</td>
<td>203 (8)</td>
<td>610 (24)</td>
<td>541 (21.3)</td>
<td>3.45</td>
<td>2.64</td>
<td>0.75</td>
<td>42 (6000)</td>
<td>50 (7210)</td>
</tr>
<tr>
<td>SFRC36a,b</td>
<td>254 (10)</td>
<td>915 (36)</td>
<td>813 (32)</td>
<td>3.5</td>
<td>2.72</td>
<td>0.75</td>
<td>42 (6000)</td>
<td>50 (7210)</td>
</tr>
<tr>
<td>SFRC48a,b</td>
<td>305 (12)</td>
<td>1220 (48)</td>
<td>1118 (44)</td>
<td>3.5</td>
<td>2.65</td>
<td>0.75</td>
<td>42 (6000)</td>
<td>50 (7210)</td>
</tr>
<tr>
<td>RC18a,b</td>
<td>152 (6)</td>
<td>457 (18)</td>
<td>394 (15.5)</td>
<td>3.6</td>
<td>2.82</td>
<td>0</td>
<td>42 (6000)</td>
<td>38 (5514)</td>
</tr>
</tbody>
</table>

Prior research has shown that the shear strength (in terms of stress) of RC beams is not a function of beam width [18, 19]. The width of each specimen pair was determined by the following required tasks: 1) to ensure that required longitudinal steel bars can be accommodated with a proper cover thickness; 2) to ensure that the shear capacity of specimens (loading) does not exceed the capacity of the equipment and setup; 3) to minimize the respective width and consequent reduced weight to ease transportation and disposal. It is well known that for plain concrete beams without shear reinforcement, the shear strengths vary with the shear span-to-depth ratios [20, 21]. The direct strut between the loading and support has great influence on the shear strength when a span to effective depth ratio ($a/d$) is approximately less than 3.0. In this study, $a/d$ ratio was selected to be 3.5 to minimize the effect from direct strut. Sufficient flexural reinforcement was provided to ensure that the failure is governed by shear rather than flexure. The amount of the longitudinal reinforcement was calculated according to highest shear capacity ($0.5\sqrt{f'_c}$ MPa (6.0$\sqrt{f'_c}$ psi)) reported for SFRC beams with 0.75% $V_f$ [17]. Self-weight of specimen was also taken into consideration. Geometry and reinforcement details of the RC and SFRC beams are shown in Figure 2. To ensure that shear failure would occur in the instrumented span, the other span was reinforced by shear reinforcement as shown in Figure 2. Mechanical terminators (headed bars) were employed at the end of the longitudinal bars to alleviate the congestion except for
the 457 mm (18 in.) deep RC and SFRC beams in which the longitudinal bars were bent 90° at the ends to provide the anchorage.

Figure 2: Geometry and reinforcement details of the large-scale RC and SFRC beams; (a) RC18; (b) SFRC18; (c) SFRC24; (d) SFRC36; (e) SFRC48 (in. = 25.4 mm)

2.2. Mixture compositions and material properties

Table 2 gives the SFRC mix proportions with a target maximum compressive strength of 42 MPa (6000 psi) according to [15].

<table>
<thead>
<tr>
<th>Type of Mix</th>
<th>Cement (Type I)</th>
<th>Fly Ash (Class C)</th>
<th>Sand</th>
<th>Coarse Aggregate 10 mm (3/8&quot;)</th>
<th>Water[1]</th>
<th>Steel Fiber</th>
<th>Total Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRC</td>
<td>1.00</td>
<td>0.5</td>
<td>1.7</td>
<td>1.00</td>
<td>0.45</td>
<td>0.117[2]</td>
<td>4.77</td>
</tr>
<tr>
<td>RC</td>
<td>1.00</td>
<td>0.5</td>
<td>1.7</td>
<td>1.00</td>
<td>0.45</td>
<td>0</td>
<td>4.65</td>
</tr>
</tbody>
</table>

[1]: W/CM = 0.3; [2]: V_f = 0.75%

2.3. Test setup and instrumentation

SFRC specimens were loaded by a concentrated force at the mid-span through a 2891 kN (650 kips) hydraulic cylinder. For the RC beams, however, the load was applied at one third
of the span length (Figure 2a). In each test, the beam was initially loaded until the first visible
flexural crack. Then, loads were monotonically increased and paused at a few loadings to
trace the cracks and take photos. The process continued until failure. For safety purposes,
lateral supports were provided for specimens with depths of 1220 mm (48 in.) and 915 mm
(36 in.). The lateral supports did not contact the specimens.

For each test, a total of three bearing plates were used at the supports and loading point.
Dimensions of the bearing plate are illustrated in Figure 3a. To provide a uniform interface
contact, a layer of non-shrink grout was used between the concrete and bearing plate at the
loading point. A schematic view of the test setup, instrumentations, and loading configuration
is depicted in Figure 3a. Specimen SFRC48b (overall depth = 1220 mm) is shown in Figure
3b. In each specimen, two pairs of strain gauges were mounted on the bottom layer
reinforcing bars at the location shown in Figure 3a. Three linear variable differential
transformers (LVDTs) were employed to measure the deflections under the loading point and
the settlement of each support. During of the tests, the applied load was measured by a load
cell. Testing was carried out 502 to 1005 days after casting. The specimens were exposed to
weather during this period.

![Figure 3: (a) schematic views of the test setup, loading configuration, and instrumentations (1
in. = 25.4 mm); (b) specimen SFRC48b.](image)

3. DISCUSSION OF TEST RESULTS

The specimens initially cracked in flexure near the mid-span. Contrary to the fast
propagation of flexural cracks in RC beams (RC18a & RC18b), the presence of steel fibers in
SFRC beams considerably slowed down the crack propagation, specifically in the deeper
SFRC specimens with 915 mm (36 in.) and 1220 mm (48 in.) overall depth. The first diagonal
crack appeared either in the form of multiple web-shear cracks with a nearly 45° slope, or flexural-shear cracks extended from initial flexural cracks. Except for SFRC18b and SFRC24a, all of the SFRC specimens developed web-shear cracks. Increasing the external load caused progressive development of many new shear cracks distributed across the shear span of SFRC beams until the failure. During this process, the propagation of the existing cracks in SFRC specimens appeared to be slow and stable toward both the compression zone and loading point as well as toward the longitudinal bars. At higher loads, a series of small inclined cracks started occurring along the very top layer of the longitudinal bars when the inclined cracks became wider (Figure 4c). Development of these small inclined cracks indicates the involvement of dowel action in resisting shear force. This observation was only noticed in SFRC specimens and can be attributed to the effectiveness of fibers in enhancing the tensile strength and bond of concrete surrounding the reinforcing bars.

In all SFRC beams, the critical shear cracks that lead to ultimate shear failure were not the first few shear cracks recorded. They either formed from a branch of existing diagonal cracks, or extended from existing web-shear cracks. In other words, they occurred at late stage of loading after multiple cracks had developed. Eventually, failure was found to be triggered by the breakdown of dowel action. It was observed that if the bottom of the critical shear crack was away from the support, dowel action was exhausted by development of the splitting crack along the longitudinal bars (Figure 4b). In the other case, the inclined crack extended all the way through the concrete cover in the tension zone, which led to kinking of the longitudinal bars and destruction of dowel resistance (Figure 4a). Sometimes, due to the high dowel force, the concrete fractured before the kinking occurred, as can be seen in SFRC36b and SFRC48b, (Figure 4c and Figure 4d).

The ultimate shear strength for the RC and SFRC specimens and the average of shear strengths for each pair of SFRC and RC beams with the same effective depth are plotted in terms of $\sqrt{f'_c}$ versus effective depth in Figure 5. Figure 5a clearly indicates that the shear strength of concrete beams were greatly increased by the addition of steel fibers when comparing SFRC18a and SFRC18b ($0.47\sqrt{f'_c}$ MPa (5.69\sqrt{f'_c} psi)) with RC18 ($0.21\sqrt{f'_c}$ MPa (2.53\sqrt{f'_c} psi)). In this particular case, the shear strength increased about 125%. In addition,
for the tested beams with the effective depth varying from 394 mm (15.5 in.) to 1118 mm (44 in.), the average of shear strength of all SFRC specimens was about \( \sqrt{f_c} \text{ MPa} (5.4 \sqrt{f_c} \text{ psi}) \), with no obvious size effect.

![Figure 5: Normalized shear strength vs. effective depth: (a) average of normalized shear strength for each pair of specimens with the same effective depth; (b) normalized shear strength for each RC and SFRC beam](image)

4. **CONCLUSIONS**

While the specimens were exposed to weather and tested after a long period of time from the casting to testing date (502 to 1005 days), the shear behavior of the specimens was satisfactory. Test results obtained from this study indicated no evident size effect on ultimate shear stress of SFRC beams with a depth of up to 1220 mm (48 in.). It should be noted that a few recent studies did show size effect in SFRC beams [22, 23]. Potential causes resulted in the different findings between the current and other studies and are discussed in other future publication by the authors.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


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