SHEAR STRENTHS OF PRESTRESSED FIBER REINFORCED CONCRETE BEAMS AS AFFECTED BY THE STEEL FIBERS USED

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ABSTRACT

As prestressed reinforced concrete beams are increasingly used in construction nationwide, examining new and novel ways of reinforcing them is essential to ensure their safe and reliable use as loads and spans increase.

To prevent against failures in flexure, the prestressing of the tendons along the length of a beam can be increased; however, this has little to no effect on the ability of the beam to resist shear forces that are often the cause its failure. To prevent against this shear failure, transverse rebar reinforcement is normally just increased along the length of the beam to provide more tensile strength perpendicular to the prestressing tendons. These added rebars are often still inadequate, however, to resist shear failures, especially as beam spans increase. Additionally, these rebar reinforcements are costly to install during casting.

Using fibers instead of these expensive steel rebars is gaining in popularity, and they have been proven to be superior at resisting shear in concrete beams. However, the types and quantities of fibers used affect beams' shear strengths. This experiment tests the abilities of various fiber indexes used in the concrete to increase the shear strength of (TxDOT Type-A) I-beams commonly used in bridge construction.

The results show that increasing the fiber index of a prestressed fiber reinforced concrete beam noticeably increases its shear strength. Additionally, the larger fiber indexes increase the ductility of the concrete beams.

INTRODUCTION

BACKGROUND

Reinforced concrete is the most common type of concrete in the United States and throughout the world. Traditional reinforcement uses internal steel rebars around and to which the concrete bonds during the curing process. Over the past two decades, however, Fiber Reinforced Concrete (FRC) has gained in prominence, especially in bridge construction. It is also growing increasingly common in manufacturing slabs, road paving, machine foundations, seismic structures, precast concrete elements and shotcrete. The immediate advantage of fibers over traditional rebar reinforcement is their cost-savings in manufacturing and installation.

One especially attractive use of fibers is in prestressed reinforced concrete beams, whose prestressing requires additional expensive manual work on top of the steel rebar reinforcement. This increases the costs of these beams further, making the spanning of gaps with beams undesirably expensive without revisions to the now standard prestressed rebar-reinforced concrete beam. However, as prestressing is critical when building over large gaps, a replacement for the reinforcing rebars instead is crucial.

These rebars are used to reinforce a concrete beam against shear, an internal product of the loads placed on the beam and the dead weight of the beam itself. Beams must be able to carry the weight of their loads through their lengths to their supports. This requires great internal cohesion between the concrete elements of the beams, like the aggregates and sand and ash. Without this, the weights of the loads will break the beams into pieces.

Due to the low tensile strength of concrete as compared to its compressive strength, however, concrete beams are indeed susceptible to shear, especially near their ends. This is compared to steel or wooden beams which are far stronger in tension and hence rarely break in shear. Structural tests have shown that even when increasing the presence of steel rebar in reinforced concrete beams by jumping up to 4% percent steel by volume at the ends, shear failure can be a problem (Dhonde et al. 2006). These same full-scale beam tests showed that steel fibers completely replacing steel rebar reinforcement actually increases the shear strengths of the beams.

Steel fiber reinforcement is both mechanically and economically superior to traditional steel rebar for prestressed concrete beams. It increases the ability of the beams to resist shear failure and lowers the overall manufacturing costs of the beams.

DETAILS OF FIBER REINFORCEMENT

Fibers are defined to be discrete, short lengths of steel having a length to diameter ratio between 20 and 100. This ensures that they remain small enough to easily and randomly disperse within the concrete during mixing (ACI 1996), guaranteeing a uniformly strengthened finished beam.

The advantages of a properly mixed and cured FRC beam are threefold. First, fibers increase the tensile capacities between adjacent concrete elements like aggregates and sand, improving the total strength of the concrete. Second, the linking systems of fibers often reallocate forces equally through the component elements, adding post-cracking protection, limiting crack escalation, and enhancing ductility. Lastly, concrete with fiber reinforcement is longer lasting and more easily repairable (Grzybowski 1989, Rapoport et al. 2001, Grzybowski and Shah 1990).

Steel fibers were first proposed for use in concrete by Porter in 1910 (Naaman 1985). Nevertheless, fiber reinforcement in concrete was not studied in the U.S. until 1963 (Romualdi and Baston 1963). FRC is composed of standard hydraulic cements, water, fine and coarse aggregates, and the reinforcing fibers. While previously not always commonly available, fibers are now commercially available and produced from steel, plastic, and glass. Steel fibers are the most common of the three used in concrete beams for bridges. Hence, each beam tested in this report uses solely steel fibers.

Since their introduction, fibers have been investigated in numerous studies detailing the mechanical advantages of this reinforcing method. Together, fibers act as multi-directional, equally distributed micro-reinforcement throughout the concrete beam and between its component elements. This allows them to cross cracks where they occur and retard their growth by carrying the tension across the gap. Thus, fibers help spread out and dissipate the forces causing shear failure (Beaudoin 1990). This also helps to control stresses during both the curing and transportation phases of construction. All this helps to impart ductility to the concrete even after it has cracked. Fibers help improve concrete in its toughness, ductility, shear and tensile strengths, fatigue, shrinkage resistance, and durability (Shah 1991).

All of these advantages of FRC help it to perform better in all failure modes (Gopalaratnam and Shah 1987), notably flexure and shear. The fibers do slightly improve the compressive strength of concrete, but more significantly improve the ductility of the concrete (Padmarajaiah and Ramaswamy

2002). They have the ability to improve the direct tensile strength of concrete up to 40% when 1.5% of the volume of FRC is fibers (Williamson 1974). This is directly responsible for FRC's ability to resist shear forces greater than traditionally reinforced concrete (Narayanan and Darwish 1987, Barr 1987, Oh et al. 1999, Noghabai 2000). FRC with 1% of its volume filled by fibers has shown up to a 170% increase in shear strength (Narayanan and Darwish 1987). Ultimately, these steel fibers are an effective method for replacing traditional reinforcing transverse steel rebars (Williamson 1978, Noghabai 2000).

DIFFERENTIATING FIBER TYPES

With a broad definition, fibers can range from long strips of steel to tiny ribbons. The ability of a particular fiber to reinforce cured FRC depends on the 'fiber index.' This parameter is determined as the product of the volume percentage the fiber occupies (fiber content) and its aspect ratio (length/diameter), or $V_f \cdot (L_f/D_f)$. If the fiber index is less .25, the strengthening of the FRC would not be significantly increased (Johnston 1980). However, when increased to more than 1.2, workability problems in the concrete appear. As a result, fiber indexes in FRC generally remain between .25 and 1.2. This experiment tests FRC beams of fiber indexes .4, .55, .83, and 1.23, using a variety of short and long steel fibers (see table 1).

Table 1: Fiber Properties by Beam

Beam Index	Volume of Fibers - V_f (%)	Aspect Ratio - L_f/D_f	Fiber Factor
R1	0.5	80	0.4
R2	1	55	0.55
R3	1.5	55	0.83
R4*	1.5 + .5*	55, 80*	1.23

*Note: Beam R4 contains two fiber types, having aspect ratios of 55 and 80. Together, they occupy 2% of the beam's volume.

RESEARCH OBJECTIVE

The objective of this report is to investigate shear behavior in prestressed fiber reinforced concrete beams and to establish how changing the fiber index influences shear strength.

EXPERIMENTAL PROGRAM

MATERIALS

These experiments were conducted on four 25 ft prestressed fiber TxDOT Type-A concrete I-beams. Each of the four beams was cast at the Texas Concrete Company casting plant in Victoria, Texas.

They were cast identically as traditional I-beams, except that the steel fibers were added into the concrete during mixing and no transverse steel rebars were included. They differ based on the type and amount of fibers used in casting (see Table 1). All four beams contained straight prestressing tendons.

TEST SETUP

The testing apparatus used was a large steel structure specifically constructed at the University of Houston to carry out beam tests (see Figure 1). This test setup and procedure was established in a previous set of tests (Dhonde et al. 2006). The same test setup was used in this experiment. The 25 ft beams rested on two steel supports at either ends of the testing bay, 24 ft apart. Large hydraulic actuators are supported above the beams; in this experiment they were moved to rest 3 ft inside the supports, leaving 18 ft between them. Below each set of actuators, a set of displacement sensors are placed to measure the downward motion of the beams as the actuator loads are increased.

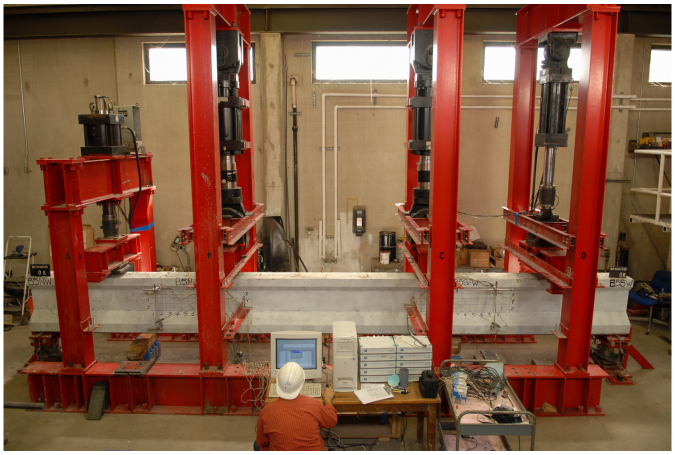

Figure 1: Experimental Apparatus

These actuators are extended in a stress-strain procedure in which the actuators are first controlled by setting and slowly raising the loads they exert on the beams. Subsequently, however, the actuators are switched to a displacement mode in which they extend downward onto the beams slowly and constantly, pushing harder and harder until the beams fail. This allows the actuators to automatically determine the loads required to extend the desired amounts. The point at which extension is switched from load to displacement control takes place when the concrete first starts to crack, located on the load-displacement results curve of a beam as the abrupt bend from a mostly upward to a mostly horizontal tend.

EXPERIMENTAL RESULTS

These load-displacement curves are created by merging the data from the actuators with the linear displacement sensors under the beams. Figure 2 displays the load-displacement curves for each of the four beams tested, R1 to R4. The ends of these curves indicate the points at which the beams failed.

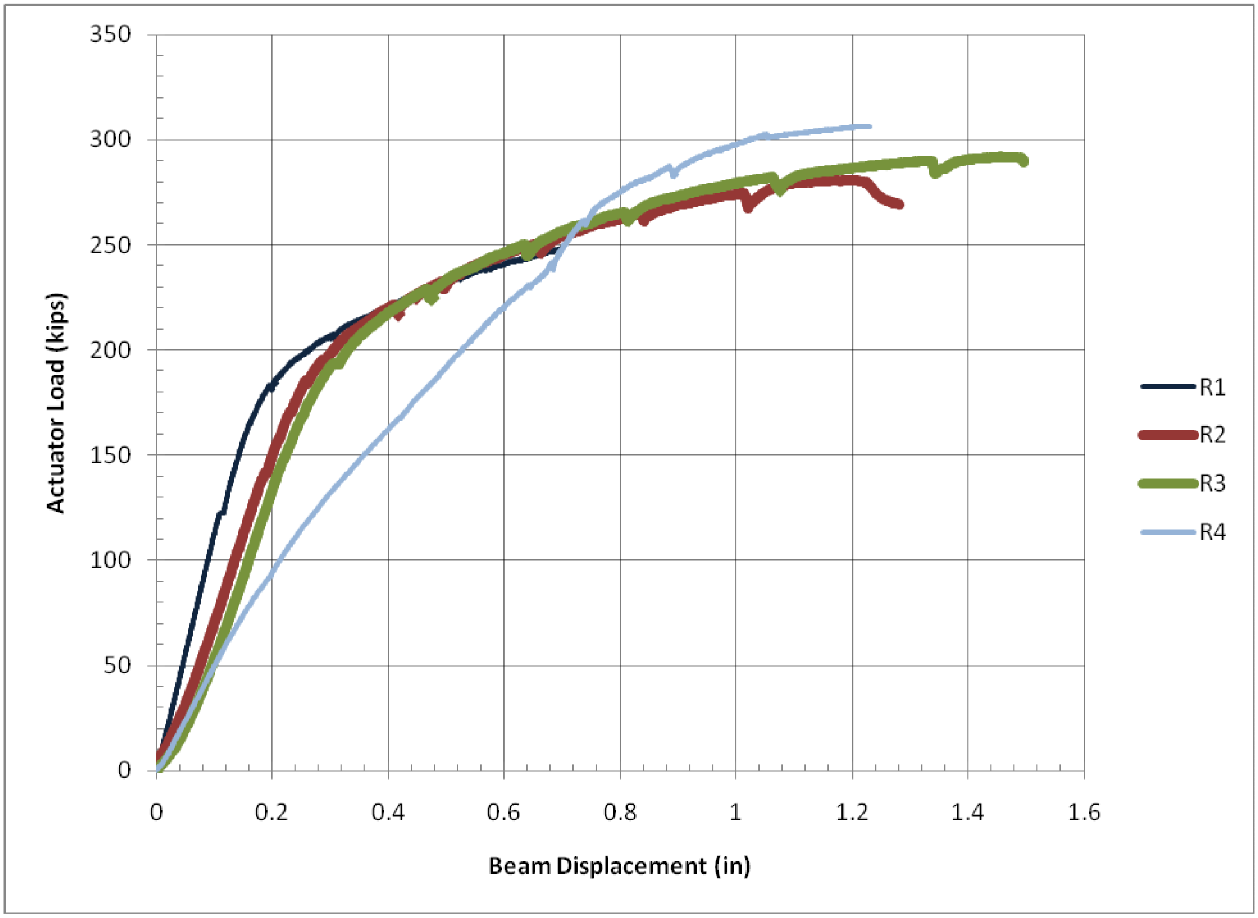

Figure 2: Shear Force – Displacement Curves for Beams R1 to R4

DISCUSSION

First, we can immediately see from Figure 2 that as the fiber indexes increased from R1 to R4, so too did their shear strengths. Beam R1 failed at 248 kips. Beams R2 and R3 failed at 269 and 289 kips, respectively. Finally, Beam R4 failed at 306 kips. With each increase in fiber index, as detailed in Table 2, the beams made clear increases in shear strength.

Beam Index	Fiber Factor	Load at Failure (kips)
R1	0.4	248
R2	0.55	269
R3	0.83	289
R4*	1.23	306

Table 2: Beam Failure Test Results

This, however, is an incomplete picture of the shear resistance. During the testing of beams R3 and R4, it became evident that the beams were going to fail in flexure rather than due to shear. For both beams, as the loads were increased, the beams started to buckle on their tops from flexure rather than crack at their bottoms, a sign of shear. This clear sign of flexure failure came as the actuator loads exceeded the ability of the prestressing tendons to it. After seeing R3 fail in flexure, we even applied fiber-reinforced polymer (FRP) strips to the bottom of beam R4 to help increase its resistance to flexure on top of the prestressing. However, even this did not prevent beam R4 from failing in flexure. These two unexpected failures strongly indicated that with high enough fiber indexes, the shear strength of beams can overtake their resistance to flexure.

Of course, this then means that the points on the load-displacement curves where beams R3 and R4 failed were not caused by shear failure. If we were able to completely eliminate the experimental possibility of flexure and focus solely on shear, we could have seen these curves extended. If, in a remote possibility, the two beams would have failed in shear soon after, then their max loads, as detailed in Table 2, would have been only slightly higher. More likely, however, is the case that each beam would have continued along the curves, sustaining higher loads from the actuators, until they broke from shear. In this case, the max loads sustainable for beams R3 and R4 would have been even higher than we found them to be.

A further inspection of Figure 2 reveals that despite changing fiber indexes, the beams followed very similar load-displacement curves. Even beam R4, set off from the others, is by no far cry different. This suggests that even as different fiber indexes affect when the beams break, the beams behave similarly before this point. It is only when one beam reaches its fiber/tensile limit that it drops off the curve and breaks. This will be important when trying to predict the future behavior of FRC; the fiber index will likely play much more of a part in determining the shear capacity than they load-displacement curve of a beam. What did change between the beams were: first, the behavior of the beams pre-cracking (the area of the curves with a mostly upward trend, before joining the more horizontal trend); secondly, the point of complete failure; and, third, the amount of ductility in each beam.

This ductility difference can be seen in both the load-displacement curves and the observable behavior of the beams during testing. While normal concrete beams are brittle when breaking in shear, doing so almost unpredictably and suddenly, with the increases in fiber index came noticeable effects on the shear strains. Even as all four beams were being tested, smaller shear cracks turned into larger ones, as normal; however, this progressed slowly and observably, indicating a new ductility allowing the concrete to ‘stretch’ without cracking outright. In normal beams, these small cracks often turn into larger ones suddenly in large and violent breaks. These events are apparently random, however, and make it hard to predict when a normal concrete beam will ultimately fail in shear. The load-displacement curves provide visible evidence of this new ductility. When looking a standard beams in shear failure, their load-displacement curves often suddenly end even while still climbing (Dhonde 2006), evidence of their sudden failures. However, our four beams each almost level out. R3 and R4 would have gone farther had they not broken in flexure. These gentle slopes are classic evidence of ductile beams that, when loaded further, start to stretch out in displacement rather than break outright.

Both of these conclusions for FRC are welcome in construction. Increased shear capacity means that the beams can withstand higher loads and/or break in flexure instead. Added ductility adds a bit of stretching ability to the beams, which allows for slower and gentler cracks resulting from shear. Both of these effects will help to alert observers, after damage, to the potential dangers of a compromised beam. Flexure failure is much more preferable to shear failure in structures and the added ability of seeing cracks develop allows us to prevent even worse events.

CONCLUSION

Increasing the fiber index in a concrete beam measurably increases its shear strength and ductility.

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