FLEXURAL STRENGTHENING OF PRECAST CONCRETE BEAMS USING A HIGH STRENGTH FIBER-REINFORCED CONCRETE LAMINATE

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ABSTRACT

High strength fiber-reinforced concrete (HSFRC) has several advantages over conventional concrete, including higher compressive strength, higher tensile strength, enhanced durability, and higher bond strength. However, due to the unconventional mixing procedures, and longer placement times, engineers must use HSFRC strategically in design. Because of its high bond strengths, HSFRC could be used as a laminate on standard reinforced concrete beams to enhance the flexural capacity and ductility. HSFRC is investigated in this paper as a way to efficiently use the material for composite construction on bridge beams.

Two non-proprietary HSFRC mixes were applied as laminates to the tension side of beams made of a standard concrete bridge mix. Rebar was embedded inside the HSFRC laminate and the composite beams were tested in flexure to determine strength increase, ductility, and failure mode. Results of the laminated beams show there was no premature delamination of the HSFRC from the concrete beams and the ultimate bending strengths were greater on average than the control beams. The failure modes, yield strength, and crack patterns were similar for the control and laminate beams. The main difference observed was the HSFRC laminate reduced service load cracking because the steel fibers arrested the cracks.

Keywords: Fiber-reinforced, Reinforced Concrete, Laminate, Flexure Strength

INTRODUCTION

One of the current "Grand Challenges" in engineering is to decrease the life cycle costs of engineered structures and extend their service life[1]. One way of accomplishing this is to look at the application of newly developed materials used in transportation structures. An example is the use of high strength (HSC) and ultra-high performance concrete (UHPC). Many mix designs have been developed, but using them effectively and efficiently is a challenge for engineers.

Some high strength concretes have a discrete steel fiber matrix. These mix designs have many beneficial properties including higher compressive and tensile strengths, longer durability, and better bond strength. However, these mixes are not always readily available, are more difficult to cast, and are more expensive than normal strength reinforced concrete. For effective use, the goal is to take advantage of the benefits while minimizing the impact of the weaknesses of the material.

The following study investigated an efficient use of high strength fiber-reinforced concrete (HSFRC) on standard reinforced concrete beams. Two non-proprietary HSFRC mixes were developed and then applied as an external laminate to the tension face of reinforced concrete beams. Standard reinforcing bars were embedded within the laminate matrix. The beams were tested in flexure to determine the strength increase and failure modes of the new composite reinforced concrete beams. The application could be used to retrofit existing bridge beams or as an economical way of strengthening precast bridge beams at a critical flexural location instead of making the beam entirely of HSFRC.

BACKGROUND

Composite construction is commonly used in structural engineering for both renovations of existing structures and creations of new structures. There are many methods and materials used in structural systems including reinforced concrete, a composite material that has been in place for over 100 years[2]. Within the last few decades, fiber-reinforced polymers (FRP) and similar polymer materials have been used in conjunction with reinforced concrete to increase design capacities[3-6]. Others have used steel plates covering a concrete core for composite construction[7]. One of the most important points with any of these systems is to ensure the materials bond to one another and act as a composite structure.

Standard concrete mixes do not bond well to existing concrete structures and generally have low bond strengths. Previous studies on transportation structures have shown that tensile bond strengths between existing concrete and new concrete or grout are less than the tensile strength of either material[8,9]. Because of this limitation concrete is typically not used as an external laminate and is only used to bond to embedded reinforcement such as reinforcing bars (rebar).

While bond strength is a problem for concrete, new tests on UHPC have shown that it has much better bonding properties. The bond formed between UHPC and normal strength concrete has been much stronger than the tensile strength of the normal strength concrete. The bond plane has been indistinguishable and behaved mechanically as if it was a monolithic concrete structure[10].

One of the best demonstrations of the bonding properties of a UHPC mix was shown on the composite connection between a prestressed concrete girder and a reinforced concrete deck. Instead of using standard shear studs or reinforcing bars, the haunch material was selected as UHPC and it provided the horizontal shear strength. The bridge system was tested with over one million truck load cycles with no structural deterioration. The UHPC clearly bonded the structural system together and provided horizontal shear strength[11].

UHPC has a number of unique factors that merit its use in specific projects. UHPC has a higher compressive strength and a corresponding higher tensile strength. The ratio of tensile to compressive strength is approximately 1 to 12. While this is similar to normal weight concrete, the compressive strengths are much higher; therefore, the tensile strength values are also much greater than standard normal weight concrete[12]. While there are benefits, UHPC mixes are proprietary and cost more to cast. There is also a learning curve for using UHPC because of its unique workability and fiber matrix.

A testing program was developed based on the material properties of UHPC and its previous uses in transportation structures. A series of non-proprietary high strength fiber-reinforced concretes were developed. The goal was to create mixes that mimicked UHPC behavior, but were more readily available and less expensive. The mixes are referred to as High Strength Fiber-Reinforced Concrete (HSFRC) because their properties are slightly different than the traditional UHPC definition. HSFRC has a compressive strength above the typical range of high strength concrete, but below that which defines UHPC. Based on the expected enhancement in tensile strength, bonding characteristics, and shear strength, HSFRC embedded with reinforcing bars (rebar) was chosen as a laminate on concrete beams. The purpose of the laminates was to increase the flexure strength capacity and ductility of normal strength concrete beams.

PROCEDURES

The objective of these tests was to compare the flexural response of two types of beams: a set of control, normal strength reinforced concrete beams (Figure 1) and a set of HSFRC laminated reinforced concrete beams (Figure 2). The beam dimensions were chosen based on previous studies performed on FRP laminated concrete beams[13]. The reinforcing bars (rebar) were designed to have a worst case clear cover of 0.375 in. for all beam types. The HSFRC laminate was applied with a uniform thickness of 1.0 in. and a 0.375 in. (#3) piece of reinforcing bar (rebar) embedded concentrically throughout. The simply supported beams were designed to have a clear span of 44 in. (Figure 3). The rebar was terminated 2 in. from the end to eliminate any confinement stress from the reaction force. All of the beams were made of the same normal strength concrete based on a Virginia A4 mix commonly used in bridge construction in the Mid-Atlantic Region[14]. The mix proportions are shown in Table 1.

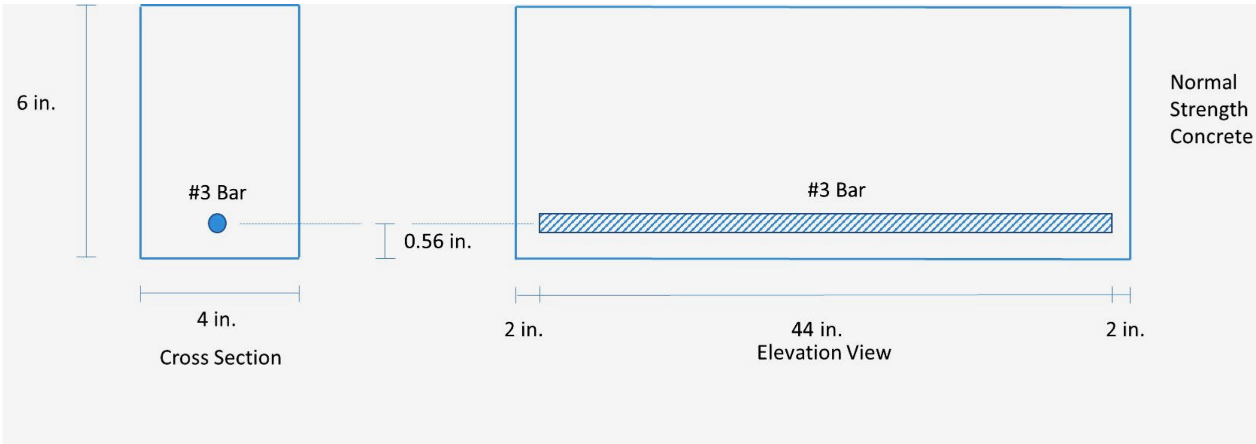

Fig. 1 Dimensions of the normal strength beam specimens.

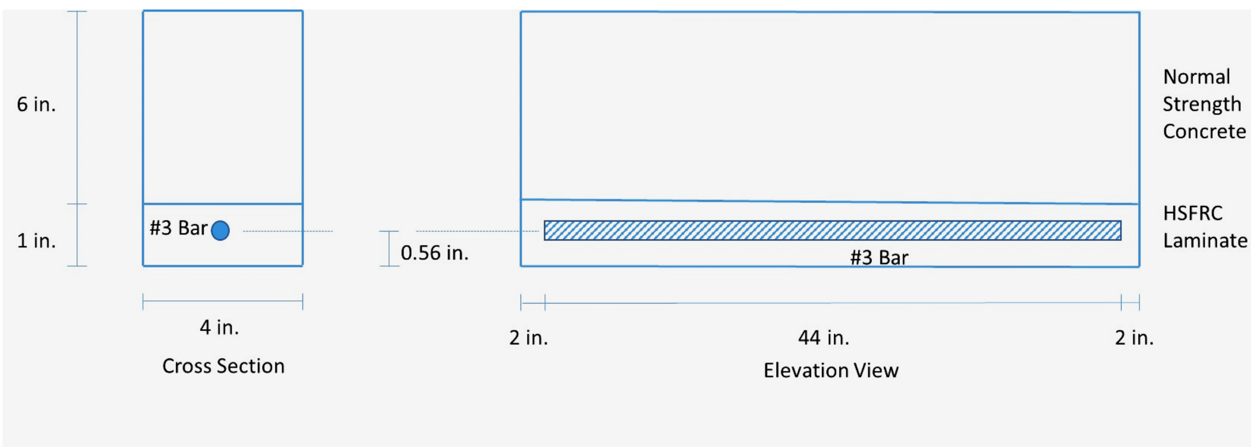

Fig. 2 Dimensions of the HSFRC laminated beam specimens.

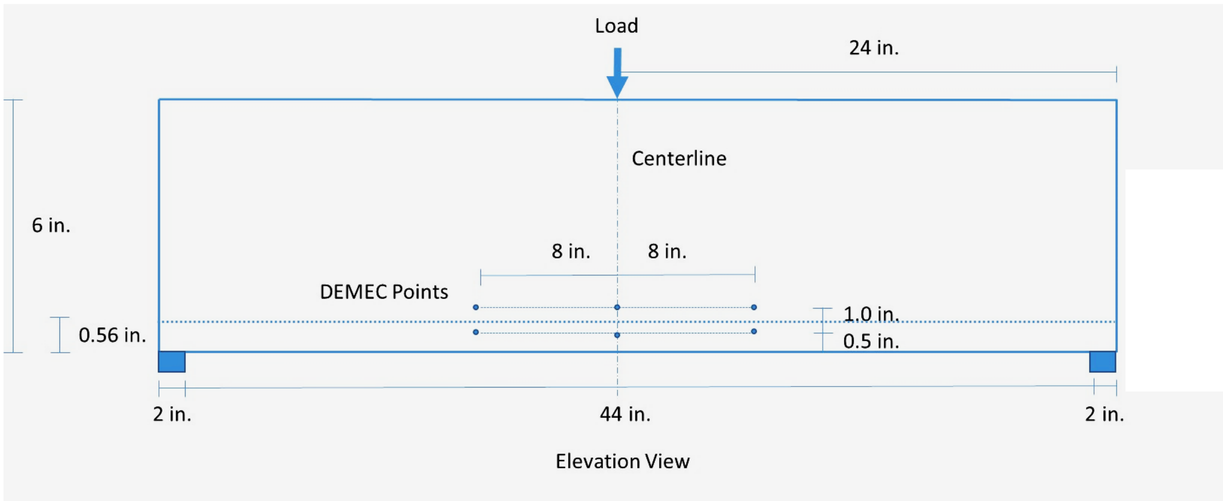

Fig. 3 Testing setup for the beams.

Table 1 Mix proportions of the normal strength concrete mix.

Material	**Weight (lbs/yd^3)**
Water	346
Fine Aggregate	1129
Course Aggregate	1871
Type I/II Cement	635

Two different HSFRC laminates were designed and applied to a set of test specimens. Both HSFRC mixes were designed as non-proprietary mixes with readily available materials. The mix proportions for each are shown in Table 2. The HSFRC mixes had differing proportions of silica fume, water to cement ratios, and fibers. Nine specimens were included in the test program: three control, three HSFRC1 laminates, and three HSFRC2 laminates. The HSFRC1 and HSFRC2 laminated beams had the same dimensions with different mix designs. HSFRC1 had 0.5 in. long, straight steel fibers, while HSFRC2 had 1.5 in. long, bent steel fibers.

Table 2 Mix proportions of the HSFRC mixes.

	HSFRC1	HSFRC2
Material	**Weight (lbs/yd^3)**	**Weight (lbs/yd^3)**
Water	350	443
Fine Aggregate	1687	1873
Type I/II Cement	1750	1273
Silica Fume	0	255
Steel Fibers*	264 (2% by Volume)	270 (2% by Volume)
Superplasticizer	40	23

*HSFRC1 had 0.5-in. long, straight steel fibers, and HSFRC2 had 1.5-in. long, bent steel fibers.

All nine beams were cast in September 2017. The three control specimens were cast with the #3 reinforcing bar embedded inside and are referred to as the control beams (Figure 1). The other six HSFRC specimens were cast without reinforcing bars or laminates. However, the tension face (i.e., the face were the laminate would be placed) was roughened to an exposed aggregate surface. This was accomplished by applying a retarder to the surface, spraying off the paste 18 hours after casting, and cleaning the surface with a wire-bristled brush (Figure 4). The surface roughness was then measured using the International Concrete Repair Institute (ICRI) surface preparation guidelines[9]. All specimens had exposed aggregate surfaces, were rated on the ICRI scale (the scale is from 1 – smooth to 10 – very rough/exposed aggregate), and were cured in a controlled environment of approximately 70°F with 100 percent humidity for 28 days[15]. Afterward, all of the beams were cured in the same indoor environment, but the humidity was changed to approximately 60 percent. The beams were left to cure for approximately 9 months to ensure dimensional stability once applying the HSFRC laminates.

The HSFRC laminates and the embedded #3 reinforcing bars were added together. HSFRC was treated as a self-consolidating concrete, similar to UHPC, during casting. To facilitate optimal fiber alignment, the HSFRC was placed in one end of the beam mold and allowed to flow across in the longitudinal direction to fill the mold. HSFRC was not tamped or vibrated; rather, beam molds were tapped on the outer edges to aid HSFRC flow and consolidation. The beams were cured in a controlled environment of approximately 70°F and 100 percent humidity until the day of testing. The beams were removed from the curing chamber and tested in bending 21 days after casting the laminates. The beams with HSFRC1 are referred to as Laminate1 beams and those with HSFRC2 are referred to as Laminate2 beams.

Fig. 4 Preparing the exposed aggregate surface on the HSFRC laminate face.

The beams were set in place and tested to failure over a period of approximately 15 minutes. Load, deflection, and strain data were collected throughout the process. Load and deflection data were collected at midspan. In addition, strain data were collected across the middle 16 in. of the beam at heights of 0.5 in. and 1.5 in. from the bottom face of the beam (Figure 3). The strain data were collected using demountable mechanical strain (DEMEC) gauges at 500 lb load increments until the steel yielded in the beams. Load data were collected until the beam lost capacity to support load; however, deflection data were only collected until the steel reached noticeable plastic behavior.

The load and deflection data provided an indication of the load carrying capacity of the beam, the first crack in the beam, yielding of the rebar, and overall ductility of the beams. The DEMEC data helped confirm the first crack in the beam and provided an indication of whether or not the HSFRC laminate delaminated from the normal strength concrete beams. Failure mechanisms and crack patterns were recorded for each beam.

Material data were taken for the HSFRC and normal strength concrete throughout the process including the day of testing the beams. Data included compressive strength and modulus of elasticity. The steel yield and tensile capacities were computed based on tensile tests performed on rebar samples from the beams.

RESULTS

The material data for the three concrete mixes are shown in Table 3. The HSFRC mixes both exceeded 15 ksi compressive strength at 28 days; however, this strength is not as high as a UHPC. Neither of these mixes were steam cured. Both moduli of elasticity were also significantly higher than most normal strength concrete moduli. The yield stress of the rebar used in all the beams was measured at 67.1 ksi, and the ultimate stress was approximately 100 ksi.

Table 3 Material data for the beams at 28 days.

	Compressive Strength (ksi)	**Modulus of Elasticity (ksi)**
Normal Strength Concrete	4.88	*
HSFRC1 (Laminate1)	16.8	6,150
HSFRC2 (Laminate2)	15.3	5,680

*Not Recorded

The nominal flexure strength of the beams with the as-built dimensions was computed using the ACI equivalent stress block method[16]. The maximum applied moment was recorded and compared to the computed nominal moments (Table 4). The actual moment carried for all beams was significantly higher than the computed nominal capacity. The moment applied exceeded the nominal moment capacity for the control beams by 38.9 percent on average, and all of the composite HSFRC laminate beams, regardless of mix, held moments over 43.9 percent higher than the nominal values on average. All of the composite beams held moments significantly higher than what was expected.

Table 4 Moment data for the beams.

	Maximum Applied Moment (k-ft)	**Nominal Moment Capacity (k-ft)**	**Extra Moment Capacity (%)**	**Average Extra Moment Capacity (%)**
Control #1	4.74	3.55	33.4	38.9
Control #2	5.33	3.49	53.0	
Control #3	4.54	3.48	30.4	
Laminate1 #1	5.33	3.93	35.7	56.0
Laminate1 #2	5.36	3.86	38.9	
Laminate1 #3	7.17	3.71	93.3	
Laminate2 #1	5.11	3.67	39.3	43.9
Laminate2 #2	5.39	3.67	46.7	
Laminate2 #3	5.45	3.75	45.6	

The cracking moment was computed using the modulus of rupture and the measured depth of each concrete beam. Precise tensile strengths of the HSFRC were not measured, therefore the compressive strength of the concrete beam was used to estimate the rupture strength of the beam. This assumption underestimates the cracking moment of the laminate, but did provide a baseline value for comparing the expected cracking moment if the beam was a monolithic concrete beam.

The first crack was measured using the plot of load versus deflection and the DEMEC strain data. As shown in Figure 5, the control specimens had very distinct first crack and yielding points on the plots. The visual cracking patterns and DEMEC data confirmed these results. On average, the control beams cracked within 15 percent of the computed cracking moment (Table 5).

The laminate beams exhibited very different behavior based on the unique material properties of the HSFRC laminate. The Laminate1 beams had 0.5 in. long, straight steel fibers, while the Laminate2 beams had 1.5 in. long, bent steel fibers. In both cases the laminate beams did not show a distinct crack at a load near the computed cracking load. Instead, as the beam started to crack, the fibers arrested the crack. As shown in Figure 6, the first crack for Laminate1 beams was closer to the yielding of the steel. The Laminate2 beams never had a distinct first crack as shown in Figure 7. The Laminate2 behavior can be contributed to the longer steel fibers which continued to arrest the cracks up until the yielding of the steel. Prolonged crack arrest was possible in the HSFRC laminates because fibers bridged cracks, indicating the placement procedures for HSFRC were successful in orienting fibers in the longitudinal direction of the beam. After the steel yielded, the deflections increased and cracking became more pronounced in all laminate beams.

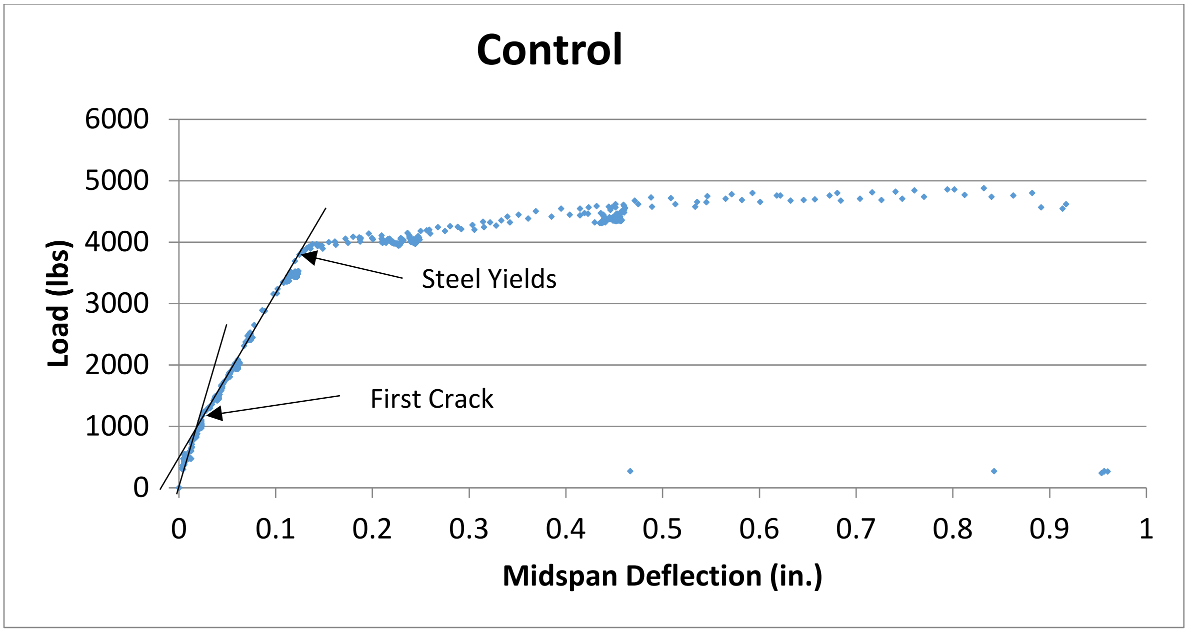

Fig. 5 Load versus midspan deflection of a typical control beam.

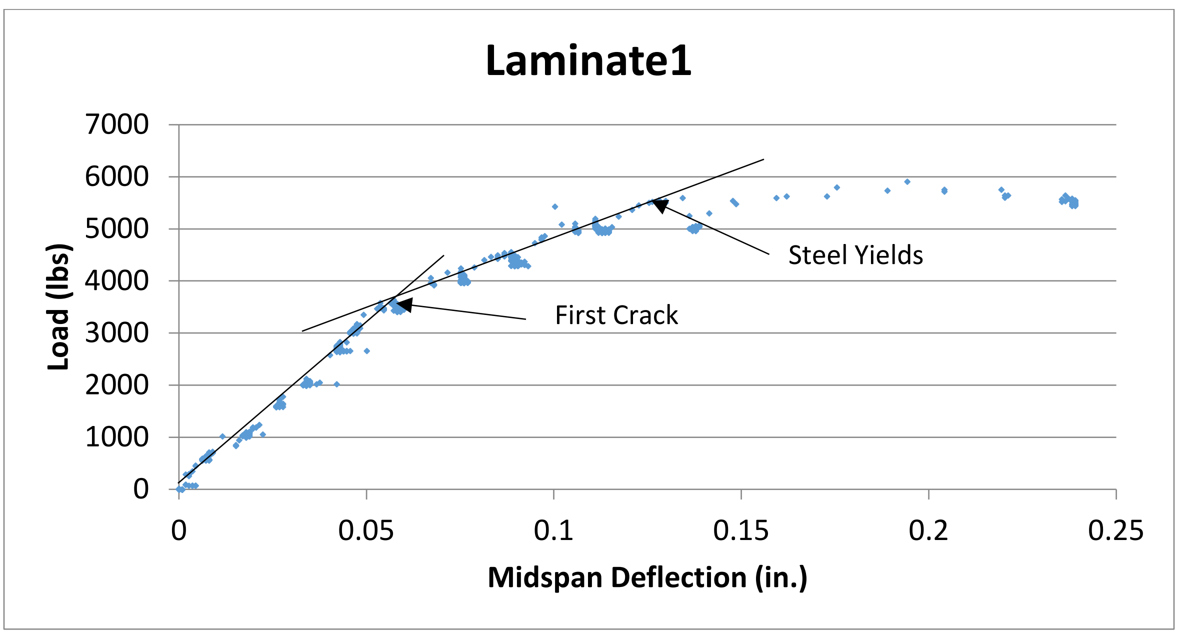

Fig. 6 Load versus midspan deflection of a typical Laminate1 beam.

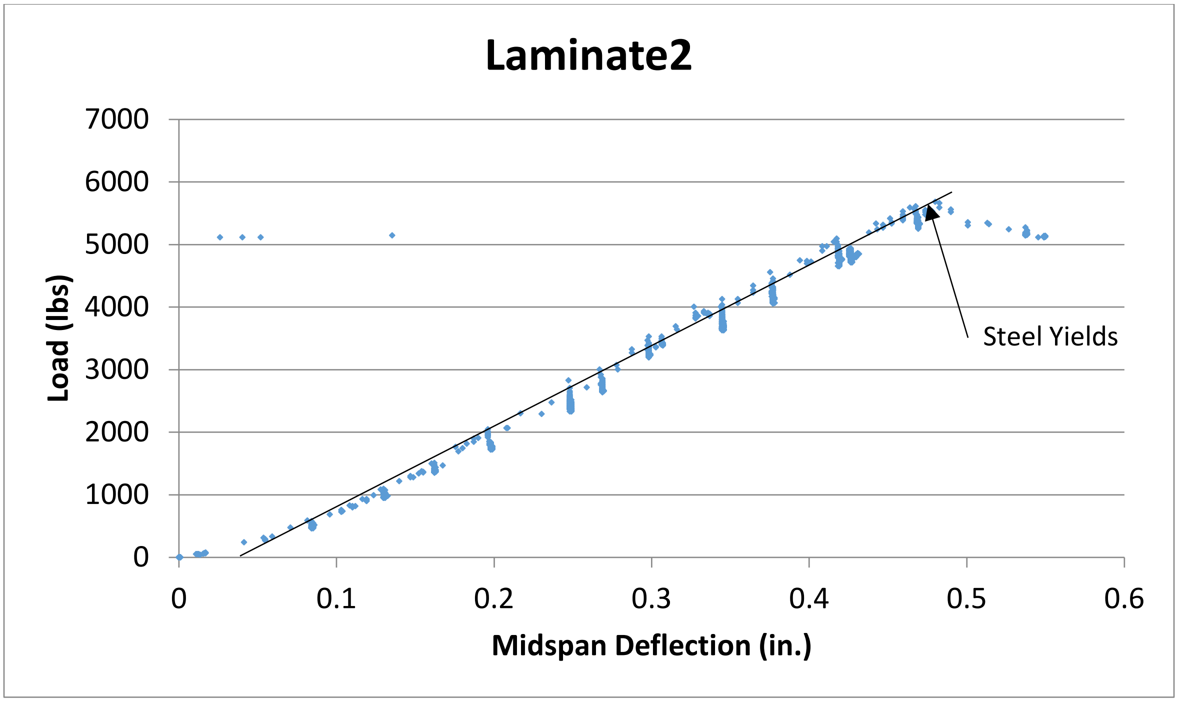

Fig. 7 Load versus midspan deflection of a typical Laminate2 beam.

Table 5 First Crack in the Beams.

	Measured Moment at First Crack (k-ft)	Computed Moment at First Crack ** (k-ft)	Percent Difference (%)	Average Percent Difference (%)
Control #1	1.36	1.13	20.6	14.3
Control #2	1.38	1.12	23.1	
Control #3	1.15	1.16	-0.8	
Laminate1 #1	3.07	1.45	113	156
Laminate1 #2	3.13	1.44	120	
Laminate1 #3	5.07	1.51	237	
Laminate2 #1	2.83	1.45	95.0	*
Laminate2 #2	*	1.45	*	
Laminate2 #3	*	1.50	*	

*The beam did not have a distinct first crack.
**Assuming the beam was a monolithic concrete beam.

The failure methods of each beam type varied (Table 6). The control beams had a traditional concrete crushing post steel yielding commonly called an under-reinforced failure. After the steel yielded the beam had significant cracking and eventually failed on the compression side of the concrete beam (Figure 8).

The Laminate1 beams had two different failure modes. The first mode was a post steel yielding, concrete crushing failure referred to as an under-reinforced failure. However, what made this failure unique was the laminate started to delaminate at the ultimate load. The failure of the compression concrete and laminate occurred simultaneously in these beams. The other failure mode was a steel rupture failure (Figure 9). In this case the laminate remained intact and the concrete did not crush until after the steel ruptured. As noted previously, all failure loads were at least 35 percent beyond the nominal moment capacity (Table 4).

The Laminate2 beams had two different failure modes. The first mode was a post steel yielding, concrete crushing failure referred to as an under-reinforced failure. However, what made this failure similar to Laminate1 beams was the laminate started to delaminate at ultimate load (Figure 10). The failure of the compression concrete and laminate occurred simultaneously in these beams. The other failure mode was a traditional post steel yielding, concrete crushing, under-reinforced failure. In this case the laminate remained intact and the failure looked identical to the control beams. As noted previously, in all failure modes the failure loads were at least 39 percent beyond the nominal moment capacity (Table 4).

All of the laminate beams had a surface roughness of at least 7 on the ICRI surface profile scale (Table 6). Values of 7 and higher correspond to varying levels of exposed aggregate surfaces. A roughened surface is important, but having an ICRI level above 7 did not improve the bond strength. Level 7 beams were the only ones that did not exhibit delamination at any time in the test. The ICRI level 8 and 9 surfaces (very rough) may lead to a weaker bond due to washing away too much cement paste around the course aggregate. This confirmed what has been reported previously for tension bond strengths between two cementitious materials[9].

Table 6 Failure methods of the beams.

Beam	**Failure Method**	**ICRI Surface Roughness Measurement (1-10)**
Control #1	Steel Yielded, Under-reinforced	*
Control #2	Steel Yielded, Under-reinforced	*
Control #3	Steel Yielded, Under-reinforced	*
Laminate1 #1	Steel Yielded, Concrete Crushed/Delamination at Ultimate Load	9
Laminate1 #2	Steel Yielded, Concrete Crushed/Delamination at Ultimate Load	8
Laminate1 #3	Steel Ruptured, No Delamination	7
Laminate2 #1	Steel Yielded, Concrete Crushed/Delamination at Ultimate Load	9
Laminate2 #2	Concrete Crushed, No Delamination	7
Laminate2 #3	Steel Yielded, Concrete Crushed/Delamination at Ultimate Load	7

*The control beams did not have a laminated surface.

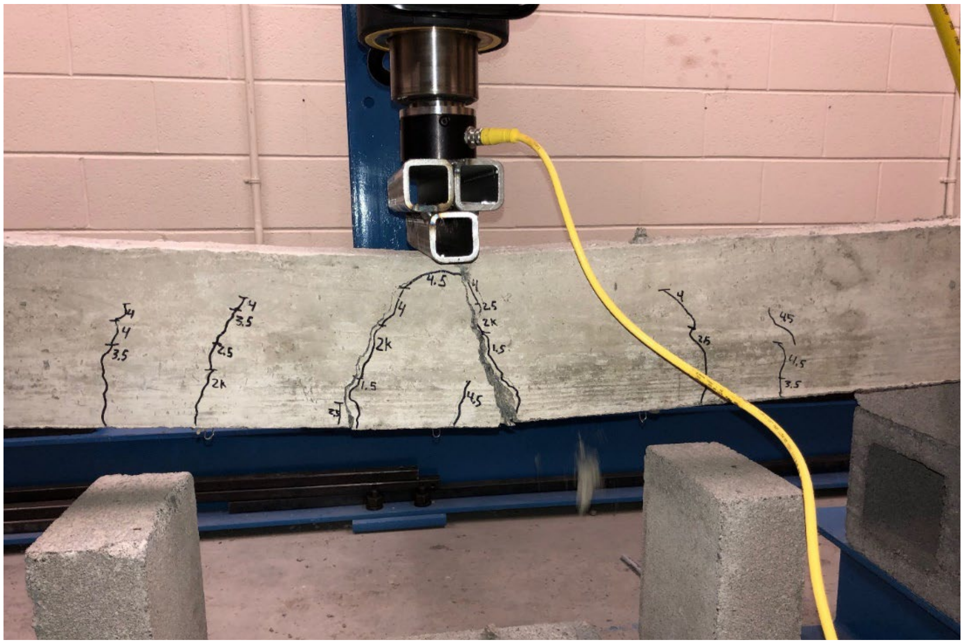

Fig. 8 Control beam failure cracking pattern.

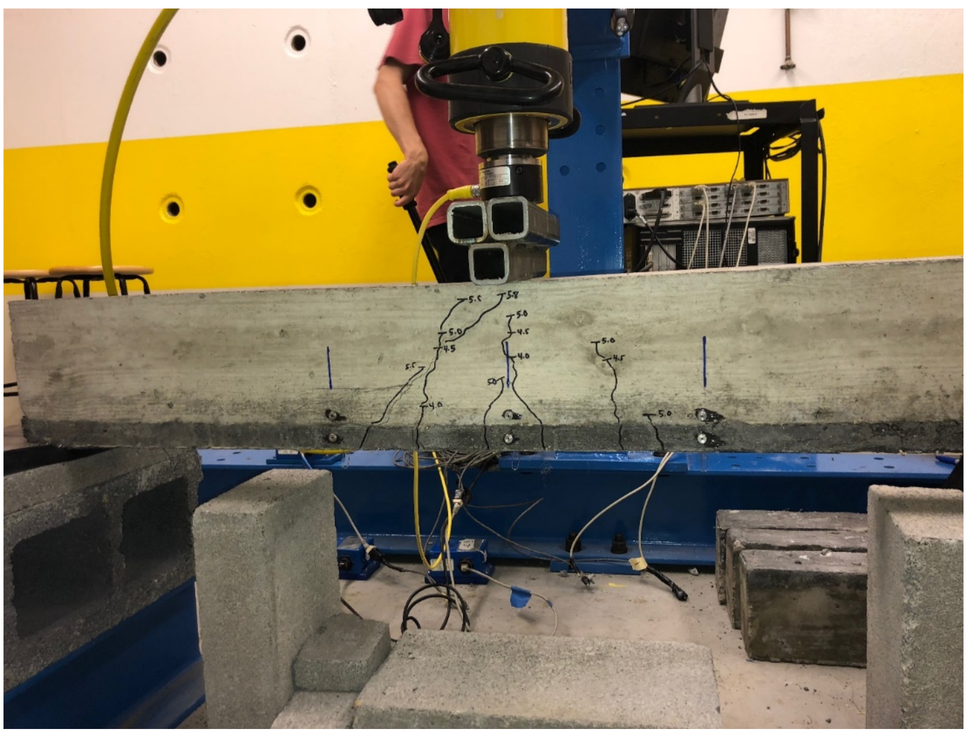

Fig. 9 Laminate1 beam cracking pattern at ultimate load without any delamination.

Fig 10 Laminate2 beam cracking pattern at ultimate load with delamination.

A post failure analysis was performed on the laminate beams that exhibited delaminations. As shown in Figure 11, both laminates bonded well with the normal strength concrete beams. The laminates pulled course aggregate out of the concrete beam. Even after the laminate started to crack at the interface under peak loads, there was still aggregate interlock holding the material together.

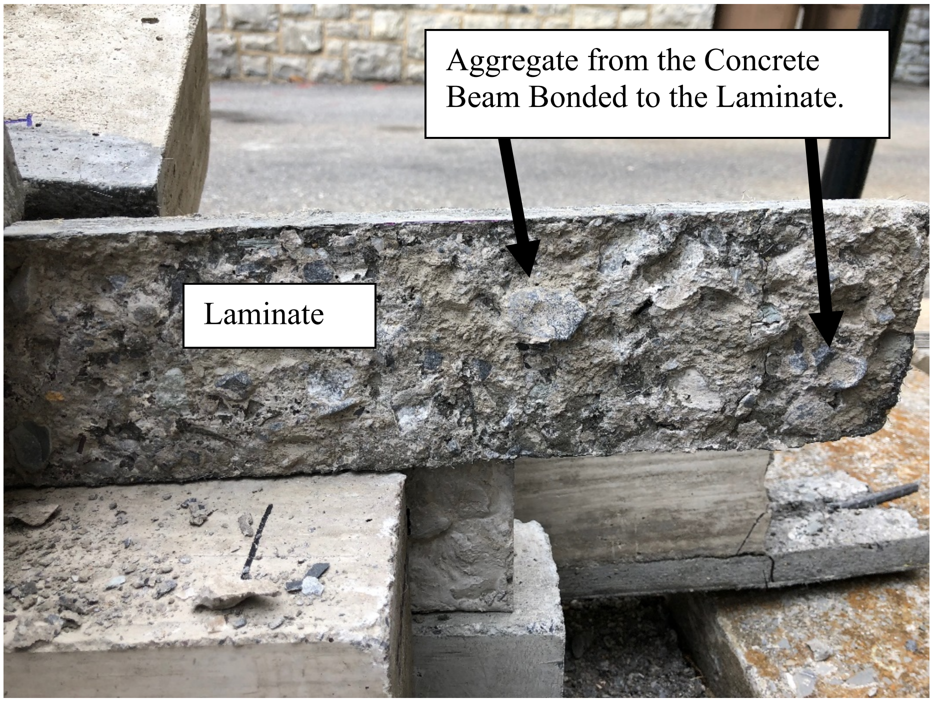

Fig. 11 Aggregate from the concrete beam embedded in the laminate after testing.

FUTURE WORK

The next phase of the project is to test beams with varying properties. This includes investigating different reinforcement ratios, development lengths, and larger clear spans. The beams in these tests all had reinforcement ratios less than 1 percent and had very ductile, under-reinforced behavior. The development length of the rebar in these beams was tested at approximately 21 in. due to the testing geometry. Additional tests on the development length of different sized reinforcing bars and the development of the laminate are planned. Previous projects demonstrated that casting a laminate next to a smooth surface did not provide a good surface bond, but the question remains how rough the surface must be to develop adequate composite behavior. The ICRI roughness of at least 7 was used to ensure a roughened surface, but there is question if a sand blasted or similar surface would be sufficient for bonding.

Additionally, casting position is a topic of future interest. All of these beams were cast with the laminate surface on top of the beam as might be performed in a precast concrete plant for new construction. Beams with laminates on the bottom could be used for retrofitting and may require additional forming and placing methods to get the HSFRC to flow much like grout in a bridge haunch. If the HSFRC laminate is used as an additional reinforcement to an existing reinforced concrete beam, another topic of interest would be the flexure strength gain.

CONCLUSIONS

A high strength fiber-reinforced concrete (HSFRC) laminate was added to standard normal strength reinforced concrete beams. The HSFRC laminate beams behaved as well or better in flexure as the control beams based on first cracking, ultimate bending strength, and ultimate cracking patterns. Specifically, the following conclusions can be drawn from the results:

1) Making an HSFRC mix with a 28-day compressive stress over 15 ksi is achievable with readily available materials and steel fibers. Two different mixes with two different types of steel fibers both achieved this goal.
2) When tested in flexure, the bond between the HSFRC and normal strength concrete was strong enough to exceed the standard computed nominal moment strengths by an average of at least 43 percent. This was the same behavior as standard reinforced concrete behavior as confirmed by the control beams.
3) The HSFRC laminates did not delaminate from the beams until significant cracking occurred well beyond when the steel yielded. Delamination was not the limiting failure mode. Using an ICRI roughness measurement value of at least 7 will ensure a solid bond.
4) The HSFRC laminates helped prevent the detection of cracks at lower flexure loads. The steel fibers arrested the cracking at lower loads that were below the yielding of the tension steel. After the steel yielded, the laminated beams cracked in patterns very similar to standard reinforced concrete beams.

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