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Flexural behavior of preflex sfrc-encased steel joist composite beams

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ABSTRACT

This research investigates the behavior of encased steel composite beams within steel fiber reinforced concrete (SFRC) in straight and preflex beams, using nonlinear analysis. ABAQUS FEA software has been adopted. Composite steel beams encased in fiber reinforced concrete are analyzed and a comparison is made with available experimental results. Good agreement with the experimental results is observed. Upwards camber of the steel section is introduced on the steel joist. It's found that the preflex section can increase the ultimate load capacity by 10% and decrease midspan displacement by 13% of the same beams without the preflex steel section. Steel fiber dosages, compressive strength, modulus of rupture are examined. The effect of cambering and mesh refinement is also investigated. The physical properties of SFRC are calculated through testing at the UTA Civil Engineering Laboratory Building. In total, nine (4″ x 8″) cylindrical specimens, nine (6″ x 12″) cylindrical specimens, and nine (6″ x 6″ x 20″) beam specimens were produced and tested for their compressive strength, tensile strength, and modulus of rupture after 28 days of curing. The addition of steel fiber will lead to a significant increase in tensile strength and modulus of rupture of concrete. Adding 1% steel fibers by volume can increase the load capacity by 33% and decrease the midspan displacement by 70% in comparison to the same beam using plain concrete. The increase in steel fibers and cambering shows an improvement to the flexural capacity and cracking point of the beam, which can provide mo re strength to structures such as long-span bridges.

1. Introduction

Preflex beams can improve the design of many structures in Civil Engineering. Bridge structures such as highways and railways require long-span girders of high strength. High-rise structures such as the Tour du Midi (1967) in Belgium use preflex beams because it utilizes concrete's high compressive strength and the ductility and toughness of structural steel. SFRC (Steel Fiber Reinforced Concrete) allows for a higher tensile and flexural strength in concrete. It also provides more ductility, toughness, and resistance to cracking [1]. Introduction of steel fibers at different percentages can add to the durability and serviceability of a structure [2]. There is a need for more understanding on the combination of these two innovations SFRC and preflex beams. The expansion of research on preflex beams with the incorporation of SFRC can improve the overall flexural performance of long-span girders.

Preflex girders are an innovative composite member that can support bridges and buildings that experience large service loads. Using a preflex section can increase the ultimate load capacity of a composite encased beam [3]. There is a limited amount of research in this field, especially as it pertains to Preflex SFRC encased steel beams. SFRC improves the material properties of the encasement so that the beam has a higher compression strength and modulus of rupture. Upwards cambering increases the flexural capacity by introducing preflexion loads to the steel portion of the beam before construction [4]. Encasing the beam with the SFRC while under this tension creates the composite beam. This preflex hybrid structure contains all the properties that are beneficial from concrete and steel [5].

Research is progressively expanding on the benefits of preflex beams and SFRC. The exploration of the two innovations in one composite structure provides better performance in flexural strength and less construction efforts and cost (Mannini & Morano, 2006).

Initially, the material properties of the SFRC are found by material testing to determine the compressive strength, tensile strength, and modulus of rupture for three different concretes, each with a different percentage of steel fibers. Then the first part of the study is done using Finite Element Analysis (FEA) to confirm the flexural behavior from the Khuntia and Goel experiment [5]. The modeled straight beam will be meshed and monotonically loaded using ABAQUS, an FEA tool that performs numerical analyses [6]. The second portion of this numerical analysis is the parametric studies, which will first investigate straight

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beams with 0–1% SFRC. The second part of the parametric study loads the preflex beam in the same manner as the straight beam with the same parameters for 0–1% SFRC to find midspan displacement. The midspan displacement will be the amount of deflection that occurs at the center of the beam where the load is acting. For each study, the beam is loaded till the collapse point by increments to achieve the most accurate approximation of midspan displacement.

2. Material testing

Material properties are found through lab testing based on [7]/C192 M procedure. The first step is to create a concrete mixture in the lab and add the volume fraction, V_f, of steel fibers. In order to do this, the following materials must go into the mix for a 27 cf batch; coarse aggregate, fine aggregate, cement, and water. The mixture quantities are shown in Table 1, and the steel fiber properties are shown in Table 2.

The mixing process is done in a standard lab concrete mixer in the Civil Engineering Laboratory Building at The University of Texas at Arlington. There are three volume fractions of steel fibers in each concrete batch. The first batch has 0% $V_f$steel fibers, the second has 0.5%, and the third has 1%. After the concrete is made in the mixer it is immediately put into the molds that ASTM specifies for each type of test. The concrete molds for the compression test are nine cylinders of 4″ x 8”. The next nine molds are the rectangular beams that are 6″ x 6″ x 20″ for the modulus of rupture test. The last set of nine molds are for the cylinders that are 6″ x 12” for the split test. Dry rodding consolidates the concrete mix and this process is important in order to ensure that the gaps/voids between the steel fibers and concrete mix are reduced. The specimens are cured for 28 days and placed in a humidity-controlled room.

Once the specimens are ready for testing [8], provides the method for testing the small cylinders (4″ x 8”) [8]. A computer-controlled compression machine from the Civil Engineering Lab Building is used. The cylinder is placed where its circular cross section is directly in contact with the load. The process is done by a consistent incremental loading of 400 lbs/sec until the cylinder reaches its ultimate load capacity. Ultimate Load capacity is the amount of load that the material can handle up until the point of failure. This load is used to calculate the compressive strength which can be found in Equation 1 where $f'_c$is the compressive strength, Prepresents the load capacity, and $r$is the radius of the cylinder.

$$f'c = \frac{P}{\pi r^2}$$

Equation 1: Compressive strength of the cylinder.

Split tests are done according to Ref. [9] using 6″ x 12” cylinders [9]. The beam lies horizontally on the testing table as a diametral compressive force loads it along its length. The machine applies the load at a rate of 100 lb/sec till the cylinder reaches failure along the vertical diameter. A steel plate with side plates is placed around the beam during this process to reduce the amount of compressive stress where the load will be applied. Once the ultimate load is recorded, the tensile strength is calculated according to Equation 2. $ft$is the tensile strength, $P$is the load capacity, Lrepresents length, and $D$is the diameter of the cylinder.

$$ft = \frac{2P}{\pi LD}$$

Equation 2: Tensile strength of cylinder.

Flexure tests are done using three-point bending on a rectangular beam (6″x6″x20″) as per [10]; and placed lengthwise under the machine as shown in Fig. 1.

Loading will occur at the 1/3 points on the beam in order to exhibit pure bending in the middle portion. The plan view of this test can be seen in Fig. 2 where the dashed lines represent the 1/3 points where the loading occurs.

This specimen is loaded at 50 lb/sec and fracture stress occurs in this middle portion called modulus of rupture as shown in Fig. 1. The machine records the ultimate load capacity and Equation 3 is used to find the modulus of rupture, f_r. $P$is the load at failure, L'is the length of the beam, D'represents the depth and $B$the width.

$$fr = \frac{PL'}{BD'^2}$$

Equation 3: Modulus of rupture of the cylinder.

The strength values from testing can be seen in Table 3 through 5. In Table 3 the concrete's compressive strength increases as the volume of steel fibers increases. The same pattern continues for the tensile strength in Table 4 and the modulus of rupture in Table 5.

3. Numerical model

Finite Element Method (FEM) analysis is the numerical approach to complicated problems such as the modeling of an element with different materials and dividing it into smaller elements to perform analysis. This concept uses many algebraic equations to find the most approximate solution for problems and yield an accurate representation of the results [11]. This research focuses on analyzing a SFRC encased steel joist composite beam using a FEA tool called ABAQUS [12]. ABAQUS is a finite element software that is applied for mathematical simulations of numerical models [6].

This study investigates how FEA can confirm the results of an experiment "Experimental Study FRC- Encased Steel Joist Composite Beams" [5]. The experiment takes two angle steel joists and encases it in 1% SFRC and performs a load analysis using an actuator and strain gauges connected to a data acquisition system as shown in Fig. 3 [5]. The propagation of cracks was marked to show the cracking pattern and extents. Crack propagation was performed by using various intervals of displacement. Crack patterns were monitored and photographed at intervals of 0.05 in.–0.5 in. Then they were monitored for intervals from 0.10 in. to 1.0 in. Finally the beam was monitored at intervals of 0.2 in Ref. [5].

The same "Experiment Specimen" is modeled in ABAQUS under monotonic load analysis to achieve the same results of load-midspan displacement. The modeling of the beam is done in ABAQUS by first creating a rectangular cross section six inches in width and 8 inches in height with a depth of 44 inches. This rectangular beam represents the SFRC, and the properties for the compressive and flexural strength are taken from the experiment's values for a SFRC of 1%. Young's Elastic Modulus is found by using the compressive strength from the experiment in the formula for normal weight normal density concrete from ACI code [13]. Two A36 steel angle joists of 3/16″ thickness and sides of 1.5″ are modeled in the beam (Khuntia& Goel, 1999). After modeling he finite

Table 1
Concrete Mix Design (Based on 27 cf).

Materials	Saturated Surface Dry (lbs.)	Moisture Correction (lbs.)	Mix Proportions (lbs.)
Cement	680	n/a	680
Coarse Aggregate	1263	17	1246
Fine Aggregate	1752	12	1741
Water	306	29	335
TOTAL	4001		4001

Table 2
Steel fiber properties.

Length (in)	Diameter (in)	Tensile Strength (ksi)
1.3	0.02	174

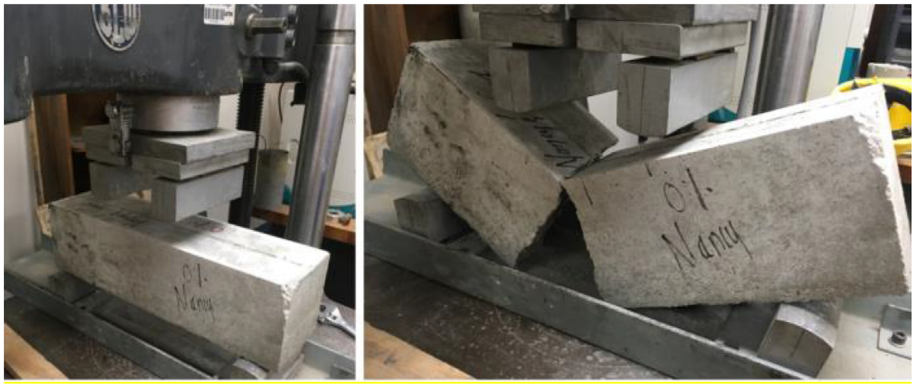

Fig. 1. Modulus of Rupture Test on a 0% SFRC beam.

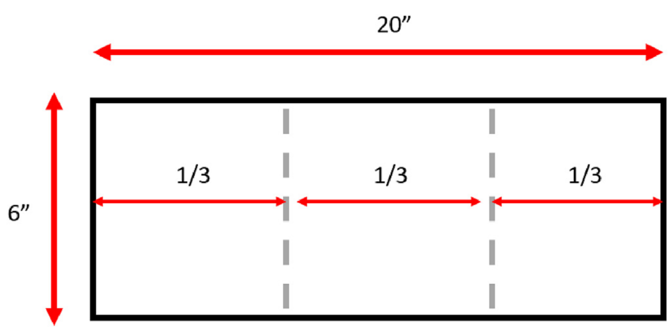

Fig. 2. Plan view of the rectangular beam for the Flexure Test.

Table 3
Concrete compression Test.

Concrete Compression Strength, f_c' (psi)			
Fiber Volume (%)	0	0.5	1
Small Cylinder 1	2810.51	3732.484	4219.745
Small Cylinder 2	2945.86	3933.121	4335.191
Small Cylinder 3	2878.185	3832.803	4277.468
Coefficient of Variation (%)	1.92	2.14	1.10
Average f_c' (psi)	**2878**	**3832**	**4277**

Table 4
Concrete split Test.

Concrete Tensile Strength, f_t (psi)			
Fiber Volume (%)	0	0.5	1
Cylinder 1	214	324	331
Cylinder 2	232	365	530
Cylinder 3	223	290	585
Coefficient of Variation (%)	3.29	9.4	22.64
Average f_t (psi)	**223**	**315**	**557**

Table 5
Concrete flexure Test.

Concrete Modulus of Rupture, f_r (psi)			
Fiber Volume (%)	0	0.5	1
Beam 1	617	856	732
Beam 2	565	648	861
Beam 3	648	556	811
Coefficient of Variation (%)	5.61	18.28	6.63
Average f_r (psi)	**609**	**686**	**801**

element model experiences load steps of 5000 lbs. to gradually analyze how the beam is deflecting at the midspan. Finally at 22 kips, the model reaches failure, which ABAQUS tells the user by stopping the run. The image of the numerical analysis of the experimental beam can be seen in Fig. 4.

A second part of the FEA is two parametric studies. While using the same dimensions of the Experiment Specimen, there are two models made in ABAQUS. The first model is a straight beam model with the parametric study parameters (PSP) of f'_c and f_r with 0%, 0.5%, and 1% volume fractions of steel fibers. The material properties from Tables 3–5

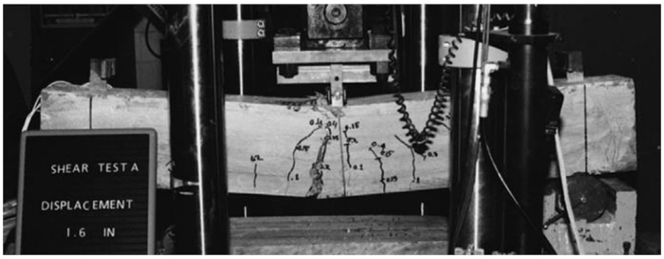

Fig. 3. Experiment Specimen at Ultimate Load (27 kips).

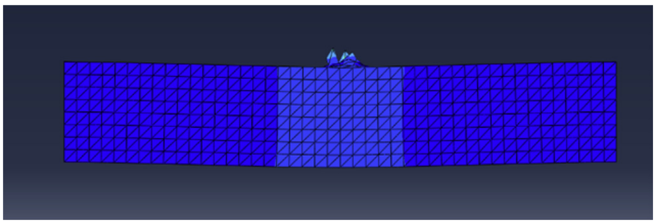

Fig. 4. Numerical Analysis of Experiment at Ultimate Load (22 kips).

are put into each model's parametric values according to which percentage of steel fibers are in the beam. The second study models a preflex beam with the same PSP values as the first model. The purpose of modeling and analyzing two different beams in ABAQUS is to see how the load-displacement relationship improves for different parameters.

The first parametric study investigates how a straight SFRC Encased Steel Joist Composite Beam responds when loaded monotonically by increments of 2 kips. For each load, ABAQUS provides the displacement values for different regions of the beam. The load is central on the beam, so the maximum displacement will be at the center. An example of how the finite element model for the 0% straight beam is loaded initially is seen in Fig. 5. After one load step of 2 kips the beam's deflection can be seen as more distributed throughout. This is because the beam has not reached failure and is able to deflect in a manner that keeps the member intact and resists the load. An example of how a straight beam is loaded for the 0% case until its final collapse can be seen in Fig. 6.

A mesh convergence study was performed to select the optimum mesh size. However, a finer mesh provides more accurate results to see how the displacement is acting in different regions of the beam. At the ultimate load capacity the member reaches a permanent fracture point. In Fig. 6 the deflection is localized in the upper midspan of the beam. In the earlier stages of loading like in Fig. 5, the displacement is more visible, but as the load increases, the deformation is not distributed because the maximum displacement occurs at the center. Despite the lack of visibility of the final displacements, the model is more accurate because of the higher number of finite elements being analyzed. This process is different from an experimental study because in reality the displacement can be seen in different parts of the beam even at its ultimate load capacity. A similar failure pattern occurs for the remaining cases.

For the second parametric study the straight beam is cambered by

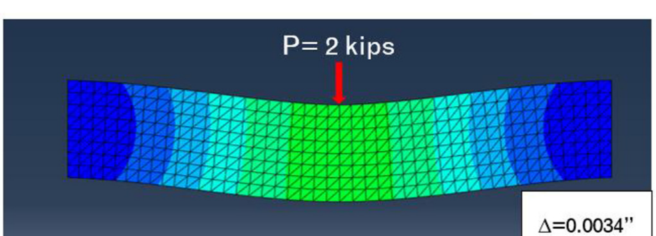

Fig. 5. 0% SFRC Straight Beam at Initial Load (2 kips).

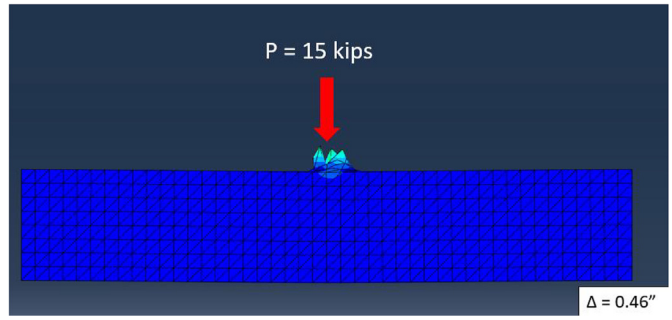

Fig. 6. 0% SFRC Straight Beam at Ultimate Load (15 kips).

0.45 inches as seen in Fig. 7. This value is found by performing a hand calculation to find load capacity of the beam. Then this load helps determine the maximum displacement the beam will experience. This amount of displacement is found to be 0.45 inches for the beam under analysis. The value is a starting point to determine how much camber should be in the preflex beam to counter what the straight beam will experience. The same load analysis is performed on the preflex beams as done on the straight beams. Example analyses of the 0% preflex beam can be seen in Figs. 8 and 9. From Fig. 8 it can be seen that the deflection distributes along the beam because it is able to withstand the initial loading of 2 kips. Then in Fig. 9 the cracking localizes at the center where

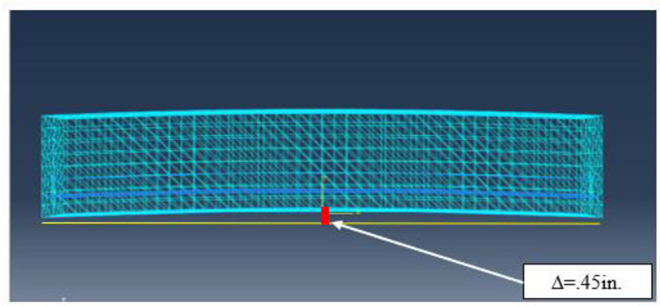

Fig. 7. Preflex Beam with upwards camber of 0.45 in.

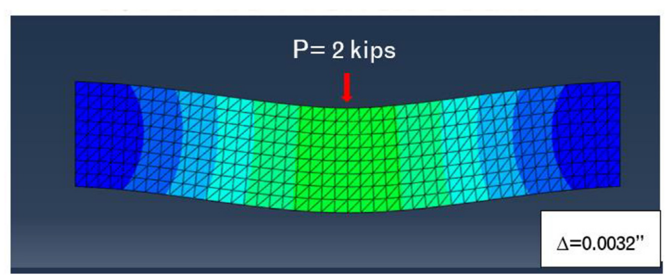

Fig. 8. 0% SFRC Preflex Beam at Initial Load (2 kips).

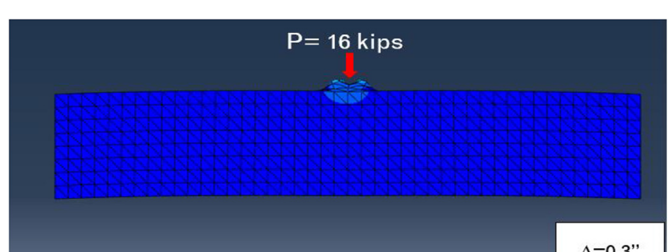

Fig. 9. 0% SFRC Preflex Beam at Ultimate Load (16 kips).

the load is acting as the preflex beam reaches its ultimate load capacity of 16 kips.

4. Numerical results

In reference to Fig. 10, the experiment specimen, the numerical analysis is variably close to the available experiment. The values for the experimental deflection are much larger than the numerical analysis because an actuator (monotonic loading) stops after the maximum displacement. The load is kept for a longer time to see the point of complete fracture in the experimental analysis, so the collapse point is based on the perspective of the researcher. Due to the realistic oppositions of lab experiments the amount of loading may become inconsistent when compared to a controlled FEA tool such as ABAQUS. The comparison between the numerical and experimental analysis of a 1% SFRC straight beam is shown in Fig. 10. For this case, the percent error for displacement and load values is 20%.

In the first parametric study, three beams with different SFRC properties are modeled with FEA and monotonically loaded by 2 kips till each reaches its ultimate load. Fig. 11 shows the load-displacement curves for each straight beam for comparison. Between 0% and 0.5% SFRC the load capacity increases by 20% and the displacement decreases by 60%. Between 0% and 1% SFRC, the load capacity increases by 33% and the midspan displacement reduces by 70%. From Parametric Study I, the FEA shows that by increasing the percent of steel fiber in the SFRC, change in f'_c and f_r has a positive impact on the beam's flexural behavior. As seen from the material testing, increasing the volume fraction of steel fibers from 0.5% to 1% in the SFRC, increases the strength of the concrete by 12%. In the case of the modulus of rupture, the strength increases by 17% with the higher volume of steel fibers. The 1% SFRC Straight Beam has the largest increase in the load capacity and the smallest amount of midspan displacement in comparison to the 0% and 0.5% SFRC Straight Beams.

In the second parametric study, a Finite Element preflex beam with an upwards camber of 0.45 inches experiences monotonic loading at 2 kips per step. The f'_c and f_r parameters for the preflex beam are consistent with parametric I study for straight beams. The load-displacement curves for the preflex beams can be seen in Fig. 12 for comparison. Between 0% and 0.5% SFRC the beam's load capacity increases by 20% and the midspan displacement decreases by about 16%. Between 0% and 1% SFRC the load capacity increases by 38% and the midspan displacement decreases by 33%. The FEA shows an increase in steel fibers in a preflex beam will increase the load capacity and decrease the midspan displacement.

The original intention of making a beam preflex is to enhance its flexural behavior. In this study, the preflex beam is meant to increase the load capacity and reduce the midspan displacement. The question is

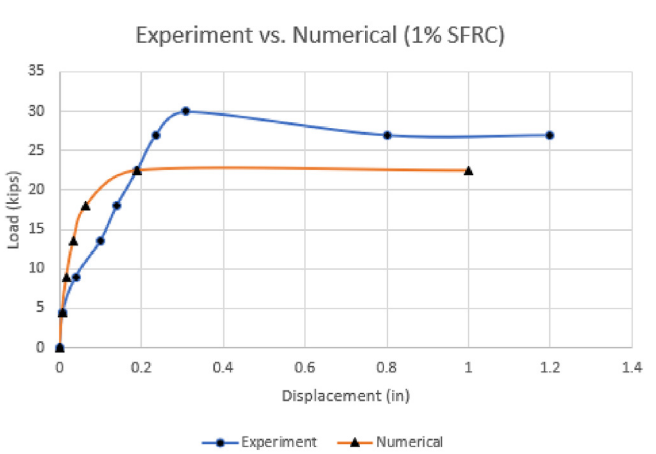

Fig. 10. Load-displacement curves of experimental and numerical model.

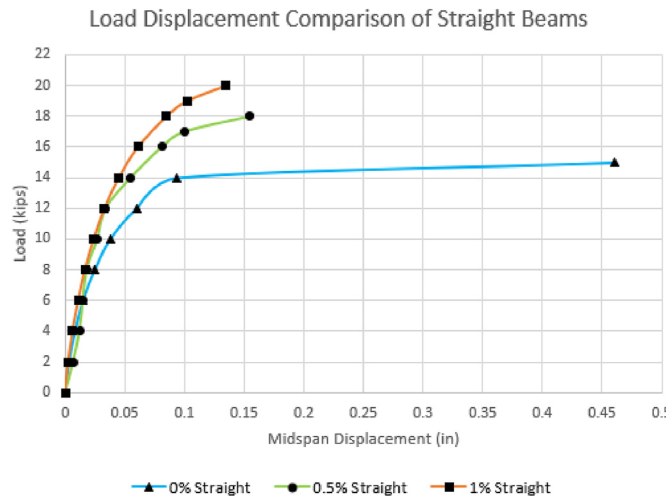

Fig. 11. Straight beam load displacement curve.

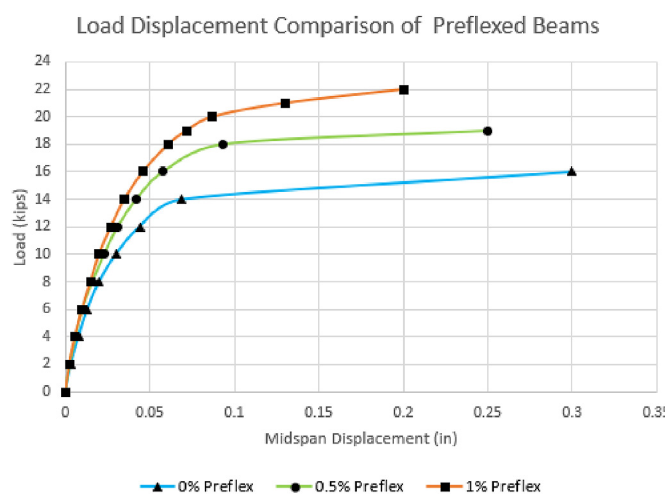

Fig. 12. Load-displacement of preflex beams.

whether the preflex combined with an increase in steel fiber percentage will add additional flexural capacity to the specimen. The FEA results improve from the straight to the preflex models. Figs. 13–15 show a comparison between the load-displacement curves of the straight and preflex beams with respect to the volume fraction of steel fibers in each beam. Between 0% SFRC Straight and 0% SFRC Preflex, the preflex beam increases the straight beams load capacity by 7% and reduces its midspan displacement by 35%. Beams 0.5% SFRC Straight and Preflex, the load capacity increases by 6% and midspan displacement decrease by 16%. For beams, 1% SFRC Straight and Preflex, the load capacity increases by 10% and the midspan displacement decrease by 13%.

5. Summarized conclusions

- Adding 1% steel fibers increases compressive strength by 48%, modulus of rupture by 30%, and tensile strength by 150%.
- For 0% and 1% SFRC, the load capacity increases by 33% and the midspan displacement decreases by 70%.
- In a comparison of a 1% SFRC straight and preflex beam, the load capacity increases by 10% and the midspan displacement decrease by 13%.

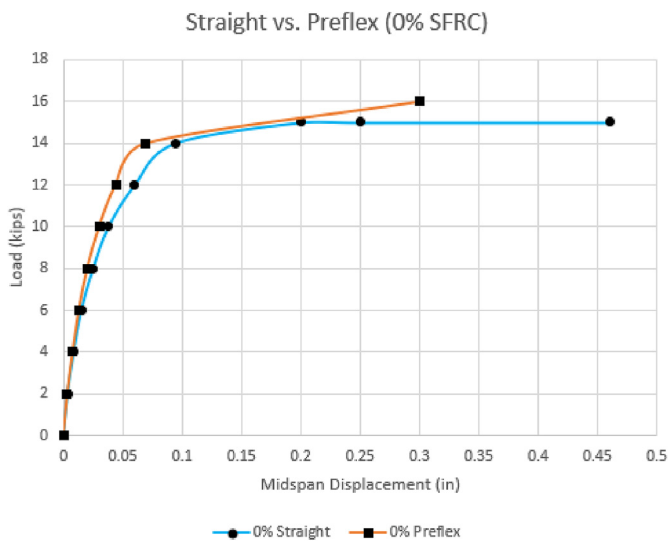

Fig. 13. 0% SFRC load-displacement curve.

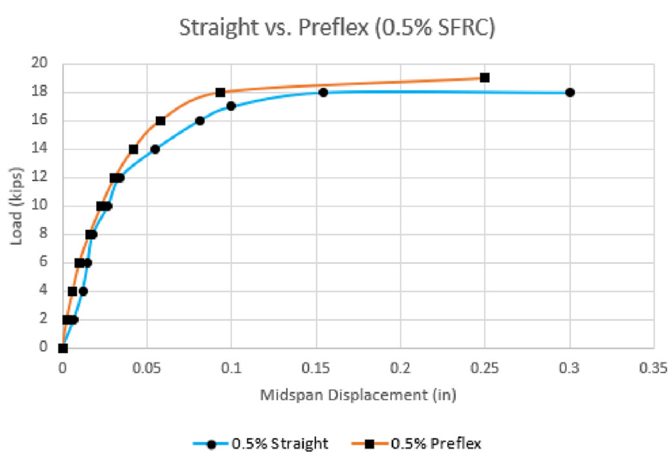

Fig. 14. 0.5% SFRC load-displacement curve.

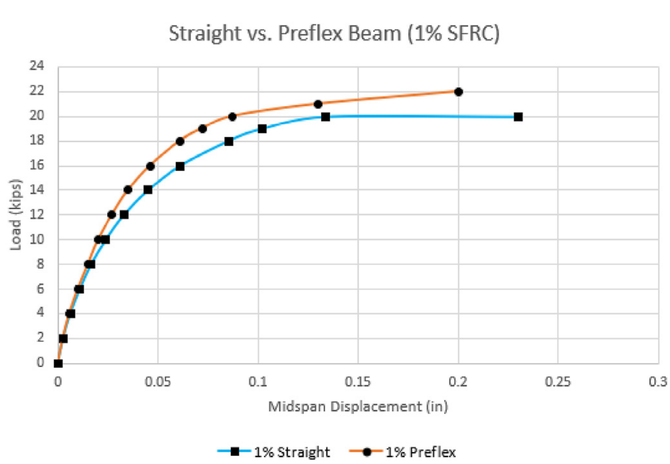

Fig. 15. 1% SFRC load displacement curve.

- In a comparison of a 0% SFRC straight and preflex beam, the midspan displacement decreases by 35%.
- Overall a 1% SFRC Preflex beam increases a plain concrete straight beam's loading capacity by 47% and reduces its midspan displacement by 60%.
- FEA results are close to the available experiment study on the SFRC encased steel beam with a percent difference of 25%.

Notation

The following Symbols are used in this paper

B	width of beam
D	diameter of cylinder
D′	depth of beam
d	diameter of anchor head
Df	fiber diameter
fr	modulus of rupture
ft	tensile strength
f'c	concrete compressive strength
L	length of cylinder
L′	span of beam
P	ultimate load
r	radius of cylinder
Vf	volume fraction of fiber

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