

Strengthening of Concrete Beams Using Innovative Ductile Fiber-Reinforced Polymer Fabric

by Nabil F. Grace, George Abdel-Sayed, and Wael F. Ragheb

An innovative, uniaxial ductile fiber-reinforced polymer (FRP) fabric has been researched, developed, and manufactured (in the Structural Testing Center at Lawrence Technological University) for strengthening structures. The fabric is a hybrid of two types of carbon fibers and one type of glass fiber, and has been designed to provide a pseudo-ductile behavior with a low yield-equivalent strain value in tension. The effectiveness and ductility of the developed fabric has been investigated by strengthening and testing eight concrete beams under flexural load. Similar beams strengthened with currently available uniaxial carbon fiber sheets, fabrics, and plates were also tested to compare their behavior with those strengthened with the developed fabric. The fabric has been designed so that it has the potential to yield simultaneously with the steel reinforcement of strengthened beams and hence, a ductile plateau similar to that for the nonstrengthened beams can be achieved. The beams strengthened with the developed fabric exhibited higher yield loads and achieved higher ductility indexes than those strengthened with the currently available carbon fiber strengthening systems. The developed fabric shows a more effective contribution to the strengthening mechanism.

Keywords: concrete; ductility; fiber reinforcement; flexure.

INTRODUCTION

The use of externally bonded fiber-reinforced polymer (FRP) sheets and strips has recently been established as an effective tool for rehabilitating and strengthening reinforced concrete structures. Several experimental investigations have been reported on the behavior of concrete beams strengthened for flexure using externally bonded FRP plates, sheets, or fabrics. Saadatmanesh and Ehsani (1991) examined the behavior of concrete beams strengthened for flexure using glass fiber-reinforced polymer (GFRP) plates. Ritchie et al. (1991) tested reinforced concrete beams strengthened for flexure using GFRP, carbon fiber-reinforced polymer (CFRP), and G/CFRP plates. Grace et al. (1999) and Triantafillou (1992) studied the behavior of reinforced concrete beams strengthened for flexure using CFRP sheets. Norris, Saadatmanesh, and Ehsani (1997) investigated the behavior of concrete beams strengthened using CFRP unidirectional sheets and CFRP woven fabrics. In all of these investigations, the strengthened beams showed higher ultimate loads compared to the nonstrengthened ones. One of the drawbacks experienced by most of these strengthened beams was a considerable loss in beam ductility. An examination of the load-deflection behavior of the beams, however, showed that the majority of the gained increase in load was experienced after the yield of the steel reinforcement. In other words, a significant increase in ultimate load was experienced without much increase in yield load. Hence, a significant increase in service level loads could hardly be gained.

Apart from the condition of the concrete element before strengthening, the steel reinforcement contributes significantly

to the flexural response of the strengthened beam. Unfortunately, available FRP strengthening materials have a behavior that is different from steel. Although FRP materials have high strengths, most of them stretch to relatively high strain values before providing their full strength. Because steel has a relatively low yield strain value when compared with the ultimate strains of most of the FRP materials, the contribution of both the steel and the strengthening FRP materials differ with the deformation of the strengthened element. As a result, steel reinforcement may yield before the strengthened element gains any measurable load increase. Some designers place a greater FRP cross section, which generally increases the cost of the strengthening, to provide a measurable contribution, even when deformations are limited (before the yield of steel). Debonding of the strengthening material from the surface of the concrete, however, is more likely to happen in these cases due to higher stress concentrations. Debonding is one of the undesired brittle failures involved with this technique of strengthening. Although using some special low-strain fibers such as ultra-high-modulus carbon fibers may appear to be a solution, it would result in brittle failures due to the failure of fibers. The objective of this paper is to introduce a new pseudo-ductile FRP fabric that has a low strain at yield so that it has the potential to yield simultaneously with the steel reinforcement, yet provide the desired strengthening level.

RESEARCH SIGNIFICANCE

FRPs have been increasingly used as materials for rehabilitating and strengthening reinforced concrete structures. Currently available FRP materials, however, lack the ductility and have dissimilar behaviors to steel reinforcement. As a result, the strengthened beams may exhibit a reduced ductility, lack the desired strengthening level, or both. This study presents an innovative pseudo-ductile FRP strengthening fabric. The fabric provides measurably higher yield loads for the strengthened beams and helps to avoid the loss of ductility that is common with the use of currently available FRP.

DEVELOPMENT OF HYBRID FABRIC

To overcome the drawbacks mentioned previously, a ductile FRP material with low yield strain value is needed.

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Table 1—Mechanical properties of composite fibers*

Fiber material	Description	Modulus of elasticity, GPa (Msi)	Tensile strength, MPa (ksi)	Failure strain, %
Carbon No. 1	Ultra-high-modulus carbon fibers	379 (55)	1324 (192)	0.35
Carbon No. 2	High-modulus carbon fibers	231 (33.5)	2413 (350)	0.9 to 1.0
Glass	E-glass fibers	48 (7)	1034 (150)	2.1

*Composite properties are based on 60% fiber volume fraction.

Literature review on hybridization

To develop this material, hybridization for different fibers was considered. Hybridization of more than one type of fibrous materials was the interest of many materials science researchers. Most of their work was concerned with combining two types of fibers to enhance the mechanical properties of either type acting alone and to reduce the cost. This has been reported in several publications such as Bunsell and Harris (1974), Philips (1976), Manders and Bader (1981), Chow and Kelly (1980), and Fukuda and Chow (1981). Hybridization interested structural engineers as a tool to overcome the problem of a lack of ductility in FRP reinforcing bars. Nanni, Henneke, and Okamoto (1994) studied bars of braided aramid fibers around a steel core. Tamuzs and Tepfers (1995) reported experimental investigations for hybrid fiber bars using different combinations of carbon and aramid fibers. Somboonsong, Frank, and Harris (1998) developed a hybrid FRP reinforcing bar using braided aramid fibers around a carbon fiber core. Harris, Somboonsong, and Frank (1998) used these bars in reinforcing concrete beams to achieve the general load-deflection behavior of concrete beams reinforced with conventional steel.

Design concept and materials

To generate ductility, a hybridization technique of different types of fibers has been implemented. Three fibers have been selected with a different magnitude of elongations at failure. Figure 1 shows the stress-strain curves in tension for the selected composite fibers, and Table 1 shows their mechanical properties.

The technique is based on combining these fibers together and controlling the mixture ratio so that when they are loaded together in tension, the fibers with the lowest elongation (LE) fail first, allowing a strain relaxation (an increase in strain without an increase in load for the hybrid). The remaining high-elongation (HE) fibers are proportioned to sustain the total load up to failure. The strain value at failure of the LE fibers presents the value of the yield-equivalent strain of the hybrid, while the HE fiber strain at failure presents the value of ultimate strain. The load corresponding to failure of LE fibers presents the yield-equivalent load value, and the

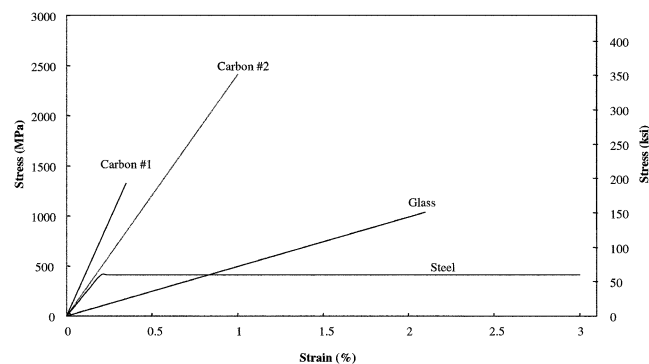


Fig. 1—Stress-strain behavior of composite fibers and steel reinforcing bars.

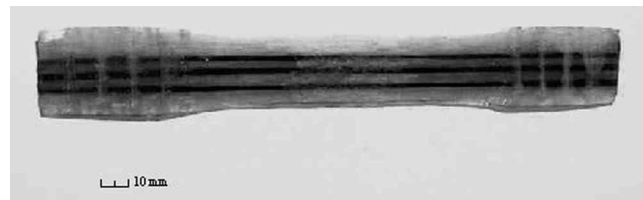


Fig. 2—Test sample for developed uniaxial hybrid fabric.

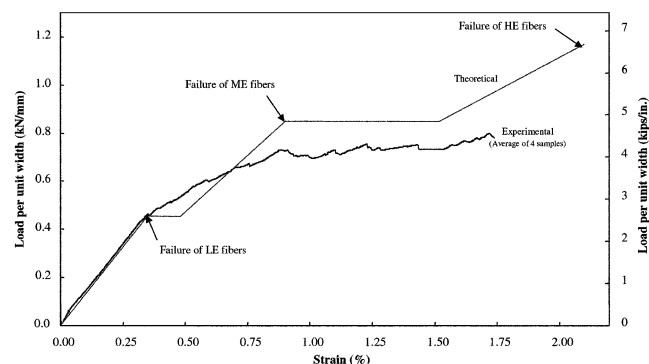


Fig. 3—Results of tensile tests for developed hybrid fabric.

maximum load carried by the HE fibers is the ultimate load value. Ultra-high-modulus carbon fibers (Carbon No. 1) have been used as LE fibers to have as low a strain as possible, but not less than the yield strain of steel (approximately 0.2% for Grade 60 steel). On the other hand, E-glass fibers were used as HE fibers to provide as high a strain as possible to produce a high-ductility index (the ratio between deformation at failure and deformation at yield). High-modulus carbon fibers (Carbon No. 2) were selected as medium-elongation (ME) fibers to minimize the possible load drop during the strain relaxation that occurs after failure of the LE fibers, and also to provide a gradual load transition from the LE fibers to the HE fibers. Based on this concept, a uniaxial fabric was fabricated and tested to compare its behavior in tension with the theoretical predicted loading behavior. The theoretical behavior is based on the rule of mixtures, in which the axial stiffness of the hybrid is calculated by a summation of the relative stiffness of each of its components. The fabric was manufactured by combining different fibers as adjacent yarns and impregnating them inside a mold by an epoxy resin. Figure 2 shows a photo of one of the fabricated samples. Woven glass fiber tabs were provided at both ends of the test coupons to eliminate stress concentrations at end fixtures during testing. The coupons had a thickness of 2 mm (0.08 in.) and a width of 25.4 mm

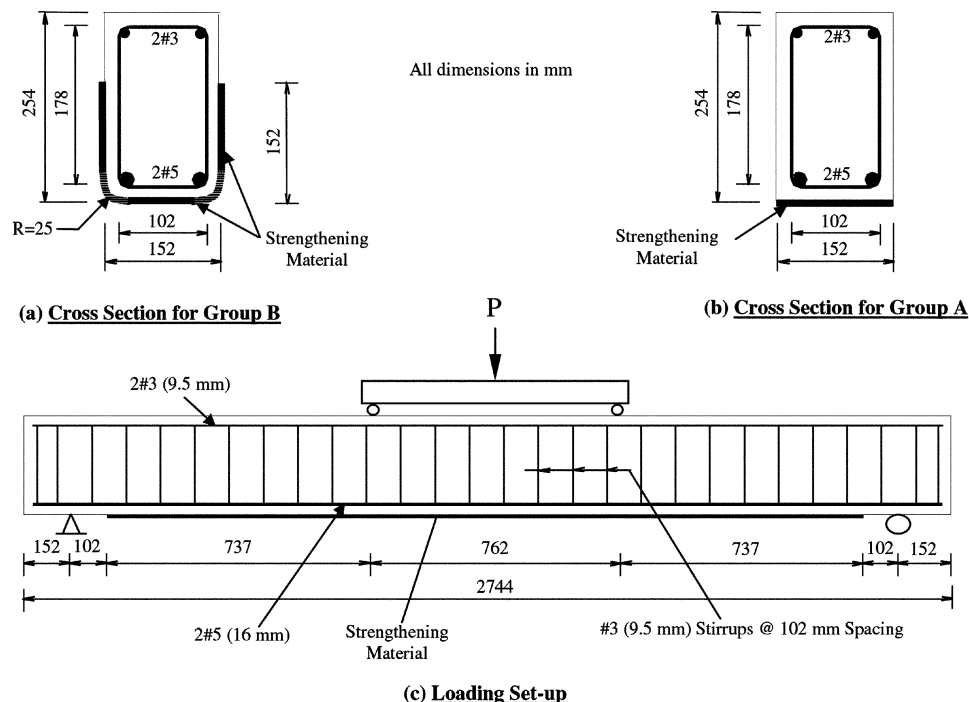


Fig. 4—Details of test beams.

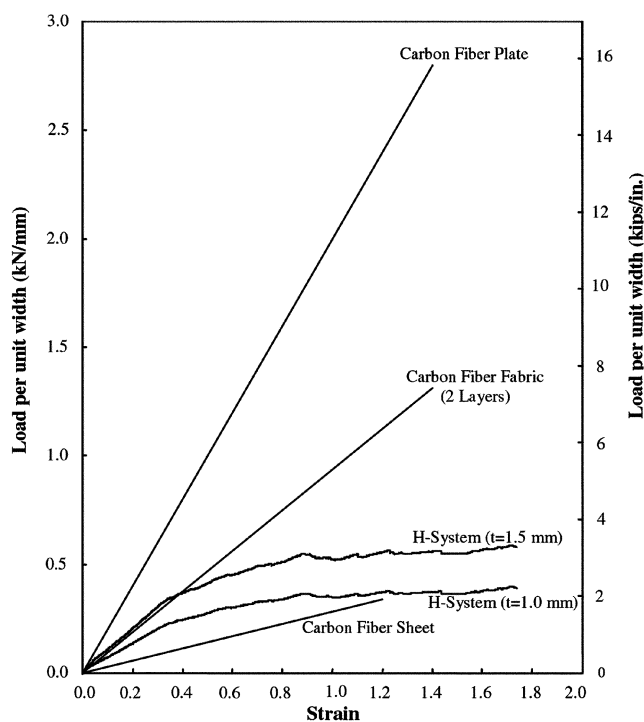


Fig. 5—Comparison between carbon fiber plate, fabric, sheet, and developed hybrid fabric (H-System).

(1 in.) and were tested in tension according to ASTM D 3039 specifications. The average load-strain curve for four tested samples is shown in Fig. 3 together with the theoretical prediction. It should be noted that the behavior is linear up to a strain of 0.35%, when the LE fibers started to fail. At this point, the strain increased at a faster rate than the load. When the strain reached 0.90%, the ME fibers started to fail, resulting in an additional increase in strain without a significant increase in load, up to the total failure of the coupon by failure of the

HE fibers. A yield-equivalent load (the first point on the load-strain curve where the behavior becomes nonlinear) of 0.46 kN/mm width (2.6 kips/in.) and an ultimate load of 0.78 kN/mm (4.4 kips/in.) are observed.

BEAM TESTS

Beam details

Thirteen reinforced concrete beams with cross-sectional dimensions of 152 x 254 mm (6 x 10 in.) and lengths of 2744 mm (108 in.) were cast. The flexure reinforcement of the beams consisted of two No. 5 (16 mm) tension bars near the bottom, and two No. 3 (9.5 mm) compression bars near the top. To avoid shear failure, the beams were over-reinforced for shear with No. 3 (9.5 mm) closed stirrups spaced at 102 mm (4.0 in.). Five beams were formed with rounded corners of 25 mm (1 in.) radius to facilitate the installation of the strengthening material on their sides and bottom faces without stress concentrations. Figure 4 shows the beam dimensions, reinforcement details, support locations, and location of loading points. The steel used was Grade 60 with a yield strength of 415 MPa (60,000 psi), while the concrete compressive strength at the time of testing the beams was 55.2 MPa (8000 psi).

Strengthening materials

The developed hybrid fabric was used to strengthen eight beams. Two different thicknesses of fabric were used. The first (H-system, $t = 1.0$ mm) had a thickness of 1.0 mm (0.04 in.), and the second (H-system, $t = 1.5$ mm) had a thickness of 1.5 mm (0.06 in.). Four other beams were strengthened with three currently available carbon fiber strengthening materials: 1) a uniaxial carbon fiber sheet with an ultimate load of 0.34 kN/mm (1.95 kips/in.); 2) two layers of a uniaxial carbon fiber fabric with an ultimate load of 1.31 kN/mm (7.5 kips/in.) for the two layers combined; and 3) a pultruded carbon fiber plate with an ultimate load of 2.8 kN/mm (16 kips/in.). The tested load-strain diagrams for

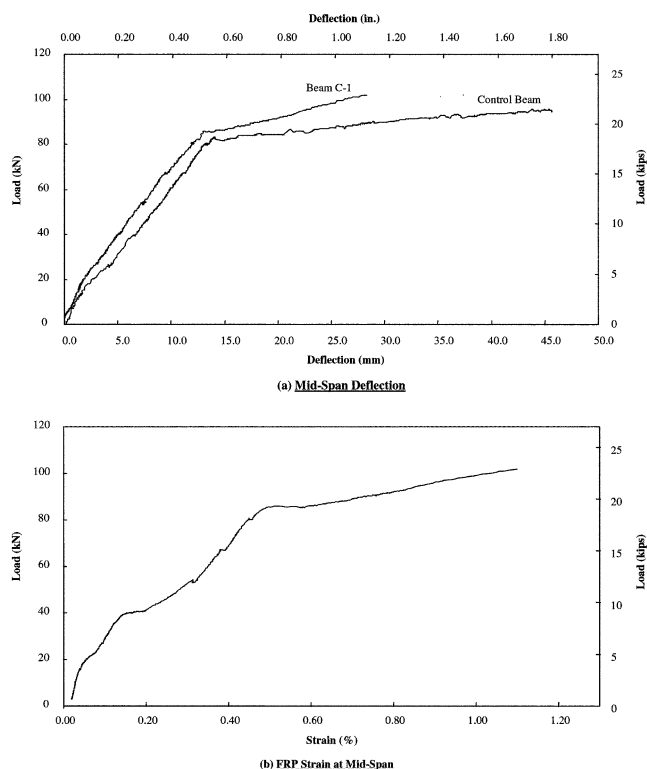


Fig. 6—Behavior of Beam C-1.

all these materials are shown in Fig. 5. Table 2 shows the properties of the strengthening materials, including the developed fabric.

Adhesives

For the hybrid fabric, an epoxy resin (Epoxy A) was used to impregnate the fibers and as an adhesive between the fabric and the concrete surface. This epoxy had an ultimate strain of 4.4% to ensure that it would not fail before the failure of the fibers. For the beams strengthened with carbon fiber sheets, plates, and fabric, an epoxy resin with an ultimate strain of 2.0% was used (Epoxy B). The mechanical properties of the adhesives provided by their manufactures are shown in Table 3.

Strengthening

The beam bottom faces and sides were sandblasted to roughen the surface. The beams were then cleaned with acetone to remove dirt. Two strengthening configurations were used: 1) strengthening material on the bottom face of the beam only (Beam Group A); and 2) strengthening material on the bottom face and extended up 152 mm (6 in.) on both sides to cover approximately all the flexural tension portions of the beam (Beam Group B). The strengthening was installed for 2.24 m (88 in.), centered along the length of the beam. The epoxy was allowed to cure for at least 2 weeks before the beams were tested. For the beams strengthened with the developed hybrid fabric (H-system), two beams were fabricated and tested for each configuration to verify the results. Table 4 summarizes the test beams.

Instrumentation

The FRP strain at midspan was measured by three strain gages located at the bottom face of the beam. The steel tensile strain was measured by monitoring the strain on the side

Table 2—Properties of strengthening materials

Type	Yield-equivalent load, kN/mm (kips/in.)	Yield-equivalent strain, %	Ultimate load, kN/mm (kips/in.)	Ultimate strain, %	Thickness, mm (in.)
Carbon fiber sheet*	—	—	0.34 (1.95)	1.2	0.13 (0.005)
Carbon fiber plate*	—	—	2.8 (16.0)	1.4	1.3 (0.05)
Carbon fiber fabric*	—	—	1.31 (7.50)	1.4	1.90 (0.075)
H-system [†] (t = 1 mm)	0.23 (1.30)	0.35	0.39 (2.24)	1.74	1.0 (0.04)
H-system [†] (t = 1.5 mm)	0.34 (1.95)	0.35	0.59 (3.36)	1.74	1.5 (0.06)

*Commercially available.

[†]Developed ductile hybrid system.

Table 3—Properties of epoxy adhesives

Epoxy type	Tensile strength, MPa (ksi)	Ultimate strain, %	Compressive strength, MPa (ksi)
A	66.3 (9.62)	4.4	109.2 (15.84)
B	68.9 (10.0)	2.0	86.2 (12.50)

Table 4—Summary of test beams

Beam group	Beam designation	Strengthening material
N/A	Control	N/A
Group A	C-1	Carbon fiber sheet
	C-2	Carbon fiber plate
	C-3	Carbon fiber fabric
	H-50-1	H-system (t = 1 mm)
	H-50-2	
	H-75-1	H-system (t = 1.5 mm)
	H-75-2	
Group B	CS	Carbon fiber sheet
	H-S50-1	H-system (t = 1 mm)
	H-S50-2	
	H-S75-1	H-system (t = 1.5 mm)
	H-S75-2	

surface of the beam at reinforcing bar level using a DEMEC (detachable mechanical gage) with gage points for Beam Group A, while strain gages were used for Beam Group B. The midspan deflection was measured using a string potentiometer. The beams were loaded using a hydraulic actuator. The load was measured by means of a load cell. All the sensors were connected to a data acquisition system to scan and record the readings.

TEST RESULTS AND DISCUSSION

Control beam

The control beam had a yield load of 82.3 kN (18.5 kips) and an ultimate load of 95.7 kN (21.5 kips). The beam failed by the yielding of steel, followed by compression failure of concrete at the midspan. Test results for the control beam are shown in the figures of the test results of the strengthened beams (Fig. 6 through 15).

Beam Group A

Beam Group A contains the beams strengthened at the bottom face only. Figure 6 to 11 show the test results for these beams. The results of Beams H-50-1 and H-75-1 were

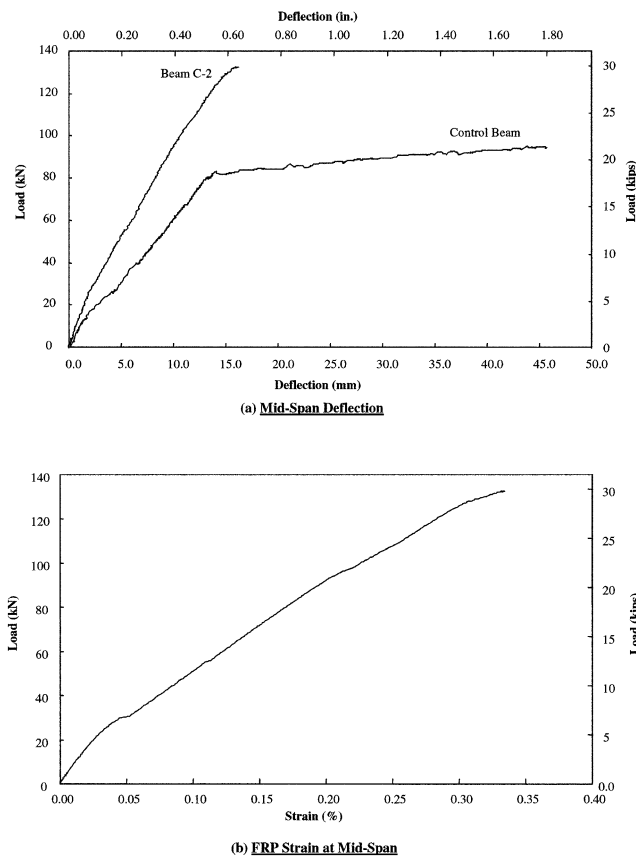


Fig. 7—Behavior of Beam C-2.

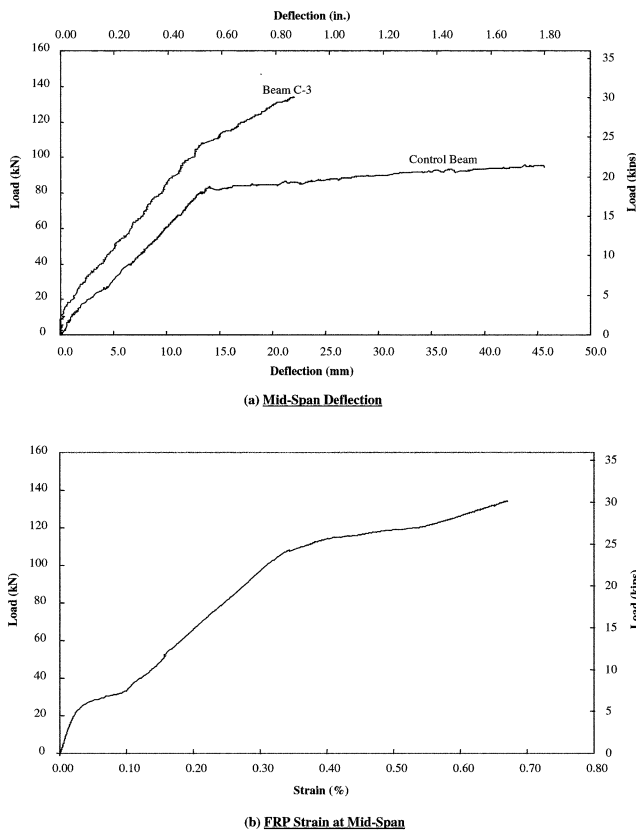


Fig. 8—Behavior of Beam C-3.

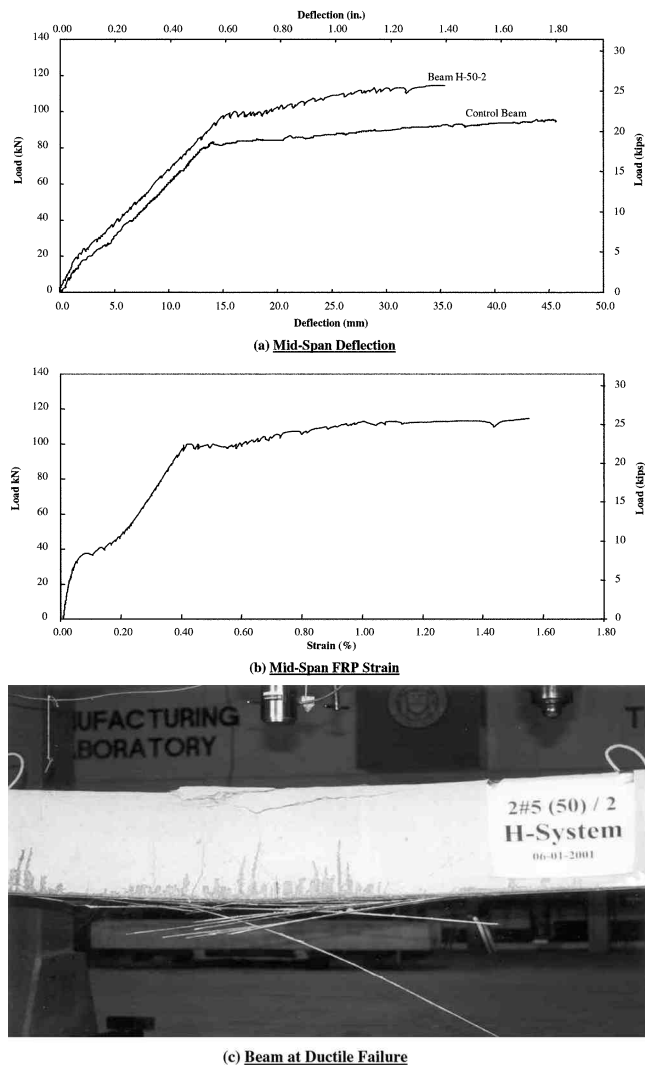


Fig. 9—Behavior of Beam H-50-2.

very close to those of H-50-2 and H-75-2, respectively, and hence, the discussions concerning these beams are focused on the last two to avoid repetition. The ductility of each beam is observed by calculating the ductility index as the ratio between the deflection of the beam at failure and its deflection at yield.

Figure 6(a) shows the load-versus-midspan deflection diagram for Beam C-1, in which the carbon fiber sheet was used for strengthening. The beam yielded at a load of 85.9 kN (19.3 kips) and failed at a load of 101.9 kN (22.9 kips) due to rupture of the carbon fiber sheet. From this figure, it should be noted that, although ductile behavior is experienced, only a 4% increase in the yield load compared with that of the control beam was achieved. A ductility index of 2.15 was experienced. Figure 6(b) shows the load versus carbon fiber strain at mid-span.

Figure 7(a) shows the load-deflection response for Beam C-2. This beam was strengthened using the pultruded carbon fiber plate. The beam showed no yielding plateau (1.0 ductility index) and had a sudden failure at 132.6 kN (29.8 kips) due to shear-tension failure at the end of the plate. Although an increase in load of 61% was obtained, the failure was brittle. Figure 7(b) shows the load versus carbon fiber strain at midspan. The maximum recorded strain of carbon fiber

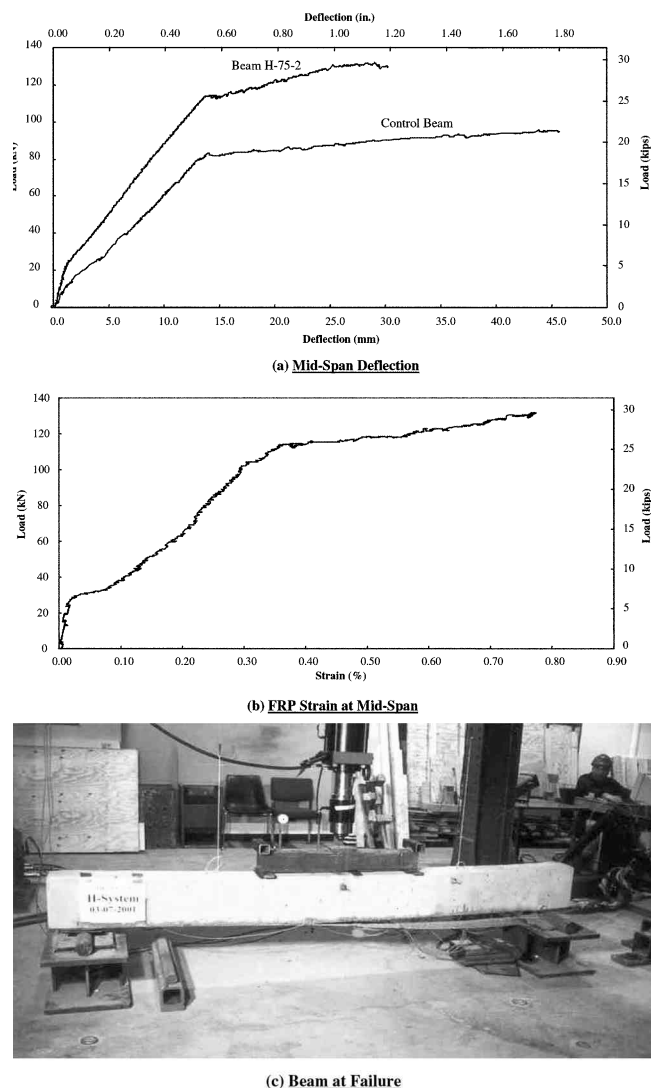


Fig. 10—Behavior of Beam H-75-2.

plate at failure was 0.33%, which indicates that 24% of the capacity of the plate was utilized.

The load-deflection response of Beam C-3 is shown in Fig. 8(a). Beam C-3 was strengthened by two layers of the carbon fiber fabric. The beam yielded at a load of 107.7 kN (24.2 kips) and failed by fabric debonding at a load of 134.4 kN (30.2 kips) before showing any significant yielding plateau similar to that of the control beam. A ductility index of 1.64 was achieved. From Fig. 8(b), it should be noted that the maximum recorded carbon fiber strain at failure was 0.67%, which indicates that approximately 48% of the fabric capacity was utilized.

Figure 9(a) shows the load-deflection response of Beam H-50-2. This beam was strengthened with developed 1 mm-thick hybrid fabric. A yield load of 97.9 kN (22.0 kips) was experienced (a 19% increase in yield load over that of the control beam). It should be noted from Fig. 9(b) that the fabric had a strain of 0.40% when the beam yielded. The beam experienced a ductility index of 2.33 and failed by total rupture of the fabric at an ultimate load of 114.8 kN (25.8 kips). Figure 9(c) shows the beam at failure.

Figure 10(a) shows the load-deflection response for Beam H-75-2. The beam was strengthened with 1.5 mm-thick developed hybrid fabric. The beam yielded at a load of

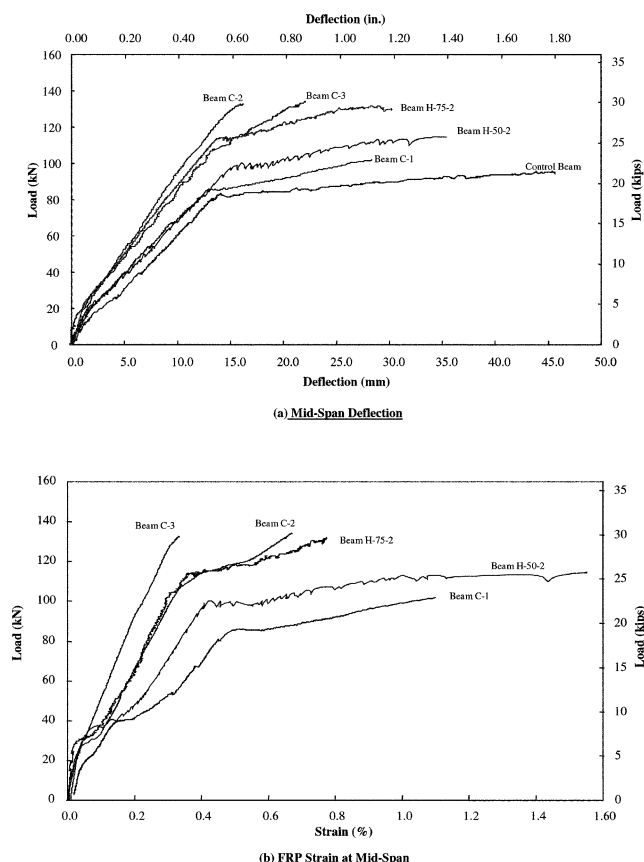


Fig. 11—Comparison between Group A beams.

113.9 kN (25.6 kips) and exhibited a ductility index of 2.13 before total failure occurred from the debonding of the fabric at an ultimate load of 130.8 kN (29.4 kips). It is noticed that, although final failure was from the debonding of the fabric, it happened after achieving a reasonable ductility. Figure 10(b) shows that the fabric had a strain of 0.35% when the beam yielded. Figure 10(c) shows the beam at failure.

Figure 11 and Table 5 compare the results from Beam Group A. The following are observed:

1. Beams C-1 and H-50-2 exhibited relatively good ductile behaviors. Beam H-50-2, however, showed a higher yield load than Beam C-1. This is because the developed hybrid fabric was designed so that it has a higher initial stiffness than the carbon fiber sheet; hence, it contributed to strengthening more effectively than the carbon fiber sheet before the steel yielded;

2. Although the carbon fiber fabric had an ultimate load several times greater than the yield-equivalent load of the 1.5 mm-thick hybrid fabric, Beam H-75-2 showed a similar behavior to Beam C-3, up to its yield. Beam H-75-2, however, exhibited a reasonable yielding plateau, and Beam C-3 did not;

3. Relative to current carbon fiber strengthening materials, the developed fabric has a yield-equivalent strain that is close to the yield strain of steel. Although it is still higher, hybrid fabric strain values were close to its yield value when the beam yielded, which indicated that it yielded simultaneously with the steel. This is attributed in part to the fabric being installed on the outer surface of the beam, which undergoes more tensile strain than inner steel. As a result, the designed yield strain value of the fabric seems to be acceptable; and

Table 5—Summary of test results

Beam designation (1)	Strengthening system (2)	Yield load, kN (kips) (3)	Deflection at yield, mm (in.) (4)	Failure load, kN (kips) (5)	Deflection at failure, mm (in.) (6)	Ductility index = $\frac{\text{Col. (6)}}{\text{Col. (4)}}$ (7)	FRP strain at failure, % (8)	Type of final failure (9)
Control	N/A	82.3 (18.5)	14.0 (0.55)	95.7 (21.5)	49.5 (1.95)	3.55	N/A	Steel yield followed by concrete failure
C-1	Carbon fiber sheet	85.9 (19.3)	13.2 (0.52)	101.9 (22.9)	28.4 (1.12)	2.15	1.10	Steel yield followed by FRP rupture
C-2	Carbon fiber plate	—	—	132.6 (29.8)	16.0 (0.63)	1.00	0.33	Shear tension failure
C-3	Carbon fiber fabric	107.7 (24.2)	13.5 (0.53)	134.4 (30.2)	22.1 (0.87)	1.64	0.67	Steel yield followed by FRP debonding
H-50-2	H-system ($t = 1.0$ mm)	97.9 (22.0)	15.2 (0.6)	114.8 (25.8)	35.6 (1.40)	2.33	1.55	Steel and FRP yield followed by FRP rupture
H-75-2	H-system ($t = 1.5$ mm)	113.9 (25.6)	13.7 (0.54)	130.8 (29.4)	29.2 (1.15)	2.13	0.74	Steel and FRP yield followed by FRP debonding
CS	Carbon fiber sheet	99.2 (22.3)	14.2 (0.56)	123.3 (27.7)	29.0 (1.14)	2.04	1.00	Steel yield followed by concrete failure
H-S50-2	H-system ($t = 1.0$ mm)	113.9 (25.6)	14.2 (0.56)	146.4 (32.9)	32.0 (1.26)	2.25	1.20	Steel and FRP yield followed by concrete failure
H-S75-2	H-system ($t = 1.5$ mm)	127.3 (28.6)	15.8 (0.62)	162.0 (36.4)	29.7 (1.17)	1.89	0.74	Steel and FRP yield followed by concrete failure

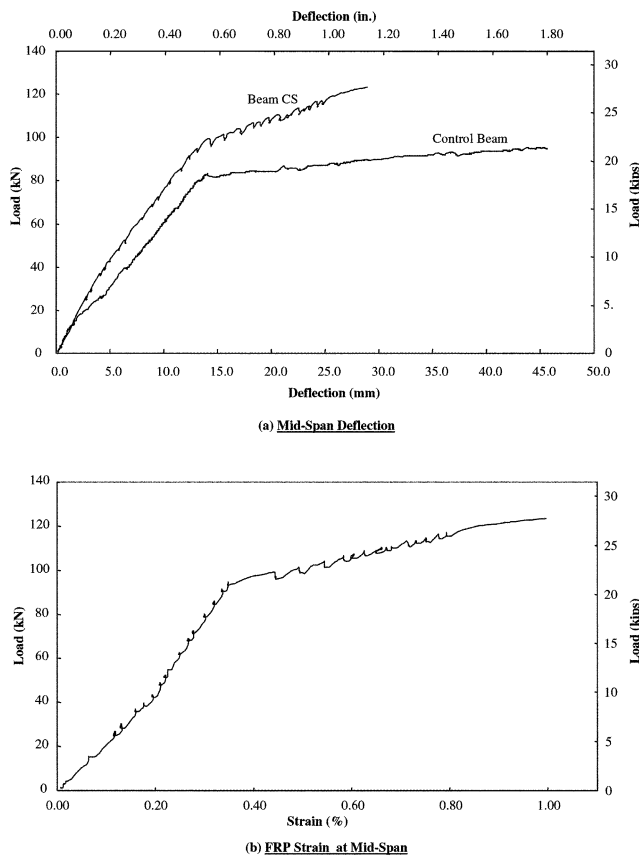
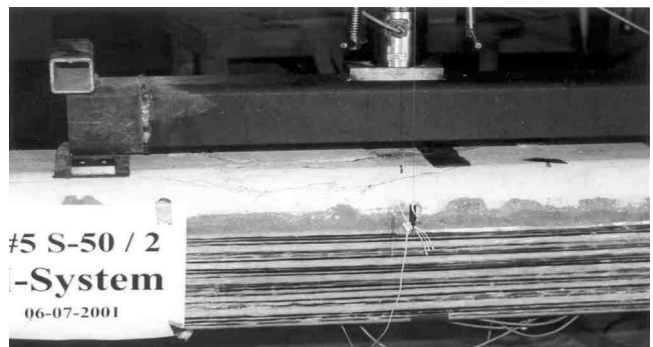
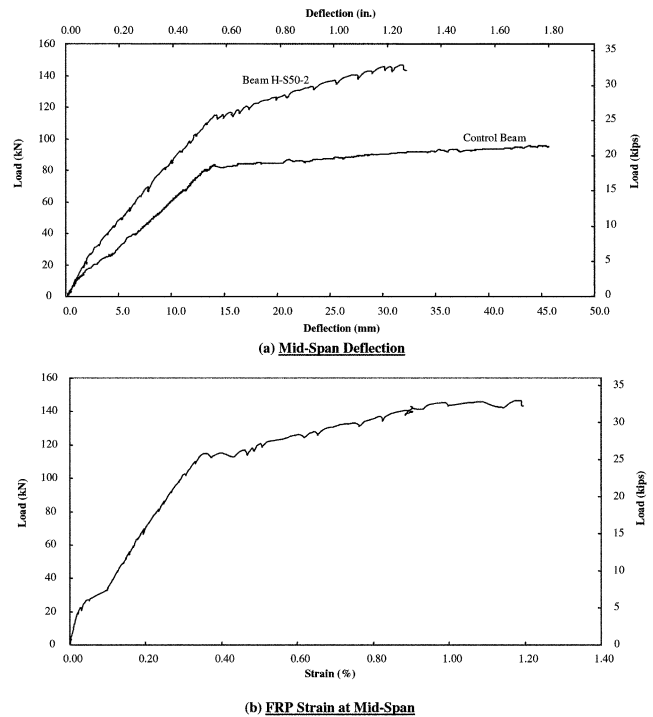


Fig. 12—Behavior of Beam CS.

4. While the use of a carbon fiber plate of a high load capacity (like the one used in Beam C-2) provided a high failure load, it also produced a brittle failure.

Beam Group B

The beams in this group were strengthened at the bottom face and also up 152 mm (6 in.) on both sides. The results of this group are shown in Table 5 and Fig. 12 through 15. The



(c) Beam at failure

Fig. 13—Behavior of Beam H-S50-2.

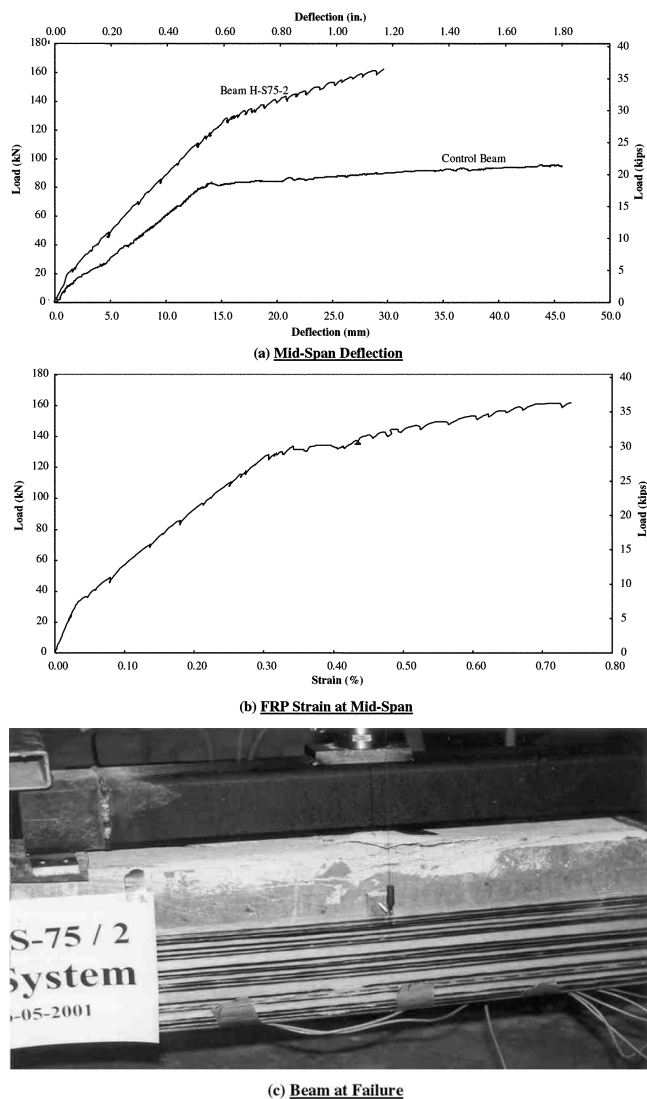


Fig. 14—Behavior of Beam H-S75-2.

results of Beams H-S50-1 and H-S75-1 were very close to those of H-S50-2 and H-S75-2, respectively, and hence, the discussions concerning these beams are focused on the last two to avoid repetition.

Figure 12(a) shows the load-versus-deflection response of Beam CS. This beam was strengthened using the carbon fiber sheet system. The beam yielded at a load of 99.2 kN (22.3 kips) due to the yielding of the steel. The increase in yield load was 20%. The beam failed at an ultimate load of 123.3 kN (27.7 kips) due to compression failure of concrete at midspan. Figure 12(b) shows that the carbon fibers had a strain of 0.35% when the beam yielded, and hence contributed approximately 30% of its capacity at this stage of loading. The maximum recorded strain before beam failure was 1.0%. A ductility index of 2.04 was attained.

The results of Beam H-S50-2 are shown in Fig. 13. This beam was strengthened by 1 mm-thick developed hybrid fabric. Figure 13(a) shows the load-versus-deflection curve of the beam. The beam yielded at a load of 113.9 kN (25.6 kips) due to the yielding of both the steel and the fabric. The increase in yield load gain was 38%. The beam failed at an ultimate load of 146.4 kN (32.9 kips) due to compression failure of the concrete. A ductility index of 2.25 occurred. Figure 13(b) shows the load versus the fabric strain

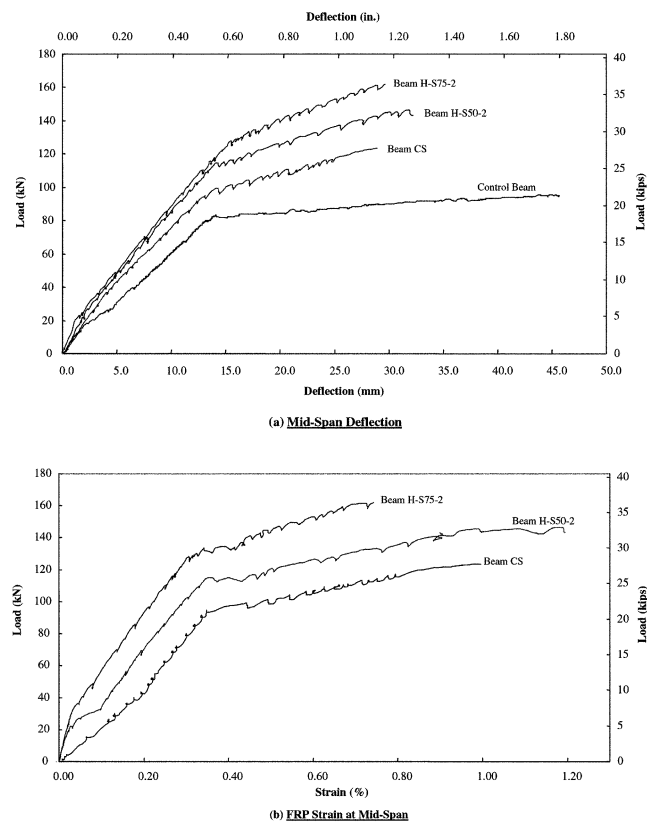


Fig. 15—Comparison between Group B beams.

at midspan. The recorded strain when the beam yielded was 0.35%, and the maximum recorded strain before beam failure was 1.2%. The beam at failure is shown in Fig. 13(c).

Figure 14 shows the results of Beam H-S75-2. This beam was also strengthened by the developed hybrid fabric, but with 1.5 mm thickness. Figure 14(a) shows that the beam yielded at a load of 127.3 kN (28.6 kips) with an increase in yield load of 55% due to yielding of both the steel and the fabric. The beam finally failed at an ultimate load of 162.0 kN (36.4 kips) by compression failure of the concrete at midspan. The beam exhibited a ductility index of 1.89. Figure 14(b) shows the load versus the fabric strain at midspan. The maximum recorded strain before beam failure was 0.74%. The beam at failure is shown in Fig. 14(c).

Figure 15 shows a comparison between the results of beams of Group B. The following are the observations from their test results:

1. Beam H-S50-2 showed a higher yield load than Beam CS, although the hybrid fabric has a lower yield-equivalent load than the ultimate load of the carbon fiber sheet. This is because the hybrid fabric has a higher initial stiffness than that of the carbon fiber sheet; and
2. The beams strengthened with the developed hybrid fabric showed high yield loads with reasonable yielding plateaus.

One of the advantages of the developed hybrid fabric is that it is easy to determine, by visual inspection, whether the fabric yielded or not, because any failed carbon fiber yarns can be seen. Also, the hybrid fabric is less expensive than the currently available carbon fiber materials, as more than 75% of the fibers used are glass fibers that are less costly than carbon fibers.

CONCLUSIONS

Based on the research investigation presented in this study, the following can be concluded:

1. Currently available FRP materials used as flexural strengthening systems for concrete structures do not always provide yielding plateaus in the strengthened beams similar to those for unstrengthened beams. In some applications, the strengthening may result in a brittle failure or an insignificant increase in the yield load of the strengthened beam, or both;

2. The hybridization of selected types of fibers was utilized to develop a pseudoductile fabric, which had a low strain value at yield (0.35%). The fabric was designed so that it had the potential to yield simultaneously with the reinforcing steel of the strengthened beam;

3. The beams strengthened using the developed hybrid fabric generally showed a higher increase in yield load than those strengthened with the carbon fiber strengthening systems. Some of the beams strengthened with the hybrid fabric showed a yield plateau similar to that of the unstrengthened beam. This is critically important to ensure an adequate warning before structural failure; and

4. The beams strengthened with the developed hybrid fabric system showed no significant loss in beam ductility. The beams strengthened with carbon fiber sheets showed also no significant loss in ductility but with relatively less yield loads.

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