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Flexural and Shear Strengthening of Concrete Beams Using New Triaxially Braided Ductile Fabric

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The effectiveness of a new triaxially braided ductile fabric designed specifically to be used for strengthening of concrete beams has been experimentally investigated. This fabric is pseudo-ductile and is a hybrid of different types of fibers. The fabric contains bundles of fibers triaxially braided in three directions (+45, 0, and –45 degrees). The 0-degree fibers are mainly used for flexural strengthening, while the +45- and –45-degree fibers are mainly used for shear strengthening. The fabric has a yield-equivalent strain value in the 0-degree direction close to the yield strain value of steel. Therefore, it has the potential to contribute significantly to the beam load before the yielding of the steel reinforcement of the strengthened beam without further sacrificing much of its ductility. In addition, the fabric is designed to exhibit a certain load-strain response in its 45-degree directions, allowing the optimum contribution to beam shear strength.

Twelve reinforced concrete beams have been strengthened in flexure or shear using the new fabric. Similar beams have been strengthened with a carbon fiber sheet and one with a steel plate to compare their behavior with those strengthened with the new fabric. The beams were loaded in four-point bending until failure. The beams strengthened in flexure with the new fabric produced greater ductility than those strengthened with the carbon fiber sheet. The new fabric produced yield plateaus similar to those of the unstrengthened beams and also to that experienced by the steel plate. The test results of the beams strengthened in shear demonstrated that the fabric stretched before beam failure to strain values that were very close to its yield-equivalent strain value. This confirmed that the fabric strength was fully exploited.

Keywords: concrete; ductility; fiber reinforcement; flexure; shear.

INTRODUCTION

Fiber-reinforced polymer (FRP) materials have been attractive new materials for structural engineers in the concrete construction field, especially for use as strengthening materials for reinforced concrete beams. Carbon, aramid, and glass fibers are the most commonly used fibers in manufacturing FRP strengthening systems. Many systems are commercially available in forms such as pultruded plates, fabrics, and sheets. Most, if not all, of these systems, however, suffer from some drawbacks when dealing with strengthening of concrete beams. They exhibit a linear stress-strain response up to failure without exhibiting any yield plateaus. The ultimate strain values of these materials are very large compared with the yield strain of the steel. As a result, when bonded with epoxy to the tension face of a reinforced concrete beam to strengthen it in flexure, the steel may yield before the strengthening material even begins to carry any significant load. Therefore, it is difficult to increase the beam stiffness or its yield load unless large cross sections of these materials are used to contribute significantly to the beam load before the yielding of the steel reinforcement. Using large FRP cross sections may not be economical and may result in a brittle response of the beam due to sudden debonding of the strengthening material from the concrete surface.

Several experimental investigations (Saadatmanesh and Ehsani 1991; Ritchie et al. 1991; Triantafillou and Plevris 1992; Norris, Saadatmanesh, and Ehsani 1997; Arduini, Tommaso, and Nanni 1997; and Bencardino, Spadea, and Swamy 2002) have been done on the behavior of concrete beams strengthened in flexure using FRP sheets, plates, or fabrics. In all these investigations, the strengthened beams showed higher ultimate loads in comparison with the nonstrengthened ones. Similar increases in beam yield loads, however, were not noted. The results of these investigations showed that for a beam strengthened with an epoxy-bonded FRP sheet on its tension face, four modes of failure could be expected: 1) concrete crushing; 2) FRP tensile rupture; 3) debonding at the concrete adhesive interface; and 4) shear-tension failure. A reduction in beam ductility is typically observed, especially with the last two modes of failure. The fact that the FRP material is linearly elastic up to tensile rupture partially explains the loss of ductility of the strengthened beam.

In the case of the first mode of failure, concrete crushing, the loss in ductility is similar to that experienced when increasing the reinforcement ratio of a beam. Because the FRP is linearly elastic up to failure and does not yield, however, compression failures would take place at less deformation than when strengthening with a steel plate of the same rigidity. The loss of ductility experienced during the second mode of failure, FRP tensile rupture, takes place when the ultimate strain of the FRP is not enough to enable the beam to exhibit large deformations before FRP rupture.

The last two modes of failure are rather complicated; however, both are related to the properties of the FRP material. As the deformation of the beam increases, the tension in the FRP increases continuously (because the FRP is linearly elastic and does not yield), requiring further anchorage. This is difficult to obtain because the maximum anchorable FRP force is always limited. This is even more difficult when the required cross section of the FRP is large. In this case, nonductile failures are likely to happen due to the loss of the composite action between the FRP and the beam, either by FRP debonding or by shear-tension failure. The last two modes of failures are also related to the orthotropic nature of FRP materials. These materials provide their high strength

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only in the fiber direction. Therefore, when they are installed on the bottom face and the sides of the beam as a U-warp, no significant improvement in anchorage would be expected unless the wrapping was perpendicular to the layer(s) at the bottom, which requires installation of additional layers of the FRP.

With respect to shear strengthening, recent experimental investigations such as Chajes et al. (1995), Sato et al. (1996), Norris, Saadatmanesh, and Ehsani (1997), Araki et al. (1997), Taerwe, Khalil, and Matthys (1997), Umezu et al. (1997), and Triantafillou (1998) showed that bonding FRP strips, fabrics, or sheets to the sides of beams improves their shear strength. These investigations showed that when the strengthened concrete beam reaches its shear capacity, the FRP typically stretches to strain values that are usually small fractions of the FRP ultimate strain due to the effect of debonding and, hence, the full strength of the FRP is not fully exploited, and their use may not be economical. Triantafillou (1998) concluded that the effectiveness of the FRP increases as the fibers' direction becomes perpendicular to the diagonal crack. Therefore, installing the FRP with the fiber direction at a 45-degree angle to the longitudinal axis of the beam increases the FRP effectiveness in beam shear strength. It is more practical, however, to install the FRP with its fiber direction perpendicular to the beam axis. Due to the orthotropic characteristics of FRP materials, they significantly strengthen only if loaded into the fiber direction. Therefore, for simultaneous flexure and shear strengthening of beams, multiple layers of the FRP must be used.

Grace, Abdel-Sayed, and Ragheb (2002a,b) developed two ductile FRP strengthening systems. These systems are unique in that they are designed specifically to be used for strengthening of concrete beams. The systems are pseudo-ductile and designed to have the potential to avoid most of the drawbacks experienced by the use of currently available FRP systems in strengthening reinforced concrete beams. The first system is a uniaxial fabric, which is a hybrid of more than one type of carbon fiber and one type of glass fiber. It is designed to be used mainly for beam flexural strengthening applications. Grace, Abdel-Sayed, and Ragheb (2002b) used this system for strengthening reinforced concrete beams in flexure.

The beams strengthened with this system exhibited higher increases in yield loads and higher ductility than those strengthened with the conventional carbon fiber strengthening systems. The second system is a triaxially braided fabric. This fabric was manufactured by triaxially braiding bundles of carbon fibers and glass fibers in three different directions (+45, 0, and –45 degrees). Figure 1 and 2 show details of the geometry and a photo of this triaxial fabric. This fabric is designed to be used for beam strengthening in flexure or shear, or both, using the same layer. The 0-degree fibers are mainly used for flexural strengthening, while the +45- and –45-degree fibers are mainly used for shear

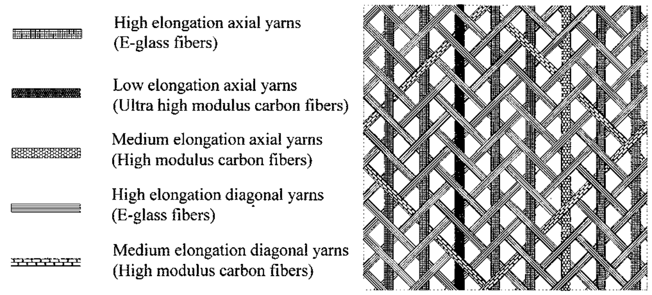


Fig. 1—Detail of triaxial fabric geometry.

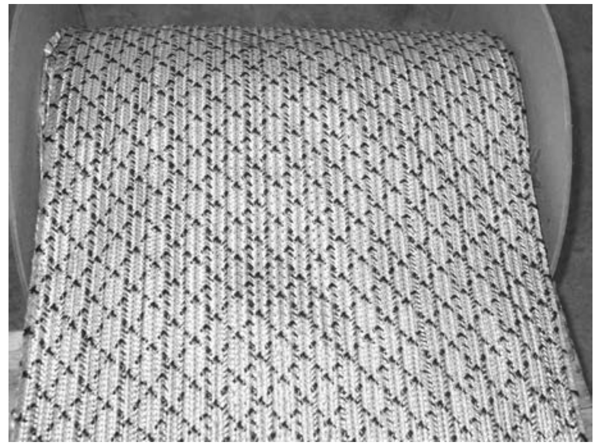


Fig. 2—Photo of triaxial fabric.

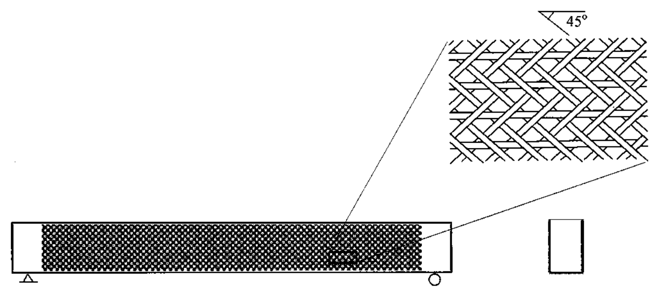


Fig. 3—Layup of triaxial fabric for simultaneous shear and flexural strengthening.

strengthening (Fig. 3) and to provide self-anchoring when wrapping the beam. The fabric has a yield-equivalent strain value in the 0-degree direction that is close to the yield strain of steel. This enables the fabric to have the potential to contribute significantly to the beam load before the yielding of the steel reinforcement of the beam. Therefore, significant increases in the beam ultimate load are achieved together with increases in beam stiffness and yield load without losing a significant amount of ductility. In addition, the fabric is designed to exhibit a certain load-strain response in its 45-degree directions, allowing the optimum contribution to beam shear strength. In this paper, the effectiveness of the second system (the triaxially braided fabric) in flexural and shear strengthening of reinforced concrete beams is experimentally investigated. The tensile behavior of the fabric (tested according to ASTM D 3039) is shown in Fig. 4. Detailed information about the development of the triaxial fabric can be found in Grace, Abdel-Sayed, and Ragheb (2002a).

RESEARCH SIGNIFICANCE

Ductility of a structure is a highly desirable feature as it enables flexural members to undergo significant deflection prior to failure serving to warn of potential failures. A loss in ductility is experienced when strengthening reinforced concrete beams in flexure using currently available FRP strengthening systems. Also, large cross sections of these systems are typically required to significantly increase beam flexural stiffness and yield load; hence, their use may not be economical. Reported investigations showed that the usable strengths of currently available FRP strengthening systems are only small fractions of their ultimate strength when used for shear strengthening due to the effect of debonding. This may not be economical, especially when dealing with relatively expensive fibers such as carbon fibers. These systems are also orthotropic and, hence, cannot be used for strengthening in more than one direction unless different layers are installed. This paper investigates the effectiveness of a new triaxially braided ductile fabric in flexural and shear strengthening of reinforced concrete beams. The fabric has the potential to avoid most of the aforementioned drawbacks experienced by currently available FRP strengthening systems.

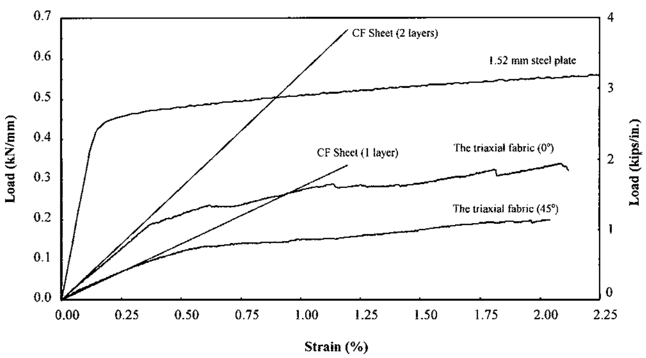


Fig. 4—Tensile properties of materials used.

EXPERIMENTAL PROGRAM

Test beams

Three groups of beams were cast. Groups A and B were used to investigate the fabric behavior in flexural strengthening, while Group C was used to investigate the fabric behavior in shear strengthening. The beams of Groups A and B had cross-sectional dimensions of 152 x 254 mm (6 x 10 in.) and lengths of 2744 mm (108 in.), and were over-reinforced for shear with No. 3 (9.5 mm) closed stirrups spaced at 102 mm (4.0 in.) to avoid shear failure. Group A beams had a flexural reinforcement of two No. 5 (16 mm) tension bars near the bottom and two No. 3 (9.5 mm) compression bars near the top (ρ = 1.25%). Group B beams had a flexural reinforcement of two No. 3 (9.5 mm) tension bars near the bottom and two No. 3 (9.5 mm) compression bars near the top (ρ = 0.44%). The beams of Group C had cross-sectional dimensions of 152 x 280 mm (6 x 11 in.) and lengths of 2744 mm (108 in.), and were deficient in shear; they were reinforced with No. 3 (9.5 mm) closed stirrups spaced at 295 mm (11.63 in.). The flexural reinforcement of the beams of Group C consisted of two No. 10 (32 mm) tension bars near the bottom and two No. 5 (16 mm) compression bars near the top. All beams except one were formed with rounded corners

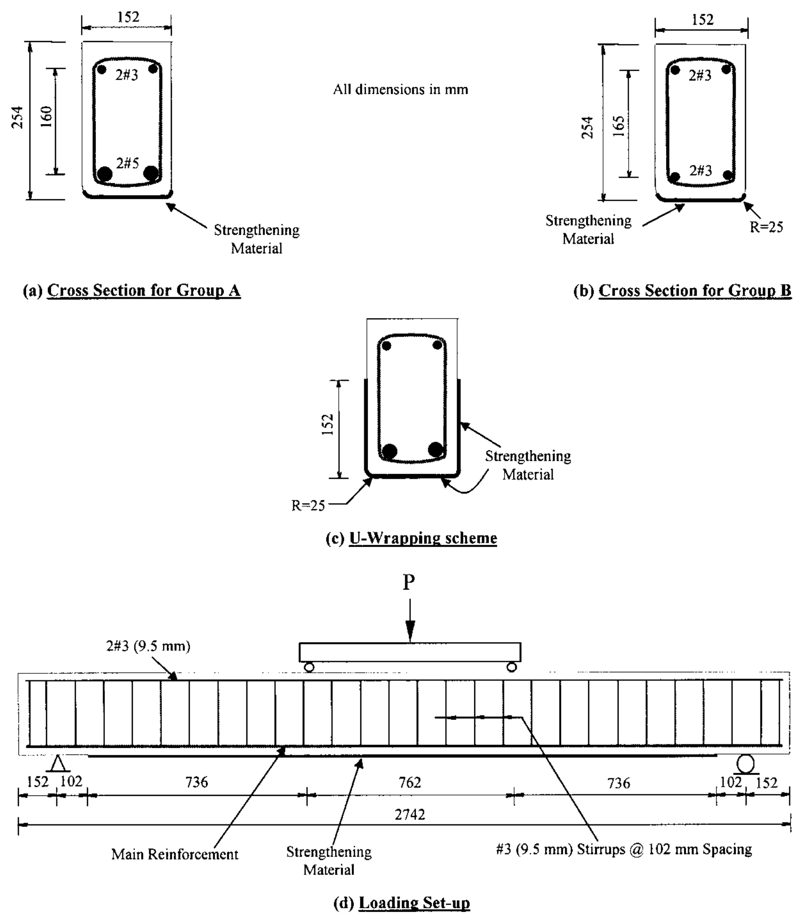


Fig. 5—Details of test beams in Groups A and B.

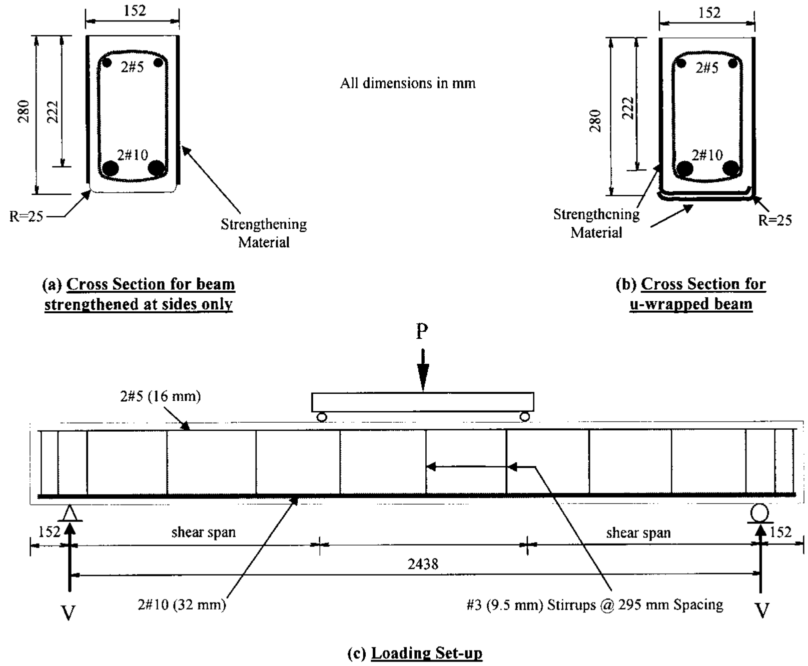


Fig. 6—Details of test beams of Group C.

Table 1—Properties of strengthening materials

Material		Yield-equivalent load, kN/mm (kips/in.)	Yield-equivalent strain, %	Ultimate load, kN/mm (kips/in.)	Ultimate strain, %	Thickness, mm (in.)
Triaxial fabric	0-degree direction	0.19 (1.08)	0.35	0.33 (1.89)	2.10	1.0 (0.039)
	45-degree direction	0.115 (0.66)	0.47	0.20 (1.15)	2.05	
Carbon fiber sheet		—	—	0.34 (1.95)	1.2	0.13 (0.005)
Steel plate		0.44 (2.50)	0.14	0.58 (3.31)	>3	1.52 (0.0598)

of 25 mm (1 in.) radius between the bottom face and the sides. Figure 5 shows the beam dimensions, reinforcement details, and loading setup for the beams of Groups A and B, while Fig. 6 shows those for the beams of Group C. The compressive strength of the concrete at the time the beams were tested was 41.5 MPa (6000 psi) for Groups A and C, while it was 55.2 MPa (8000 psi) for Group B. The steel reinforcement that was used had a yield stress of 490 MPa (71,000 psi).

Strengthening materials

The triaxially braided ductile fabric previously described (referred to as the triaxial fabric) was used to strengthen 12 beams. A commercially available carbon fiber sheet was used to strengthen five beams to compare their behavior with those strengthened with the triaxial fabric. Another beam was strengthened with a Grade 40 steel plate of 1.52 mm (0.0598 in.) thickness. The tested load-strain diagrams for all these materials are shown in Fig. 4 and their properties are listed in Table 1. To objectively compare the behavior of the triaxial fabric with that of the carbon fiber sheet, the number of carbon fiber layers was selected so that it would exhibit the same load-strain response as that initially (before it yields) exhibited by the triaxial fabric. Based on the tensile properties of the materials, it was determined that two layers of the carbon fiber sheet would exhibit a load-strain response similar to that initially exhibited by one layer of the triaxial fabric in its 0-degree direction, and one layer of the carbon fiber sheet would exhibit a load-strain response similar to that initially exhibited by one layer of the triaxial fabric in its 45-degree direction. An epoxy resin was used to impregnate the fibers and as an adhesive between the strengthening material and the concrete surface. This epoxy has an ultimate tensile strength of 66.2 MPa (9.62 ksi) with an ultimate strain of 4.4% and a compressive strength of 109.2 MPa (15.84 ksi).

Strengthening and instrumentation

The beams were prepared by sandblasting their surfaces to roughen them, cleaned with an air nozzle, and finally wiped off to remove any dust or loose particles. For flexural strengthening beams, Groups A and B, two strengthening configurations were applied: 1) strengthening material on the bottom face of the beam only, and 2) strengthening material on the bottom face and extended up 152 mm (6 in.) on both sides to cover approximately all the flexural tensile zone of the beam. For shear strengthening beams, Group C, two strengthening configurations were applied: 1) strengthening on the beam sides only, and 2) strengthening on the bottom face of the beam with extension up on both sides as a U-wrap. The strengthening material was installed for 2.24 m (88 in.) for Groups A and B beams, and 2.26 m (89 in.) for Group C beams, centered along the length of the beam. The epoxy was allowed to cure for at least 2 weeks before the beams were tested. Table 2 summaries the test beams.

Flexural strengthening beams, Groups A and B, were instrumented with three strain gages for each beam located

Table 2—Summary of test beams

Beam group	Beam designation	Flexure or shear	Shear span	Strengthening scheme	Strengthening material
Group A	Control 1	Flexure	838 mm (33 in.)	N/A	N/A
	F-B-1			Bottom face only	Triaxial fabric (two layers)
	F-B-2				
	F-CB-1				Carbon fiber sheet (four layers)
	F-ST-1				Steel plate
	F-BL3-1				Triaxial fabric (three layers)
	F-U-1			U-wrap	Triaxial fabric (one layer)
	F-U-2				
	F-CU-1				Carbon fiber sheet (two layers)
Group B	Control 2	Flexure	838 mm (33 in.)	N/A	N/A
	F3-B-1			Bottom face only	Triaxial fabric (two layers)
	F3-CB-1				Carbon fiber sheet (four layers)
	F3-U-1			U-wrap	Triaxial fabric (one layer)
	F3-CU-1				Carbon fiber sheet (two layers)
Group C	Control 3	Shear	838 mm (33 in.)	N/A	N/A
	S-S-1		838 mm (33 in.)	Sides only	Triaxial fabric (one layer)
	S-S-2				
	S-S-3		736 mm (29 in.)		
	S-U-1		838 mm (33 in.)	U-wrap	Triaxial fabric (one layer at sides + two layers at bottom)
	S-U-2				
	S-CU45-1				Carbon fiber sheet (one layer) at 45 degrees

at the bottom face of the beam to measure the FRP strain at midspan. Shear strengthening beams, Group C, were instrumented with two strain gages for each beam located at the top surface of the beam to measure the concrete compression strain at midspan, and with rosette strain gages located at the expected locations of shear cracks to measure the FRP strain at the beam sides. The deflection was measured at the mid- and quarter-span using string potentiometers. The beams were loaded using a hydraulic actuator. The load was measured by means of a load cell. A data acquisition system was used to scan and record the readings of all sensors.

TEST RESULTS AND DISCUSSION

Group A

The beams of Group A had a steel reinforcement ratio of 1.25%, which is 42% of the balance steel ratio ρ_b. The triaxial fabric was used to strengthen five beams, while two similar beams were strengthened with the carbon fiber sheet. One beam was strengthened with the steel plate and one other beam was a control beam. Test results for all these beams are shown Fig. 7 to 10 and listed in Table 3. The ductility of each beam is determined by calculating its ductility index; that is, the ratio between the ultimate deflection and the yield deflection.

Control beam—The control beam had a yield load of 77 kN (17.3 kips) and an ultimate load of 87 kN (19.6 kips). The beam failed by yielding of steel followed by compression failure of the concrete at the midspan.

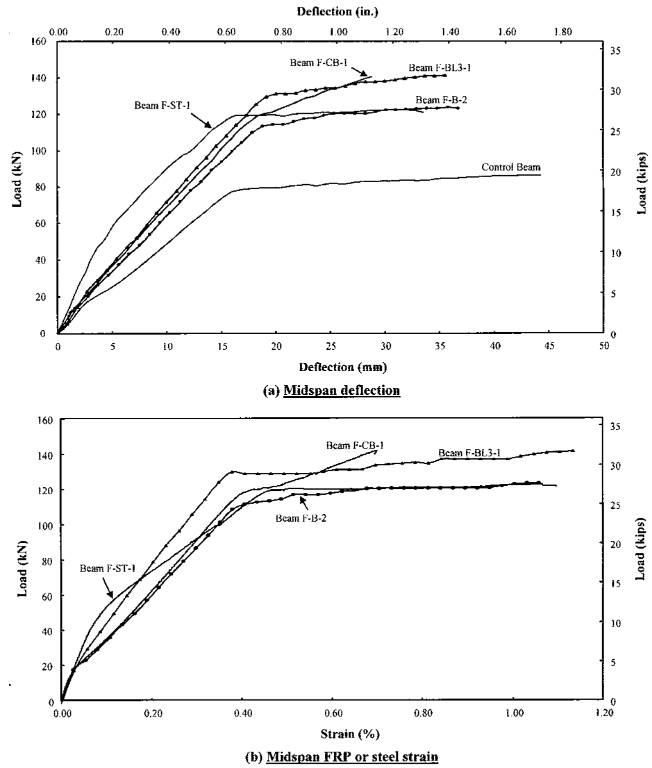
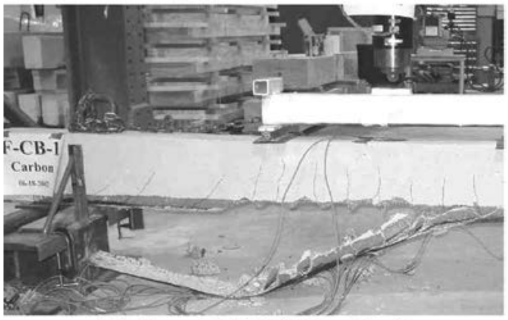


Fig. 7—Behavior of Group A beams strengthened at bottom face only.

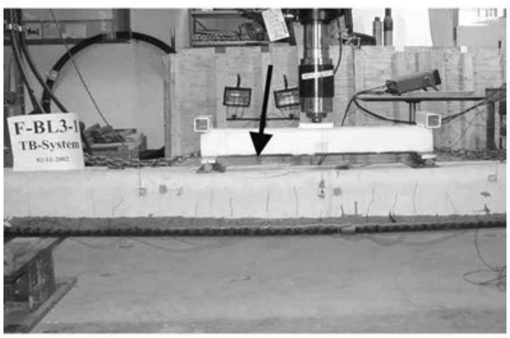
Beams F-B-1, F-B-2, and F-CB-1—Beams F-B-1 and F-B-2 were identically strengthened with the triaxial fabric to determine if the test results were repeatable. Two layers 135 mm (5.33 in.) wide were installed on the bottom faces of each beam. Beam F-CB-1 was strengthened with four layers of the carbon fiber sheet 146 mm (5.75 in.) wide. The test results of beams F-B-1 and F-B-2 were very similar. Hence, the discussion herein will be focused on Beam F-B-2 to avoid repetition. Figure 7 shows the test results for Beams F-B-2 and F-CB-1. Beam F-B-2 yielded at a load of 113 kN (25.4 kips) and failed at a load of 123 kN (27.6 kips) by compression failure of the concrete at the midspan, after exhibiting a considerable amount of ductility. Some debonded areas of fabric were noticed near the midspan just before failure. However, this did not affect the behavior of the beam as the anchoring portions of the fabric away from the midspan were still attached. Beam F-CB-1 yielded at a load of 119 kN (26.7 kips) but failed suddenly by debonding of the carbon fiber sheet at a load of 141 kN (31.7 kips), after exhibiting less ductility than Beam F-B-2. The ductility index of Beam F-B-2 was 1.95, while the ductility index of Beam F-CB-1 was 1.61.

The difference in failure modes between the two beams is due to the difference in the load-strain response between the triaxial fabric and the carbon fiber sheet. Both the triaxial fabric and the carbon fiber sheet carried almost the same amount of load up to yielding of the beam. The tensile force in the carbon fiber sheet, however, increased after the steel yielded. This increase in force appeared to be the reason for the debonding of the carbon fiber sheet. On the other hand, degradation of the stiffness of the triaxial fabric (as it yielded) in case of Beam F-B-2 helped to limit the force increase in it and, hence, debonding was avoided, leading to a more ductile failure. Both beams showed considerable increases in beam yield load and stiffness; however, Beam F-B-2 showed higher ductility and

(a) Beam F-B-2 (concrete compression failure)



(b) Beam F-CB-1 (debonding)



(c) Beam F-BL3-1 (concrete compression failure)

Fig. 8—Beams F-B-2, F-CB-1, and F-BL3-1 at failure.

failed less catastrophically than Beam F-CB-1. Beam F-B-2 yielded due to the yielding of both the steel reinforcement and the fabric, while beam F-CB-1 yielded due to the yielding of the steel only. The carbon fiber sheet had a midspan strain of 0.7%, which indicates that it reached 58% of its load capacity when it failed. In contrast, the triaxial fabric had a midspan strain of 1.06% at beam failure, which was more than the strain necessary to reach most of its load capacity (more than its yield-equivalent strain). Figure 8(a) and (b) show photos of the two beams after failure.

Beam F-ST-1—This beam was strengthened with a Grade 40 steel plate 1.52 mm (0.0598 in.) thick and 152 mm (6 in.) wide. The objective of including this test specimen in the program was to compare the behavior of a beam strengthened with a highly ductile material, such as steel, with the behavior of a beam strengthened with the triaxial fabric. This beam had no rounded corners to facilitate the installation of the plate. To isolate the effect of debonding, the plate was well anchored to the concrete using steel screws (see Fig. 9). Test results for this beam are included in Fig. 7. Beam F-ST-1 exhibited a higher initial stiffness than Beam F-B-2. The steel plate yielded at a load of 60 kN (13.5 kips), causing a decrease in beam stiffness. The inner steel reinforcing bar yielded at a load of 119 kN (26.7 kips) and the beam exhibited

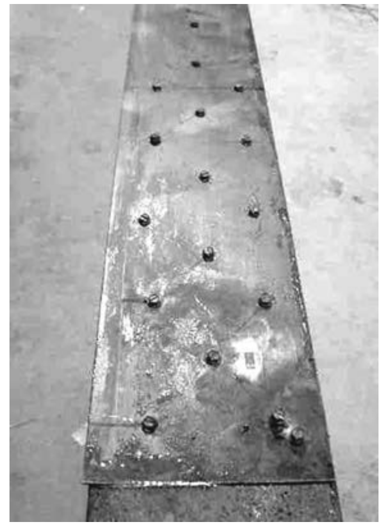
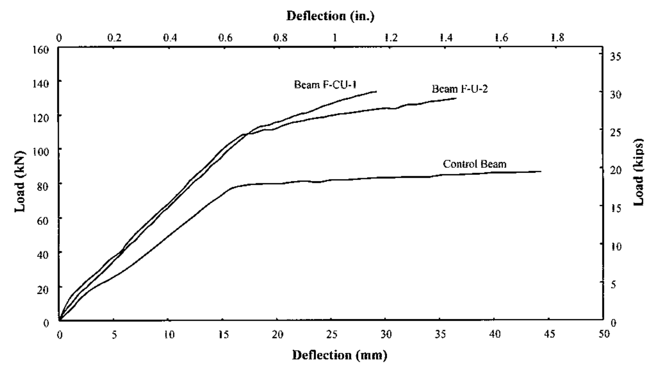
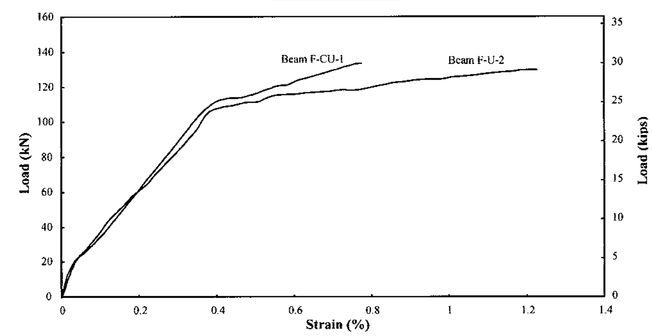


Fig. 9—Anchoring of steel plate of Beam F-ST-1 using steel screws.



(a) Midspan deflection



(b) Midspan FRP strain

Fig. 10—Behavior of Group A beams with U-wrap scheme.

a yield plateau similar to that of Beam F-B-2. Beam F-ST-1 failed by compression of the concrete at midspan at a load of 121 kN (26.7 kips). The test indicated that the beam strengthened with the triaxial fabric produced a similar yield plateau to that of a beam strengthened with a highly ductile material such as steel.

Beams F-U-1, F-U-2, and F-CU-1—Beams F-U-1 and F-U-2 were strengthened with one layer of the triaxial fabric as a U-wrap along the bottom face, which extended 152 mm (6 in.) on both sides. Beam F-CU-1 had the same U-wrap scheme but with two layers of the carbon fiber sheet. The results of Beams F-U-1 and F-U-2 were very similar and, hence, the discussion that follows is focused on Beam F-U-2 to avoid repetition. Test results from Beams F-U-2 and F-CU-1 are shown in Fig. 10. Both beams showed similar initial stiffnesses. Beam F-U-2

Table 3—Summary of test results of Groups A and B

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 = Column (6) / Column (4) (7)	FRP strain at failure, % (8)	Type of final failure (9)
Control 1	N/A	77 (17.3)	16 (0.63)	87 (19.6)	44 (1.73)	2.75	N/A	Steel yield followed by concrete failure
F-B-2	Triaxial fabric (two layers)	113 (25.4)	19 (0.75)	123 (27.6)	37 (1.46)	1.95	1.06	Steel and fabric yield followed by concrete failure
F-CB-1	Carbon fiber sheet (four layers)	119 (26.7)	18 (0.71)	141 (31.7)	29 (1.14)	1.61	0.70	Steel yield followed by sheet debonding
F-ST-1	Steel plate	119 (26.7)	16 (0.63)	121 (27.2)	34 (1.33)	2.13	1.10	Steel yield followed by concrete failure
F-BL3-1	Triaxial fabric (three layers)	130 (29.2)	19 (0.75)	141 (31.7)	36 (1.41)	1.89	1.14	Steel and fabric yield followed by concrete failure
F-U-2	Triaxial fabric (one layer)	108 (24.3)	17 (0.67)	130 (29.2)	37 (1.46)	2.18	1.23	Steel and fabric yield followed by concrete failure
F-CU-1	Carbon fiber sheet (two layers)	111 (24.9)	18 (0.71)	133 (29.9)	29 (1.14)	1.61	0.78	Steel yield followed by concrete failure
Control 2	N/A	22 (4.9)	7 (0.28)	42 (9.4)	57 (2.24)	8.14	N/A	Steel yield followed by concrete failure
F3-B-1	Triaxial fabric (two layers)	53 (11.9)	13 (0.51)	70 (15.7)	38 (1.50)	2.92	1.21	Steel and fabric yield followed by fabric debonding
F3-CB-1	Carbon fiber sheet (four layers)	58 (13.0)	12 (0.47)	67 (15.1)	18 (0.71)	1.5	0.42	Steel yield followed by sheet debonding
F3-U-1	Triaxial fabric (one layer)	58 (13.0)	12 (0.47)	91 (20.5)	45 (1.77)	3.75	1.68	Steel and fabric yield followed by fabric rupture
F3-CU-1	Carbon fiber sheet (two layers)	58 (13.0)	11 (0.43)	92 (20.7)	25 (0.98)	2.27	0.80	Steel yield followed by sheet debonding

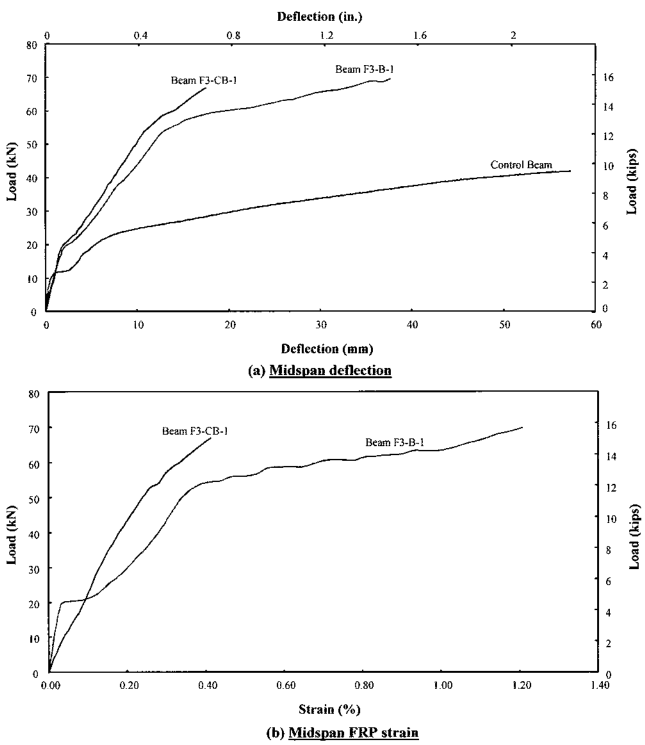


Fig. 11—Behavior of Group B beams strengthened at bottom faces only.

yielded at a load of 108 kN (24.3 kips) and failed by compression failure of the concrete at midspan at a load of 130 kN (29.2 kips). Beam F-CU-1 yielded at a load of 111 kN (24.9 kips) and also failed by compression failure of the concrete at midspan at a load of 133 kN (29.9 kips). Beam F-U-2, however, showed more ductility than Beam F-CU-1. This is attributed to the degradation of the fabric stiffness after it yielded, which in turn led to a compression failure at a higher FRP strain value than that of Beam F-CU-1 in which the stiffness of the carbon fiber sheet did not decrease.

Beam F-BL3-1—To provide additional experimental data for the behavior of concrete beams strengthened with the triaxial fabric, Beam F-BL3-1 was strengthened with three layers of the triaxial fabric 135 mm (5.33 in.) wide installed at the bottom face of the beam. Test results for this beam are included in Fig. 7. The beam yielded at a load of 130 kN (29.2 kips) and reached its ultimate strength at 141 kN (31.7 kips) by compression failure of the concrete at midspan. Before failure of the beam, the fabric debonded from the concrete surface near the midspan. This, however, did not affect the behavior of the beam as the anchoring portions of the fabric located away from the midspan were still attached. The beam experienced reasonable ductility before failure (a ductility index of 1.89). The failed beam is shown in Fig. 8(c).

Group B

The beams of this group had a flexural reinforcement ratio of 0.44% (13% of ρ_b), which is close to minimum steel reinforcement ratio required by ACI code. Therefore, these beams were lightly reinforced. This group contained five beams. Two beams were strengthened with the triaxial fabric and two beams were strengthened using the carbon fiber sheet. One beam was a control beam. Test results for all these beams are shown Fig. 11 to 13 and listed in Table 3.

Control beam—The control beam had a yield load of 22 kN (4.9 kips) and an ultimate load of 42 kN (9.40 kips). The beam failed by yielding of steel followed by compression failure of the concrete at the midspan.

Beams F3-B-1 and F3-CB-1—Both beams were strengthened by bonding the FRP on their bottom faces only. Beam F3-B-1 was strengthened with two layers of the triaxial fabric 135 mm (5.33 in.) wide. Beam F3-CB-1 was strengthened with four layers of the carbon fiber sheet 145 mm (5.75 in.) wide. Test results for the two beams are shown in Fig. 11 along with the test results for the control beam. Beam F3-B-1 yielded at a load of 53 kN (11.9 kips), while Beam F3-CB-1 yielded at a load of 58 kN (13.0 kips). Beam F3-CB-1 showed a slightly greater stiffness and failed at a load of 67 kN (15.1 kips). Beam F3-CB-1 failed by debonding of the carbon fiber sheet from the concrete surface initiated by cracks opening near the midspan loading points and propagated towards the sheet ends. Beam F3-CB-1 had a ductility index of 1.5. Beam F3-B-1 also failed by debonding of the fabric from the concrete surface initiated by cracks forming near the midspan and propagated towards the fabric ends at a load of 70 kN (15.7 kips). Beam F3-B-1, however, exhibited a reasonable ductile plateau with a ductility index of 2.92.

Beams F3-U-1 and F3-CU-1—Beam F3-U-1 was U-wrapped with one layer of the triaxial fabric on the bottom face, which extended 152 mm (6 in.) up on both sides. Beam F3-CU-1 had a similar wrapping scheme but with two layers of the carbon fiber sheet. Test results for the two beams are shown in Fig. 12 along with the test results of the control beam. Beam F3-CU-1 showed a slightly higher stiffness than Beam F3-U-1. The two beams yielded at a load of 58 KN (13.0 kips). Beam F3-U-1 showed an increase in deflection and strain after yielding. Beam F3-U-1 failed by rupture of the fabric near the midspan at a load of 91 kN (20.5 kips), and after exhibiting considerable ductility with a ductility index of 3.75. Beam F3-CU-1, however, did not show similar deflections and strains after yield. Beam F3-CU-1 failed suddenly at a load of 92 kN (20.70 kips) due to debonding of the sheet from the bottom face only. The two failed beams are shown in Fig. 13. The triaxial fabric has an advantage over the carbon fiber sheet as it contains yarns in the (+45- and –45-degree) directions. These yarns worked to self-anchor the fabric in Beam F3-U-1 during wrapping; hence, debonding failure was not experienced. On the other hand, the carbon fiber sheet is uniaxial; hence wrapping the beam did not improve the anchoring of the fibers on the bottom face.

Just after yielding of all the beams strengthened with the triaxial fabric, distinguishable sounds were heard. These sounds were due to rupture of the low and medium elongation fibers in the triaxial fabric. No similar sounds were experienced by the beams strengthened with the carbon fiber sheet or the steel plate.

Group C

The beams of Group C were to investigate the fabric behavior in shear strengthening. The midspan defection, 45-degree rosette strain gage reading from the beam sides, and concrete compression stain diagrams for the beams strengthened at the sides only are shown in Fig. 14, while those for the U-wrapped beams are shown in Fig. 15. Photos for the failed beams are shown in Fig. 16 and 17 for the beams strengthened at the sides only and the U-wrapped beams, respectively.

Control beam—The beam initially exhibited some tension cracks in the constant moment region near the midspan. Then large diagonal cracks formed in the constant shear span, which led to shear failure of the beam at a shear force *V* of 101 kN (22.7 kips). The test results for the control beam are shown in the figures of the test results of the strengthened beams (Fig. 14 and 15).

Beam S-S-1—The midspan deflection diagram indicates that the beam did not yield. The 45-degree fabric strain diagram shows that the fabric was not active before the beam experienced shear cracks, which occurred at a shear force of 84 kN (18.9 kips). After cracking, the fabric experienced an increase in strain up to failure at a shear force of 137 kN (30.8 kips). The failure started by concrete cover spalling in the constant shear zone near the loading point on the top of the beam. The beam failed in shear without rupture of the fabric (Fig. 16(a)). The 45-degree strain diagram shows that the fabric exhibited a maximum strain value of 0.34%.

Beam S-S-2—This beam had exhibited a similar deflection behavior to Beam S-S-1. However, it failed by concrete

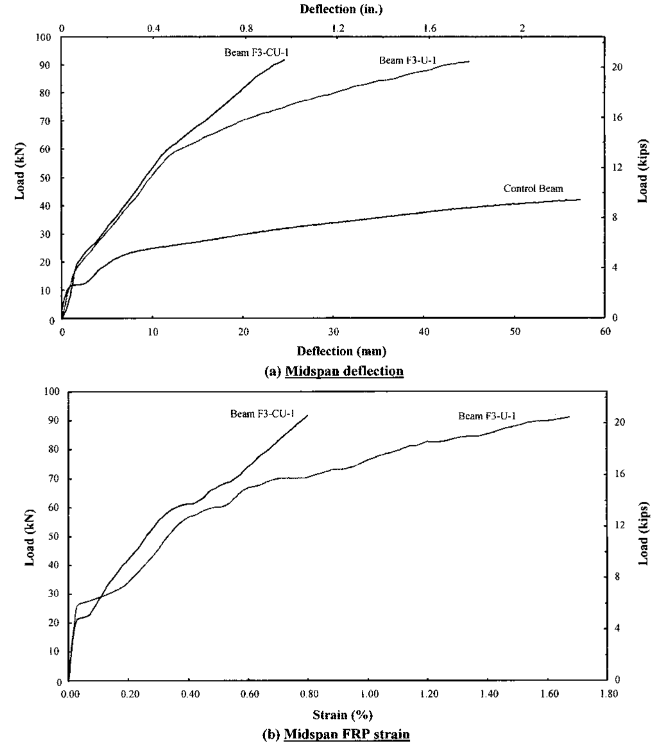
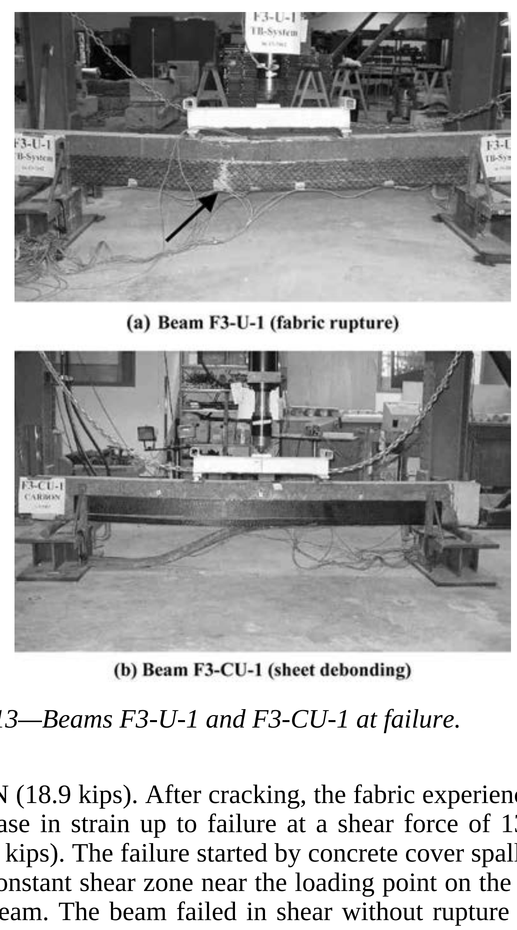


Fig. 12—Behavior of Group B beams with U-wrap scheme.



(a) Beam F3-U-1 (fabric rupture)

(b) Beam F3-CU-1 (sheet debonding)

Fig. 13—Beams F3-U-1 and F3-CU-1 at failure.

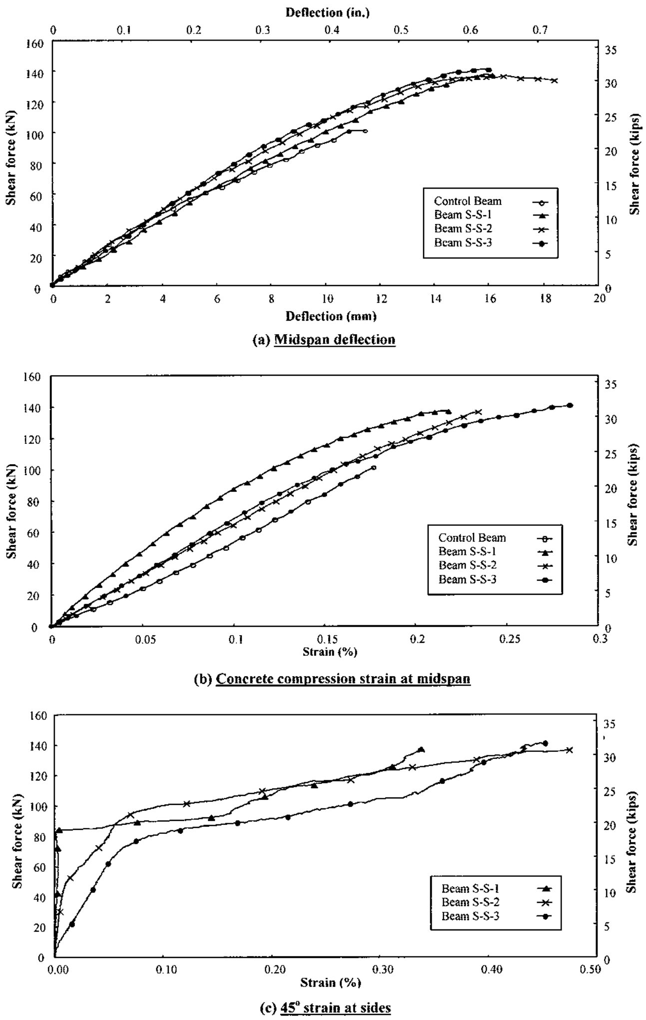


Fig. 14—Behavior of Group C beams strengthened at sides only.

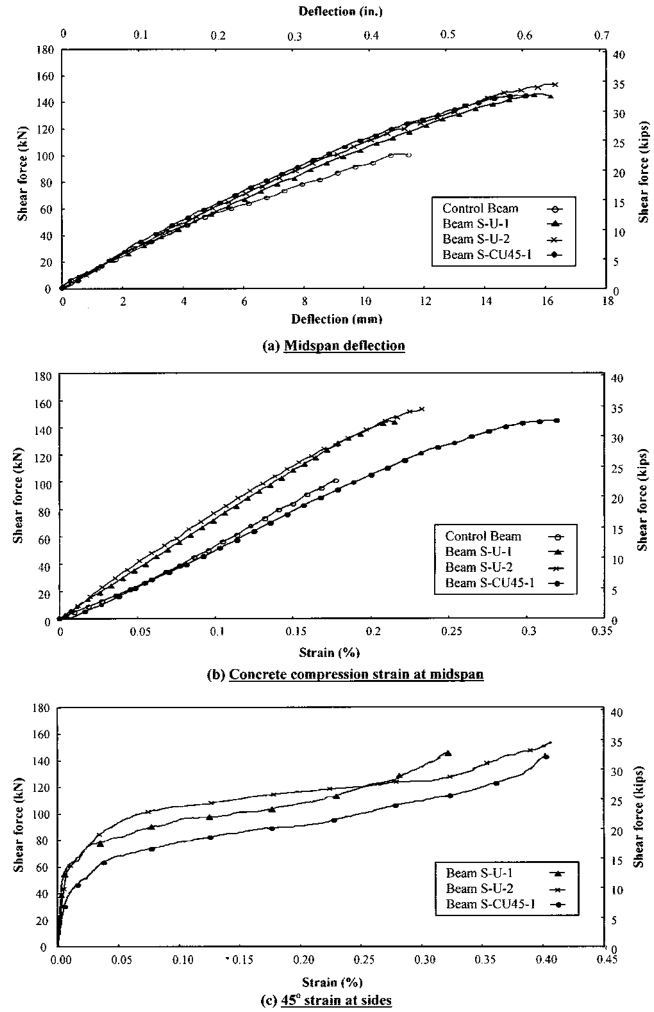


Fig. 15—Behavior of U-wrapped beams of Group C.

damage in the constant moment zone near the midspan at a shear force of 137 kN (30.8 kips). This damage appeared to be caused by buckling of the fabric in the compression zone, causing lateral tensile stresses in the concrete leading to premature failure. The concrete exhibited a compression strain of 0.23%, which is less than the concrete failure strain (0.3%). The fabric strain readings at beam sides showed a 45-degree strain of 0.48% when the beam failed. The failed beam is shown in Fig. 16(b).

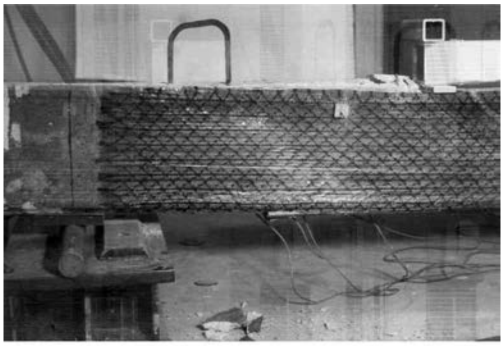
Beam S-S-3—This beam was tested at a shear span of 736 mm (29 in.), slightly less than that of the other two beams. The beam had a similar strengthening scheme to that of Beams S-S-1 and S-S-2. To avoid damage of the concrete in the compression zone due to buckling of the fabric, as experienced by Beam S-S-2, however, a 76 mm (3 in.) wide strip at the top of the beam in the constant moment zone was not covered with the fabric. The beam failed by debonding of the fabric (Fig. 16(c)) at a shear force of 141 kN (31.7 kips). The fabric strain readings showed a strain of 0.45% when the beam failed.

Beam S-U-1—Beam S-U-1 did not yield but failed due to damage of the concrete near the midspan, caused by buckling of the fabric at a shear force of 145 kN (32.6 kips). The midspan strain gages at the top surface of the beam showed that the concrete had a compression strain of 0.21%, which is less than the failure compression strain of the concrete (0.3%). The rosette strain gage readings showed that the fabric contributed to the shear capacity of the beam after it cracked. The maximum recorded 45-degree strain on the beam side before the beam failed was 0.32%. The failed beam is shown in Fig. 17(a).

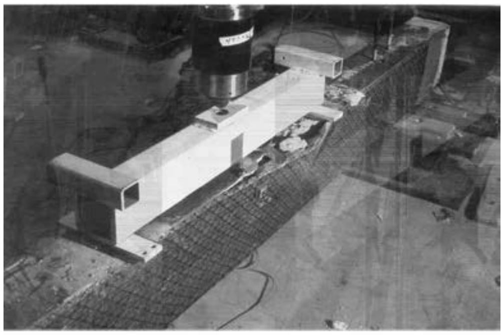
Beam S-U-2—This beam showed a similar deflection behavior to that of Beam S-U-1; however, it failed by debonding of the fabric, followed by shear failure in the constant shear zone at a shear force of 154 kN (34.6 kips). The rosette strain gages at beam sides showed a 45-degree strain value of 0.41% before the beam failed. The failed beam is shown in Fig. 17(b).

Beam S-CU45-1—This beam was strengthened with one layer of the carbon fiber sheet. This layer has a similar load-strain response to that initially exhibited by the triaxial fabric in its 45-degree direction (Fig. 4). The beam exhibited a similar load-deflection behavior to that of Beams S-U-1 and S-U-2 and failed in flexure at a shear force of 146 kN (32.8 kips). The rosette strain gages showed that the sheet contributed to the shear strength of the beam after shear cracking. The maximum recorded 45-degreee strain reading for the sheet at beam sides was 0.40%, as compared to its ultimate strain of 1.2%.

The test results for the beam of Group C revealed that the fabric exhibited strain values that were close to the fabric yield-equivalent strain before failure of the beam. This indicates that the fabric strength was almost fully used, which meets its



(a) Failure of beam S-S-1

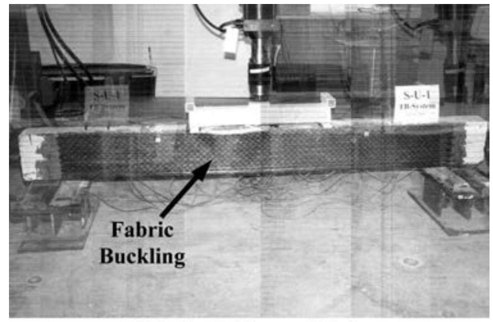


(b) Failure of beam S-S-2

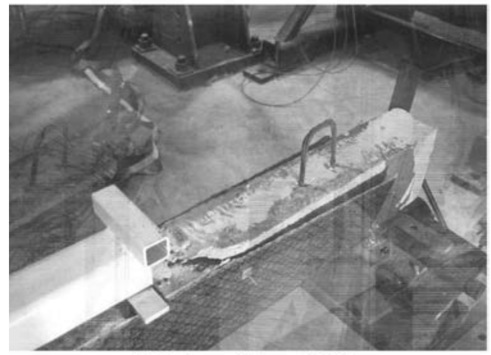
(c) Failure of beam S-S-3

Fig. 16—Failure of Group C beams strengthened at sides only.

design objectives. The triaxial fabric has fibers in the 0-degree direction, in addition to the +45- and –45-degree ones, which contribute to the flexural strength of the beam. The fabric demonstrated the capability of increasing the beam flexural and shear strength using only one layer. None of the beams strengthened with the fabric failed in flexure, while the beam strengthened with carbon fiber failed in flexure. This is because the U-wrapped carbon fibers had no fibers parallel to the longitudinal axes of the beam and, hence, did not contribute in an optimum manner to its flexural strength. The U-wrapped beams showed higher ultimate loads than those strengthened only on the sides. The difference in ultimate load, however, was in the range of 6 to 12%. The existence of the fabric in zones of high compression may lead to premature failure due to damage of the concrete as a result of buckling of the fabric as experienced by Beams S-S-2 and S-U-1. This may be solved by avoiding the installation of the fabric in high compression zones whenever possible, as done in Beam S-S-3.



(a) Failure of beam S-U-1



(b) Failure of beam S-U-2

Fig. 17—Failures of Beams S-U-1 and S-U-2.

CONCLUSIONS

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

1. The beams strengthened in flexure with the triaxial fabric behaved in a more ductile manner than those strengthened with the carbon fiber sheet. The triaxial fabric produced a yield plateau similar to that of the unstrengthened beam and also similar to that produced by a beam strengthened with a ductile material such as steel;

2. The beams strengthened in flexure using the triaxial fabric were generally less likely to exhibit debonding failures. Yielding of the fabric limits the force increase in it and, as a result, the fabric was less vulnerable to exhibit such failures;

3. Although the beam strengthened with the steel plate exhibited considerable ductility, the steel plate yielded at a lower load than the inner reinforcing steel because the plate has both a lower yield strain than the steel bars and was installed on the outside surface of the beam;

4. In the case of U-wrapped beams, the triaxial fabric had an advantage over the carbon fiber sheet as it contains yarns in the +45- and –45-degree directions. These yarns worked to self anchor the fabric when bonded around the tension face and sides of the beam to strengthen it in flexure and, hence, debonding failure was not experienced. On the other hand, the carbon fiber sheet is uniaxial; hence, it did not have the self-anchoring advantage;

5. Yielding of the fabric was accompanied by distinguishable sounds due to failure of the low and medium elongation fibers. No similar sounds were experienced by the beams strengthened with the carbon fiber sheet or the steel plate; and

6. The fabric was effective in strengthening reinforced concrete beams in shear. The maximum strain readings in the fabric were very close to its yield-equivalent strain; hence, its strength was fully exploited. The fabric should not be

installed in zones of high compression stresses as it may buckle, causing damage to the strengthened beam.

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REFERENCES

ACI Committee 318, 1995, "Building Code Requirements for Structural Concrete (ACI 318-95) and Commentary (318R-95)," American Concrete Institute, Farmington Hills, Mich., 369 pp.

Araki, N.; Matsuzaki, Y.; Nakano, K.; Kataoka, T.; and Fukuyama, H., 1997, "Shear Capacity of Retrofitted RC Members with Continuous Fiber Sheets," *Non-Metallic (FRP) Reinforcement for Concrete Structures*, Japan Concrete Institute, V. 1, pp. 515-522.

Arduini, M.; Tommaso, A. D.; and Nanni, A., 1997, "Brittle Failure in FRP Plate and Sheet Bonded Beams," *ACI Structural Journal*, V. 94, No. 4, July-Aug., pp. 363-370.

ASTM D 3039, 2000, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials," *Annual Book of ASTM Standards*, ASTM, V. 15.03, pp. 106-118.

Bencardino, F.; Spadea, G.; and Swamy, R. N., 2002, "Strength and Ductility of Reinforced Concrete Beams Externally Reinforced with Carbon Fiber Fabric," *ACI Structural Journal*, V. 99, No. 2, Mar.-Apr., pp. 163-171.

Chajes, M. J.; Januszka, T. F.; Mertz, D. R.; Thomson, T. A.; and Finch, W. W., 1995, "Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabric," *ACI Structural Journal*, V. 92, No. 3, May-June, pp. 295-303.

Grace, N. F.; Ragheb, W. F.; and Abdel-Sayed, G., 2002a, "Development and Application of Innovative Triaxially Braided Ductile FRP Fabric for Strengthening Concrete Beams," *Journal of Composite Structures*. (accepted for publication)

Grace, N. F.; Abdel-Sayed, G.; and Ragheb, W. F., 2002b, "Strengthening of Concrete Beams Using Innovative Ductile Fiber-Reinforced Polymer Fabric," *ACI Structural Journal*, V. 99, No. 5, Sept.-Oct., pp. 692-700.

Norris, T.; Saadatmanesh, H.; and Ehsani, M. R., 1997, "Shear and Flexural Strengthening of R/C Beams with Carbon Fiber Sheets," *Journal of Structural Engineering*, ASCE, V. 123, No. 7, pp. 903-911.

Ritchie, P. A.; Thomas, D. A.; Lu, L.; and Connelly, G. M., 1991, "External Reinforcement of Concrete Beams Using Fiber Reinforced Plastics," *ACI Structural Journal*, V. 88, No. 4, July-Aug., pp. 490-500.

Saadatmanesh, H., and Ehsani, M. R., 1991, "RC Beams Strengthening with GFRP Plates I: Experimental Study," *Journal of Structural Engineering*, ASCE, V. 117, No. 11, pp. 3417-3433.

Sato, Y.; Ueda, T.; Kakuta, Y.; and Tanaka, T., 1996, "Shear Reinforcing Effect of Carbon Fiber Sheet Attached to Side of Reinforced Concrete Beams," *Advanced Composite Materials in Bridges and Structures*, M. M. El-Badry, ed., Canadian Society of Civil Engineering, pp. 621-628.

Taerwe, L.; Khalil, H.; and Matthys, S., 1997, "Behavior of RC Beams Strengthened in Shear by External CFRP Sheets," *Non-Metallic (FRP) Reinforcement for Concrete Structures*, Japan Concrete Institute, V. 1, pp. 483-490.

Triantafillou, T. C., 1998, "Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites," *ACI Structural Journal*, V. 95, No. 2, Mar.-Apr., pp. 107-115.

Triantafillou, T. C., and Plevris, N., 1992, "Strengthening of RC Beams with Epoxy-Bonded-Fiber-Composite Materials," *Materials and Structures*, V. 25, pp. 201-211.

Umezu, K.; Fujita, M.; Nakai, H.; and Tamaki, K., 1997, "Shear Behavior of RC Beams with Aramid Fiber Sheet," *Non-Metallic (FRP) Reinforcement for Concrete Structures*, Japan Concrete Institute, V. 1, pp. 491-498.