AN INNOVATIVE DUCTILE COMPOSITE FABRIC FOR STRENGTHENING CONCRETE STRUCTURES

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Abstract

The lack of ductility of the currently available fiber reinforced polymer (FRP) composite materials has contributed to the delay in their wide spread use as strengthening materials for concrete structures. In this investigation, an innovative uniaxial ductile FRP fabric has been researched, developed, and manufactured for strengthening structures. The fabric is a hybrid of two types of carbon fibers and one type of glass fibers and designed to provide a ductile behavior with a low yield strain value in tension. The effectiveness and ductility of the developed fabric has been investigated by strengthening and testing four 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 hybrid fabric. The developed 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 non-strengthened beams can be achieved. The beams strengthened with the developed fabric exhibited higher yield loads than those strengthened with currently available carbon fiber strengthening systems. Furthermore, a higher ductility was achieved for beams strengthened with the developed fabric. The developed fabric shows more effective contribution to the strengthening mechanism.

Introduction

The use of externally bonded fiber reinforced polymer (FRP) sheets and strips has been recently 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[1] examined the behavior of concrete beams strengthened for flexure using glass fiber reinforced polymer (GFRP) plates. Ritchie et al.[2] tested reinforced concrete beams strengthened for flexure using GFRP, carbon fiber reinforced polymer (CFRP), and G/CFRP plates. Triantafillou[3] studied the behavior of reinforced concrete beams strengthened for flexure using CFRP sheets. Norris et al.[4] investigated the behavior of concrete beams strengthened using CFRP unidirectional sheets and CFRP woven fabrics. In all these investigations, the strengthened beams showed higher ultimate loads compared to the non-strengthened ones. One of the drawbacks experienced by most of these strengthened beams is a considerable loss in beam ductility. Besides, an examination of the load-deflection behavior of the beams shows 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 the 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 strengthening mechanism. 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. Since steel has a relatively low yield strain value compared to those of most of the FRP materials, the degrees of force contribution of both the steel and the strengthening FRP materials differ with deformation of the strengthened element. As a result, steel reinforcement may yield before the strengthened element gain any measurable load increase. Some designers place greater FRP cross section, which is not economical, in order to provide measurable contribution even when deformations are limited (before the yield of steel). Besides, debonding of the strengthening material from the surface of the concrete is more likely to happen in such cases, due to higher stress concentrations. Debonding is one of the non-desired 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 failure of fibers. The objective of this paper is to introduce a new ductile FRP material that has a low strain at yield, so that it can yield simultaneously with the steel reinforcement and yet provide the desired strengthening level.

Development of A Hybrid Fabric

In order 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 together to enhance the mechanical properties as well as to reduce the cost [5-9]. Hybridization interested structural engineers as a tool to overcome the problem of ductility lack of FRP reinforcing bars[10-13].

Design Concept and Materials

To generate ductility, hybridization technique of different types of fibers has been implemented. These fibers have been selected so that they have different magnitude of elongations at failure. Table 1 shows the mechanical properties of the selected composite fibers.

The technique is based on combining these fibers together and controlling the mix ratio so that when they are loaded together in tension, the fibers with the lowest elongation (LE) fail first, allowing a strain relaxation (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 of the LE fibers presents the value of the yield strain of the hybrid while the HE fiber strain presents the value of ultimate strain. The load corresponding to LE fibers failure presents the yield load value, and the maximum load carried by the HE fibers is the ultimate load value. Ultra high modulus carbon fibers (Carbon #1) have been used as LE fibers to have as low a strain as possible, but not less than the yield strain of steel (about 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 first yield). High modulus carbon fibers (Carbon #2) were also selected as medium elongation (ME) fibers in order to minimize the load drop during the strain relaxation that may occur after failure of the LE fibers, and also to a guarantee gradual load transition from the LE fibers to the HE fibers. Based on this concept, a uniaxial fabric was fabricated to compare its behavior in tension with the theoretical predicted loading behavior (rule of mixtures). The fabric was developed by combining different fibers as adjacent yarns and impregnating them inside a mold by an epoxy resin. The epoxy was selected so that its ultimate strain is larger than the ultimate strains of any of the fibers. Figure 1 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 (1 in.) and were tested in tension according to ASTM D3039 specifications. The average load-strain curve for four tested samples is shown in Figure 2 together with the theoretical prediction. It is to be noticed 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 significant increase in load up to the total failure of the coupon by failure of the HE fibers. A yield load of 0.46 kN/mm width (2.6 kips/in.) and an ultimate load of 0.78 kN/mm (4.4 kips/in.) were observed.

Beam Tests

Beam Details

Eight reinforced concrete beams with cross sectional dimensions of 152 mm × 254 mm (6 in. × 10 in.) and lengths of 2744 mm (108 in.) were cast. The flexure reinforcement of the beams consisted of two #5 (16 mm) tension bars and two #3 (9.5 mm) compression bars. To avoid shear failure, the beams were over-reinforced for shear with #3 (9.5 mm) closed stirrups spaced at 102 mm (4.0 in.). Figure 3 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 (8,000 psi).

Strengthening Materials

The developed hybrid fabric was used to strengthen four 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.). Three other beams were strengthened with three currently available carbon fibers strengthening materials: (i) a uniaxial carbon fiber sheet with an ultimate load of 0.34 kN/mm (1.95 kips/in.), (ii) 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 (iii) a pultruded carbon fiber plate with an ultimate load of 2.8 kN/mm (16 kips/in.). The tested load-strain diagrams for all these materials are shown in Figure 4. Table 2 shows the properties of the strengthening materials, including the developed fabric.

Strengthening

The beams were strengthened by installing the strengthening material on the beam bottom faces along 2.24 m (88 in) using an epoxy resin. 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. For the beams strengthened with carbon fiber sheet, plate, and fabric, an epoxy resin with an ultimate strain of 2.0% was used (epoxy B). The mechanical properties of the adhesives used are shown in Table 3. To guarantee full curing of the epoxy, the beams were left for more than two weeks before testing. For the beams strengthened with the developed hybrid fabric (H-system), two beams were tested for each configuration to verify the results. Table 4 summarizes the test beams.

Test Results and Discussion

Control Beam

The 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 mid-span. Figure 5 shows the test results for the beams.

Beam C-1

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 carbon fiber sheet. It is noticed from figure 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.

Beam C-2

The beam showed almost 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 yield load of 61% was obtained, the failure was brittle. The maximum recorded strain of carbon fiber plate at failure was 0.33%, which indicates that 24% of the capacity of the plate was utilized.

Beam C-3

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. A ductility index of 1.64 was experienced. The maximum recorded carbon fiber strain at failure was only 0.67%, which indicates that about 48% of the fabric capacity was utilized.

Beam H-50-2

This beam was strengthened with 1 mm thick hybrid fabric developed. A yield load of 97.9 kN (22.0 kips) was experienced (a 19% increase in yield load over that of the control beam).

The beam experienced a considerable yielding plateau (ductility index is 2.33) up to failure by total rupture of the fabric at an ultimate load of 114.8 kN (25.8 kips).

Beam H-75-2

The beam was strengthened with 1.5 mm thick hybrid fabric developed. The beam yielded at a load of 113.9 kN (25.6 kips). The beam showed a considerable yielding plateau before total failure occurred by debonding of the fabric at an ultimate load of 130.8 kN (29.4 kips). Although final failure was by debonding of the fabric, it happened after achieving a reasonable ductility. A ductility index of 2.13 is experienced.

Table 5 compares the results from beam group A. The following are the observed:

1- Beams C1 and H-50-2 exhibited relatively good ductile behaviors. However, beam H-50-2 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 yielding of steel.
2- Although the carbon fiber fabric has an ultimate load several times greater than the yield 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. However, beam H-75-2 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 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.
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.

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, since any failed carbon fiber yarns can be seen. Besides, the cost of the fabric is not significant, as more than 75% of the fibers used are glass fibers that are relatively inexpensive.

Conclusions

1- If loaded for flexure, currently available FRP materials used as strengthening systems for concrete structures do not provide yielding plateaus in the strengthened beams similar to those for unstrengthened beams. This may result in a brittle failure and/or an insignificant increase in the yield load of the strengthened beam.
2- The hybridization of selected types of fibers is utilized to develop a ductile fabric, which has a low strain value at yield. The fabric is designed so that it has the potential to yield simultaneously with the reinforcing steel of the strengthened beam.

3- The beams strengthened using the developed hybrid fabric showed a higher increase in yield load than those strengthened with other currently available carbon fiber strengthening systems. The strengthened beams showed a yield plateau similar to that of the unstrengthened beam. This is critically important to ensure adequate warning before structural failure.
4- The beams strengthened with the developed hybrid fabric system showed no significant loss in beam ductility.

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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 #1	Ultra High Modulus Carbon Fibers	379 (55)	1324(192)	0.35
Carbon #2	High Modulus Carbon Fibers	231 (33.5)	2413 (350)	0.9-1.0
Glass	E-Glass Fibers	48 (7)	1034 (150)	2.1

* Composite properties are based on 60 % fiber volume fraction

Table 2. Properties of the strengthening materials

Type	Yield Load kN/mm (kips/in.)	Yield Strain (%)	Ultimate Load kN/mm(kips/in.)	Ultimate Strain (%)	Thickness mm (in.)
Carbon Fiber Sheet**	0.34 (1.95)	1.2	0.34 (1.95)	1.2	0.13 (0.005)
Carbon Fiber Plate**	2.8 (16.0)	1.4	2.8 (16.0)	1.4	1.3 (0.05)
Carbon Fiber Fabric **	1.31 (7.50)	1.4	1.31 (7.50)	1.4	1.90 (0.075)
H-System*** (t=1mm)	0.23 (1.30)	0.35	0.39 (2.24)	1.74	1.0 (0.04)
H-System*** (t=1.5mm)	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 Designation	Control	C-1	C-2	C-3	H-50-1	H-50-2	H-75-1	H-75-1
Strengthening Material	N/A	Carbon Fiber Sheet	Carbon Fiber Plate	Carbon Fiber Fabric	H- System (t = 1 mm)		H- System (t = 1 mm)	

Table 5. Summary of Test Results

Beam	Yield Load kN (kips)	Deflection at Yield mm (in.)	Failure Load kN (kips)	Deflection at Failure mm (in.)	Ductility Index	Strain at Failure of FRP (%)	Type of Final Failure
Control	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	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	132.6 (29.8)	16.0 (0.63)	132.6 (29.8)	16.0 (0.63)	1.00	0.33	Shear tension Failure
C-3	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	97.9 (22.0)	15.2 (0.6)	114.8 (25.8)	35.6 (1.40)	2.33	1.55	Steel & FRP yield followed by FRP rupture
H-75-2	113.9 (25.6)	13.7 (0.54)	130.8 (29.4)	29.2 (1.15)	2.13	0.74	Steel & FRP yield followed by FRP debonding

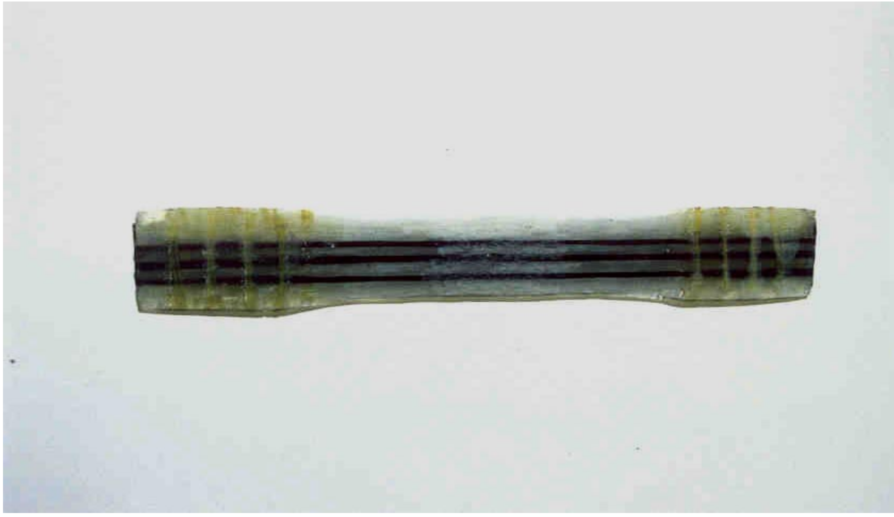


Figure 1. Test Sample for the Developed Uniaxial Hybrid Fabric

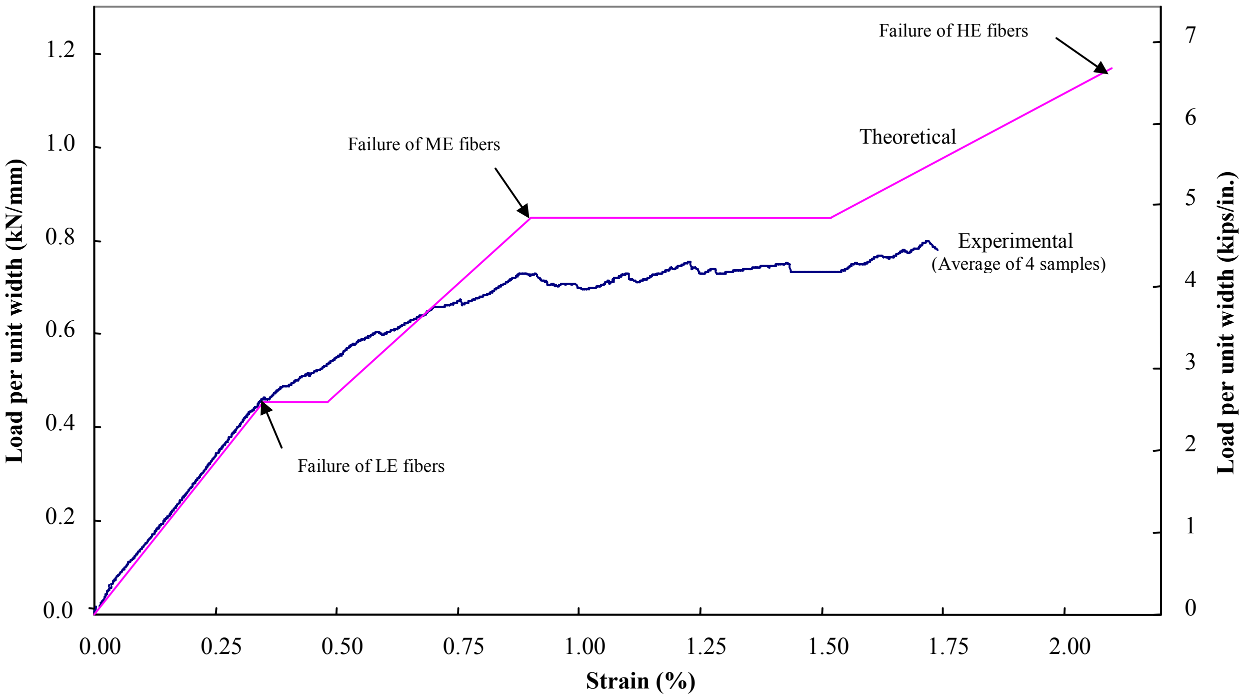
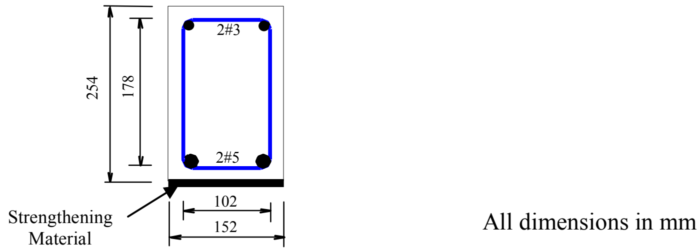
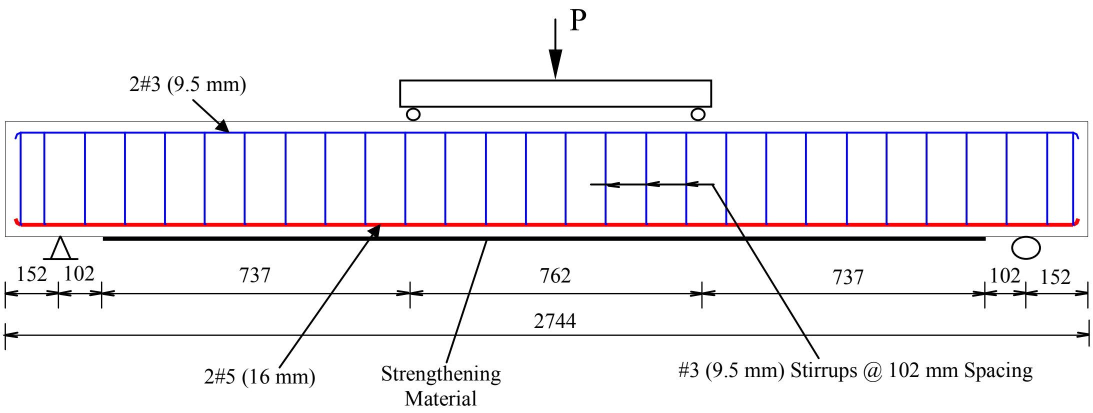


Figure 2. Results of Tensile Tests for the Developed Hybrid Fabric



a) Beam Cross Section



(b) Loading Set-up

Figure 3. Details of Test Beams

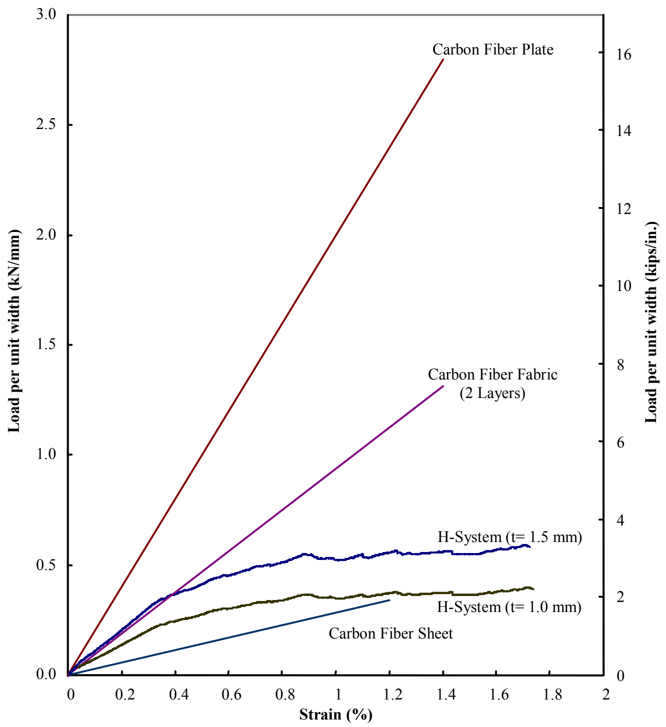
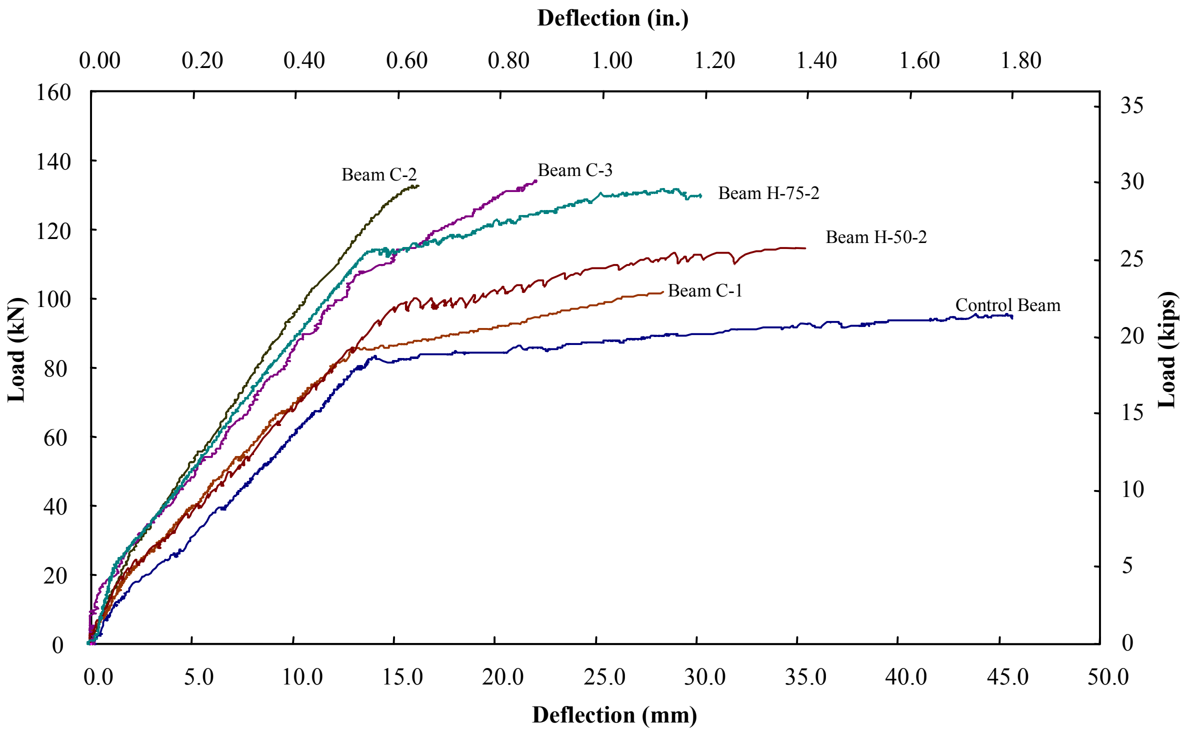
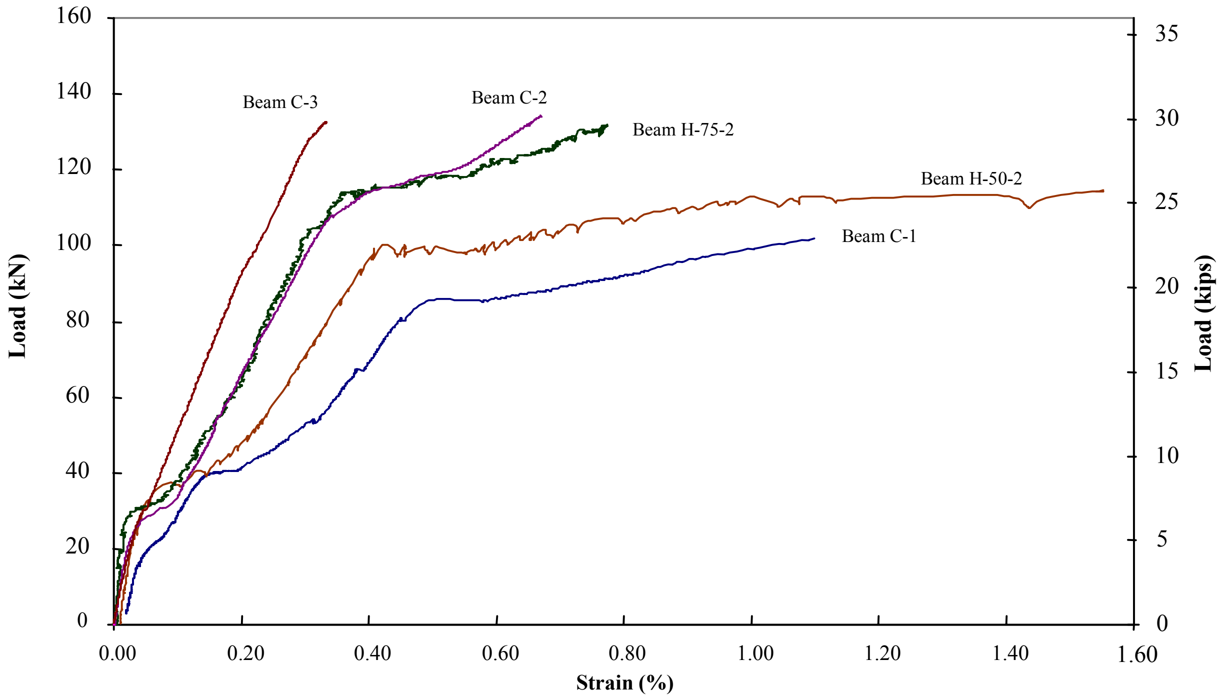


Figure 4. Comparison between Commercially Available Plate, Fabric, Sheet, and Developed Hybrid System (H-System)



(a) <u>Mid-Span Deflection</u>



(b) <u>FRP Strain at Mid-Span</u>

Figure 5. Test Results of Beams