

Ductile FRP Strengthening Systems

Hybridization allows strengthening of reinforced concrete beams without drawbacks typical of fiber-reinforced polymer systems

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Fiber-reinforced polymer (FRP) products have become attractive materials for structural engineers in the concrete construction field, especially for strengthening existing reinforced concrete structural elements. Several FRP systems are now commercially available, incorporating glass, aramid, or carbon fibers. FRP products are available in many forms such as pultruded plates, fabrics, and sheets.

Unfortunately, there are several drawbacks associated with using commercially available FRP systems for flexural and/or shear strengthening of reinforced concrete beams. The objective of this article is to introduce two hybrid, pseudo-ductile FRP strengthening systems designed to potentially avoid many of these drawbacks. The article also reviews some of the important findings of an experimental study¹⁻⁴ to evaluate the effectiveness of these new systems in flexural and/or shear strengthening of reinforced concrete beams.

CURRENT PROBLEMS

Although external strengthening of reinforced concrete beams using epoxy-bonded FRP has been established as an effective tool for increasing their flexural and/or shear strength, the method still suffers from some drawbacks. Many of these drawbacks are attributed to the characteristics of currently available commercial FRP strengthening systems. Although FRPs have high strengths, they are very brittle. When loaded in tension,

FRPs exhibit a linear stress-strain behavior up to failure without exhibiting a yield plateau or any indication of an impending failure.

The strain response of FRPs is different from that of conventional steel, which yields after elastically deforming to relatively small values of strain (0.2% for Grade 60 [410 MPa] and 0.14% for Grade 40 [280 MPa]); FRP materials exhibit elastic deformation to relatively large strain values before rupture. As a result, when FRPs are used for flexural strengthening of concrete beams reinforced with conventional steel, the steel reinforcement may yield before the FRP contributes any additional capacity to the beam. Therefore, it can be difficult to obtain a significant increase in yield load or stiffness for a beam.⁵⁻⁸ When an increase in beam yield load or stiffness is required, larger cross sections of FRPs must be used (before the steel yields), which generally increases the cost of strengthening. Although using some special, low-strain fibers, such as ultra-high-modulus carbon fibers, may appear to be a solution, they can result in brittle failures due to fiber failure.

Taking advantage of the high strength of FRPs during flexural strengthening of reinforced concrete beams is limited by the bond capacity between them and the concrete surface. In many cases, debonding occurs at stress levels that are a small fraction of the FRPs' strength.

In beams strengthened in shear, FRP materials are usually stretched to strain values that are only small

fractions of their ultimate strains when the beam reaches its shear capacity.⁹⁻¹¹ Therefore, the benefits of the FRP are not fully realized in this application. Furthermore, strengthening the beam in shear requires orienting the fibers perpendicular to the beam's longitudinal axis, or for better effectiveness, at 45 degrees to the beam longitudinal axis.¹¹⁻¹² Therefore, simultaneous flexural and shear strengthening of beams requires using more than one layer of FRP. Finally, carbon FRP (CFRP) systems, the most commonly used FRP strengthening systems, are relatively expensive.

DEVELOPMENT OF NEW DUCTILE SYSTEMS

A research program¹⁻⁴ conducted at Lawrence Technological University resulted in the development of two

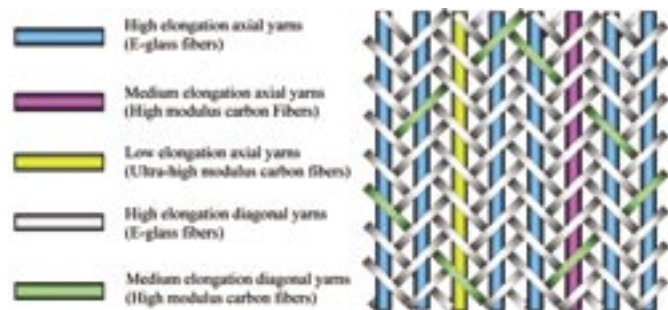


Fig. 1: Details of the triaxially braided HFRP fabric (THD system)



Fig. 2: Photo of the triaxially braided HFRP fabric (THD system)

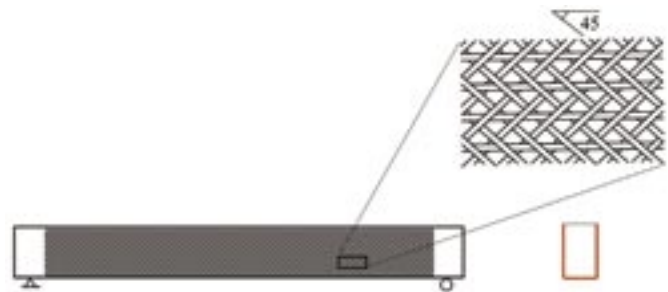


Fig. 3: Lay-up of triaxially braided HFRP fabric for simultaneous flexural and shear strengthening

hybrid FRP (HFRP) strengthening systems that differ from currently available CFRP systems. They were designed specifically for use in strengthening reinforced concrete beams for flexure and/or shear while potentially avoiding the drawbacks mentioned previously. Hybridization has also been used to compensate for the lack of ductility of FRP reinforcing.¹³⁻¹⁵

The first HFRP system (H system) is a uniaxial fabric consisting of different types of carbon and glass fibers. The fabric was mainly designed for use in strengthening reinforced concrete beams for flexure by mimicking the behavior of steel in tension (a linear stress-strain behavior followed by a yield plateau). Designed with a relatively low yield-equivalent strain value (around 0.35%), the fabric can potentially contribute significantly to the beam capacity before the steel reinforcement yields. Therefore, significant increases in beam yield capacity and stiffness can be achieved.

The second HFRP system (THD system) is a triaxially braided fabric (Fig. 1 and 2) designed for use in strengthening reinforced concrete beams for flexure and/or shear. A hybrid of different types of carbon and glass fibers, the fabric is triaxially braided in three different directions: 0, +45, and -45 degrees. The fabric was designed to exhibit a linear stress-strain behavior followed by a yield plateau if loaded in tension in any of these directions. The 0-degree direction (referred to as the axial direction) acts mainly for flexural strengthening, while the +45- and -45 degree directions (referred to as the diagonal directions) primarily provide shear strengthening (Fig. 1 to 3). Providing fibers perpendicular to potential shear cracks increases their effectiveness in strengthening the beam's shear capacity. In addition, the diagonal yarns work to self-anchor the fabric when bonded around the tension face and the sides of the beam, significantly reducing the potential of debonding or shear-tension failures.

Figure 4 and Table 1 show a comparison between the tensile behavior of the HFRP systems and the commercially available FRP strengthening systems used in this experimental program.

PROBLEMS SOLVED

Testing¹⁻⁴ was conducted at the Structural Test Center at Lawrence Technological University to evaluate the effectiveness of the HFRP systems in flexural and/or shear strengthening of reinforced concrete beams. Identical beams were strengthened using some commercially available carbon fiber systems to compare their behavior with those strengthened with the HFRP systems.

Yield load increase

Because HFRP systems have a relatively small yield-equivalent strain value (around 0.35% [Fig. 4]), they have

the potential to contribute most of their strength when the steel reinforcement of the beam yields, which may significantly increase the beam's yield capacity (Fig. 5). Experimental investigations¹⁻³ showed that beams strengthened with HFRP systems generally had an increase in beam yield capacity similar to the increase shown in identical beams strengthened with carbon fiber sections of similar rigidity. The ultimate strains of the beams strengthened with the HFRP system, however, were several times greater than those of the beams strengthened with CFRP sections.

Ductility loss and brittle failures

Test results of reinforced concrete beams strengthened in flexure using the HFRP systems showed that those beams were generally less vulnerable to significant loss of beam ductility compared with identical beams strengthened with carbon fiber sections of similar rigidity.¹⁻³ Table 2 compares the ductility and the failure modes of some of the tested beams.

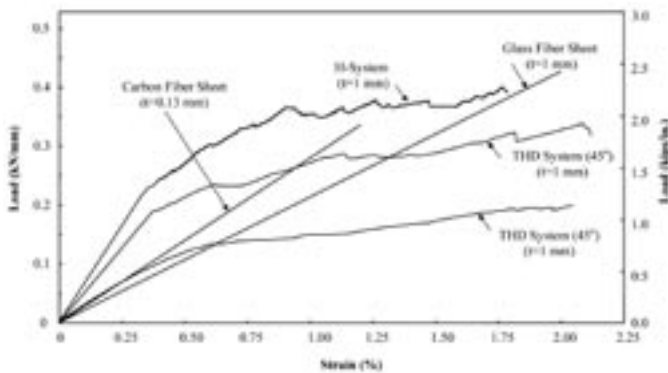


Fig. 4: Comparison between the tensile behavior of the developed systems and some commercially available FRP strengthening systems

It is clear that the beams strengthened using the THD system had ductility indexes 21 to 95% greater than those strengthened with carbon fibers sheets. Because the HFRP systems behave like steel in tension, they play a role in two different ways. First, the reduction in stiffness of the HFRP systems past the yield-equivalent point limits the force in them. With less force, it becomes less likely that the HFRP will exceed its anchorable limit, which significantly reduces the potential of a brittle debonding failure. Second, the reduction in stiffness of the HFRP systems past the yield-equivalent point reduces the beam's stiffness, which generates higher deformations before failure and more ductility.

The HFRP systems exhibited very limited permanent strains. However, unlike steel, they did exhibit a permanent loss in stiffness when unloaded and reloading past the yield-equivalent point. Steel exhibits permanent strains without a loss in its stiffness after unloading and reloading. Despite this difference, the beams strengthened with the HFRP systems still exhibited a considerable permanent

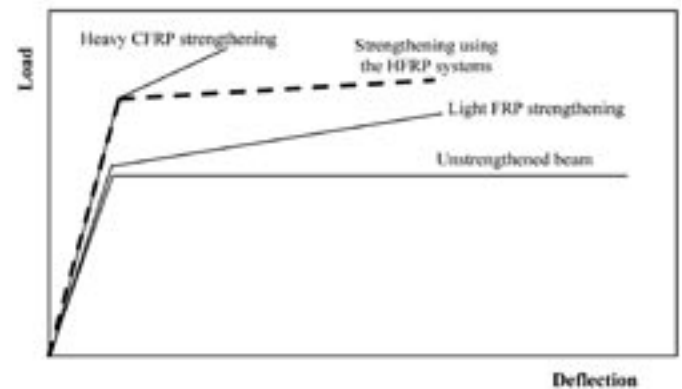


Fig. 5: Schematic diagrams of load-deflection relationships experienced by reinforced concrete beams strengthened in flexure using commercially available FRP and the hybrid systems

TABLE 1:

COMPARISON BETWEEN THE TENSILE BEHAVIOR OF THE DEVELOPED SYSTEMS AND SOME COMMERCIALY AVAILABLE FRP STRENGTHENING SYSTEMS

Material		Yield-equivalent load, kN/mm (kip/in.)	Yield-equivalent strain, %	Ultimate load, kN/mm (kip/in.)	Ultimate strain, %	Thickness, mm (in.)
THD system	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	
H system		0.23 (1.30)	0.35	0.39 (2.24)	1.74	1.0 (0.039)
Carbon fiber sheet		—	—	0.34 (1.95)	1.2	0.13 (0.005)
Glass fiber fabric		—	—	0.42 (2.4)	2.00	1.0 (0.039)

deformation (in addition to the permanent loss in stiffness) after unloading and reloading. This is attributed to the steel reinforcement existing in the beam before strengthening. A reduction in stiffness of the HFRP systems after the yield-equivalent point allows the steel reinforcement to exhibit an increase in strain. After the beam is unloaded, the steel reinforcement helps to maintain a permanent deformation in the beam.

The test results of Beam F-U65-1, (Fig. 6) indicated that the beam exhibited a permanent deflection after

unloading and reloading. The beam had a cross-sectional area of 152 x 254 mm (6 x 10 in.), length of 2740 mm (108 in.), and contained two No. 5 (16 mm) tension bars (near the bottom) and two No. 3 (10 mm) compression bars (near the top). The compressive strength of the concrete at the time the beam was tested was 41.5 MPa (6000 psi) and the steel reinforcement used had a yield stress of 490 MPa (71 ksi). Beam F-U65-1 was strengthened with one layer of the THD system 1594 mm (62 in.) long, centered along the beam's span, and U-wrapped along the bottom face, extending 152 mm (6 in.) on both sides.

The beam was tested as a simple beam in four-point bending at a shear span of 838 mm (33 in.) until failure. For more information about the test procedure refer to Reference 2. Further, the THD system contains bundles of fibers in the ± 45 -degree directions that anchors it when bonded around the tension face and the vertical sides of the beam along its length. Therefore, it is generally less vulnerable to debonding or shear-tension failures (shown in Fig. 7 for Beam F-CU65). This coincided with the findings of Bencardino, Spadea, and Swamy⁸ in the case of biaxial fabrics.

Ductility is very important for statically indeterminate structures, such as continuous beams, because it allows for moment redistribution through the rotations of plastic hinges. Thus, the effectiveness of the THD system in strengthening two-span continuous beams strengthened in flexure has been experimentally investigated.³ Test results for Beams F-CT and F-CTC that were strengthened in flexure with the THD system and a commercially available carbon fiber sheet, respectively, were compared. The ductile behavior of the THD system resulted in a reasonable ductility in the plastic hinge of Beam F-CT, which in turn allowed for the redistribution of moment between positive and negative moment zones. Beam F-CT also exhibited a load-deflection response that was similar to that of the unstrengthened beam (Fig. 8) and failed after exhibiting a reasonable ductility.

TABLE 2:
COMPARISON BETWEEN DUCTILITY AND FAILURE MODE OF SIMPLE BEAMS STRENGTHENED IN FLEXURE

Group	Beam designation	Strengthening system*	Ductility index [†]	Mode of final failure
1 [‡]	F-B-2	THD system	1.95	Steel and fabric yield followed by concrete failure
	F-CB-1	Carbon fiber sheet	1.61	Steel yield followed by sheet debonding
2 [‡]	F-U-2	THD system	2.18	Steel and fabric yield followed by concrete failure
	F-CU-1	Carbon fiber sheet	1.61	Steel yield followed by concrete failure
3 [‡]	F ₃ -B-1	THD system	2.92	Steel and fabric yield followed by fabric debonding
	F ₃ -CB-1	Carbon fiber sheet	1.5	Steel yield followed by sheet debonding
4 [‡]	F ₃ -U-1	THD system	3.75	Steel and fabric yield followed by fabric rupture
	F ₃ -CU-1	Carbon fiber sheet	2.27	Steel yield followed by sheet debonding
5	F-U65-1	THD system	1.95	Steel and fabric yield followed by concrete failure
	F-CU65	Carbon fiber sheet	1.33	Steel yield followed by shear-tension failure at sheet end

*The sections of the strengthening systems in each group are similar in rigidity.

[†] The ratio between the deflection at failure and the deflection at first yield.

[‡] Grace, Ragheb, and Abdel-Sayed²

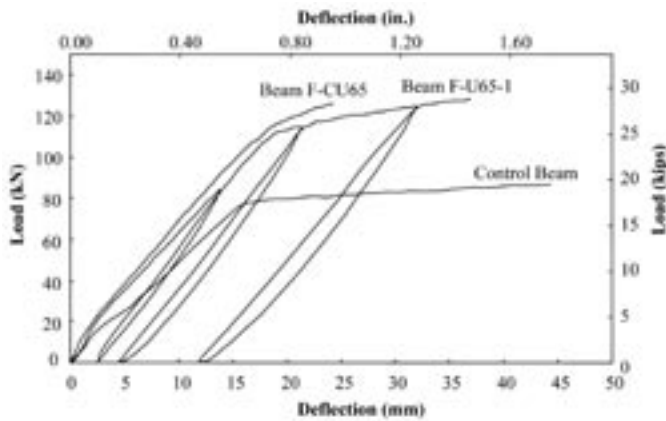


Fig. 6: Load-midspan deflection relations of Beam F-U65-1, strengthened with HFRP, and Beam F-CU65, strengthened with CFRP

Distinguished audible warnings before failure

Yielding of the HFRP system is always accompanied by audible sounds. The generation of ductility by these systems is based on allowing the fibers to rupture successively and the fiber rupture causes loud, audible sounds. Because the fiber rupture is audible, it can be used as an indication of a potential failure. That is critically important because it adds a failure warning sign to the visual sign of a potential failure revealed by the ductile behavior of the beam (excessive increase in strains and deformations).

Cost and material exploitation

As an added benefit, the increased strength, ductility, and built-in warning features of HFRP systems are available at a cost that is relatively low compared to CFRP systems. This is because more than 75% of the fibers used are glass fibers, which are relatively inexpensive. Furthermore, the new systems were designed to allow the fibers to fail successively starting with the most expensive ones (the carbon fibers), which start to fail after exceeding the yield-equivalent strain. Therefore, the HFRPs have the potential to fully exploit their components, especially the most expensive ones. This was verified by the test results¹⁻⁴ for reinforced concrete beams strengthened using the HFRP systems, which showed that the maximum recorded strains of these systems before beam failure were much more than their yield-equivalent strain, and also more than the failure strain of all the carbon fiber yarns in the system. In contrast, the maximum recorded strains of the carbon fiber systems used to strengthen identical beams were noticeably less than their ultimate strains, which indicated that their strength was underutilized.

With respect to shear strengthening, the behavior of the THD fabric in the 45-degree directions allows



Fig. 7: Failure of two identical beams strengthened in flexure using two strengthening systems: a) carbon fiber sheet strengthening of Beam F-CU65, which was identical to Beam F-U65-1 except that it was strengthened with a uniaxial CFRP sheet that had a similar rigidity to that of the triaxially braided fabric system used in Beam F-U65-1; and b) triaxially braided fabric strengthening (Beam F-U65-1)

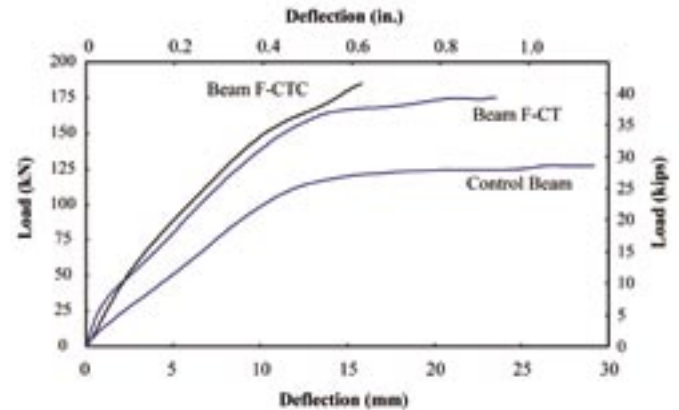


Fig. 8: Load-midspan deflection curves of two-span continuous beams. Beams F-CTC and F-CT were strengthened in flexure with CFRP and HFRP, respectively³

optimum fabric contribution to beam shear strength. In other words, the fabric yield-equivalent strength was designed to be equal to the maximum possible usable fabric stress in beam shear strength.⁴ In addition, the THD fabric was designed to have the diagonal yarns at 45 degrees to the beam longitudinal axis to increase the effectiveness of these yarns in the shear strength of the beam. At the same time, the existence of the axial yarns at the same layer with the diagonal yarns makes the fabric capable of strengthening the beam for flexure and shear simultaneously.

APPLICATIONS

No special technique is required to apply these HFRP systems on the beams. The HFRP systems were designed

to be installed using the “wet lay-up” technique, which is the same technique currently used to install most of the commercially available FRP systems.

Both pseudo-ductile FRP strengthening systems show promise of optimizing FRP properties without the drawbacks associated with typical FRP strengthening systems.

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