EXPERIMENTAL STUDY ON NSM FRP SHEAR RETROFITTING OF RC BEAMS

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Abstract

The shear strength of reinforced concrete (RC) members can be significantly enhanced with near-surface mounted (NSM) fibre-reinforced polymers (FRPs). Although scant research has been conducted on the subject to date, this technique has proven to be highly effective and to feature a number of advantages over other strengthening approaches, either with FRPs or more conventional materials. This paper describes the experimental findings for trials with 17 NSM-CFRP shear-strengthened, rectangular cross-section beams. Each beam was tested twice, once at each end. The variables analysed in the study were: FRP type; angle of the NSM reinforcement with respect to the longitudinal axis of the beam, and spacing between FRP elements.

Keywords: FRP; laboratory test; near-surface mounting (NSM); RC beams; shear strength.

1. Introduction

Fibre-reinforced polymers (FRPs) have been extensively used to strengthen reinforced concrete structures because of their excellent mechanical properties and corrosion resistance. Moreover, being very lightweight, they can be readily applied and inexpensively shipped to the worksite. Several design guides have recently been published on the subject [1-3]. In the most popular of these strengthening methods, FRP sheets or laminates are externally bonded to the member to be strengthened. This technique is subject to two main drawbacks, however: member failure is generally due to FRP debonding well below its ultimate strength, and the system is highly sensitive to external factors such as impact, fire or vandalism.

Alternatively, FRP strips or bars can be embedded in epoxy resin- or cement paste-filled grooves made in the concrete cover. This approach, the near-surface mounted (NSM) technique, clearly mitigates the aforementioned drawbacks. While NSM FRP retrofitting is a well-known strengthening technique [4-6] and despite the general consensus that it is effective, its fairly recent appearance has limited the amount of papers published on its use. Shear strengthening in particular has been the object of very little empirical research. The present study was designed to provide greater insight into the effectiveness of NSM as a shear strengthening technique.

2. Experimental

The test programme called for designing and casting 17 RC beams, all 3750 mm long with a 200 x 350 mm^2 rectangular cross section. These specimens were much more lightly reinforced transversely than longitudinally to ensure that they would fail due to shear rather than to bending forces, even after strengthening. The compression and tension reinforcement respectively consisted of two and four 20 mm diameter B500S cold-formed steel bars. The shear reinforcement comprised 6 mm diameter B400S closed steel stirrups uniformly spaced at 230 mm (Figure 1).

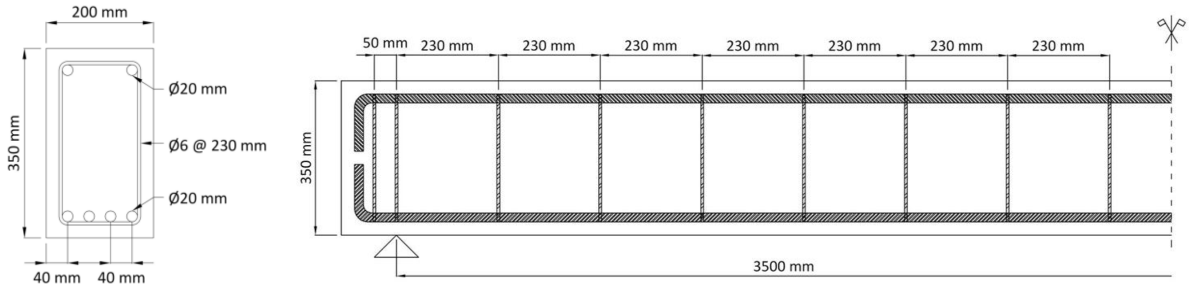


Figure 1. Steel reinforcement geometry

Two beams per series and one (non-strengthened) control beam were cast with B20/25 ready-mix concrete. The test conditions are summarised in Table 1.

Table 1. Test programme

Beam code	FRP type	NSM angle [º]	Spacing [mm]	Number of beams
Control	-	-	-	1
B90-6	Bars	90	115	2
B90-3	Bars	90	230	2
B45-6	Bars	45	115	2
B45-3	Bars	45	230	2
S90-6	Strips	90	115	2
S90-3	Strips	90	230	2
S45-6	Strips	45	115	2
S45-3	Strips	45	230	2

The test variables were: type of CFRP (8 mm diameter bars (**B**) or 2.5 x 15 mm^2 strips (**S**)); reinforcement angle with respect to the beam axis (**90**º or **45**º); and element spacing. Two spacing intervals were used for each angle arrangement: 115 mm (**6** bars or strips per beam) or 230 mm (**3** bars or strips per beam) along the shear span.

Special care was taken to immobilise the FRP during placement to ensure a minimum cover of 20 mm. To characterize the concrete compression strength, three standard cylindrical specimens 150 mm in diameter and 300 mm high were made from each batch. Twenty mm grooves were sawn into the specimens no earlier than 21 days after casting. Groove width depended on the type of FRP element: 12 mm for the bars and 7 for the strips. They were sawn from the bottom of the beam to a height 50 mm from the top of the beam in all cases. This 50 mm gap was intended to simulate the unfavourable situation that arises when a structural slab prevents running the NSM groove into the compression zone of the beam.

One week later, the beams were strengthened using the supplier-recommend procedure. According to BASF, the characteristics of the CFRP supplied (MBrace CUT-IN and MBar GALILEO) were: fibre content, 65%; average tensile strength, 2500 MPa; and elastic modulus, 165 GPa. The resin used was MBrace Adhesive 220 for the bars and Masterflow 920 SF for the strips.

3. Instrumentation and testing

Strain gauges were placed at mid-height on both vertical arms of the steel stirrups positioned in the shear span and at the same height on all three elements on the beams with only three. The beams with six elements were instrumented on every other bar or strip on each side, alternating the position so that at least one of the two stirrup strain gauges had a matching FRP strain gauge. Mid-span deflection was monitored with a linear variable differential transformer (LVDT).

The beams were simply supported at each end and tested under one load point. Two consecutive tests were conducted on each specimen, varying the span (Figure 2) to make the most of the beams.

- Long span (L): the first test was conducted on the entire 3500 mm span of the beam, applying a single load at a distance from one end support equal to three times the effective depth of the beam (930 mm).

- Short span (S): the support closest to the loading point in the preceding trial was moved to support the broken end of the beam, forming a total new span of 2570 mm. The beam was again loaded, now at a distance from the opposite end equal to three times the effective depth (930 mm).

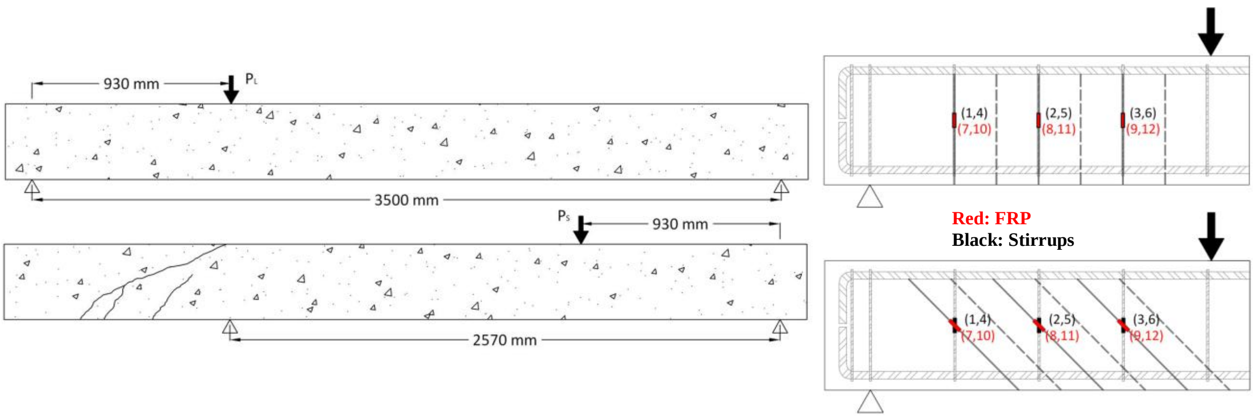


Figure 2. Test set-up and strain gauge position

The load was applied with a hydraulic jack travelling at 1 mm/min. Load, strain and LVDT data were recorded by a data acquisition system at a sampling rate of 1 Hz. After the first crack appeared, testing was briefly interrupted to monitor its width and pattern.

4. Results

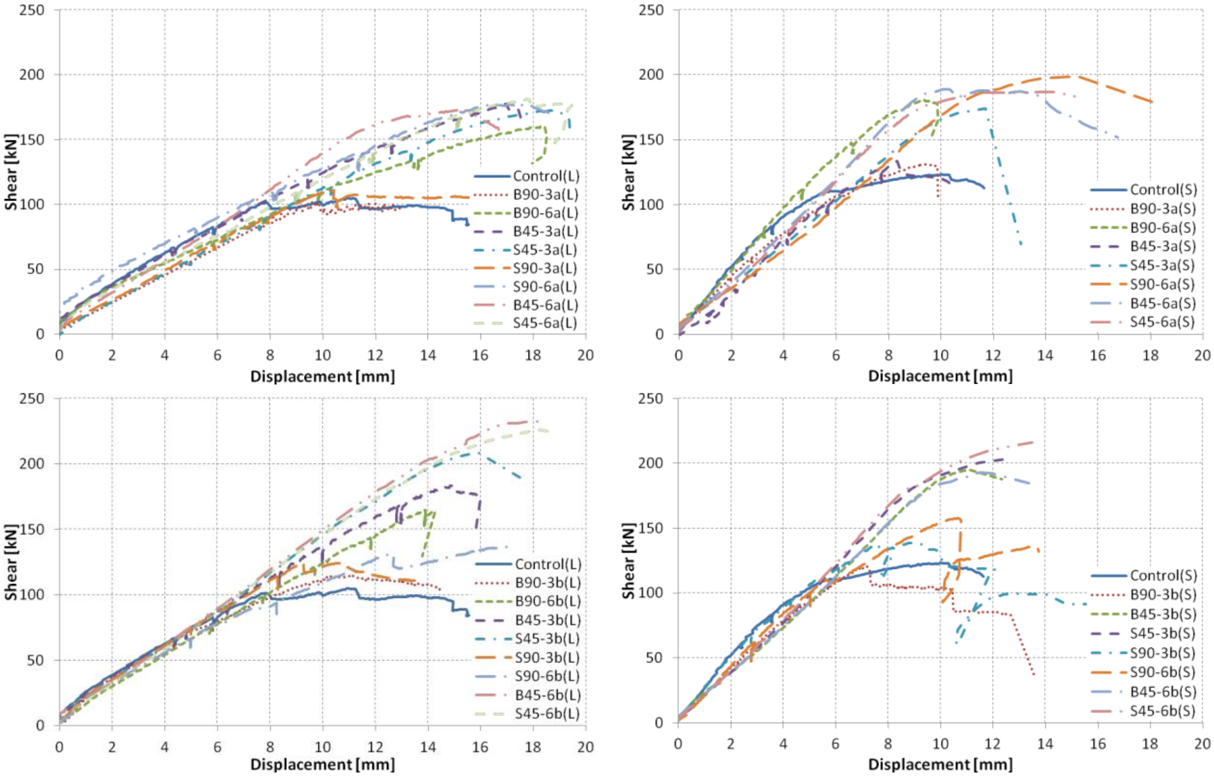
4.1 Shear failure load and strain

Table 2 summarises the shear failure load results for all the beams. The letters **a** and **b** specify the two beams in each series. The table gives the average concrete strength for each beam, along with the ultimate shear recorded in each test (long or short), the mean of the two, and the rise in shear strength attributable to FRP retrofitting. This fifth parameter was found by subtracting the ultimate shear recorded in the control beam, corrected for the difference in concrete strength, from the shear failure load for the trial beam. The correction factor used, derived from the expression given in Eurocode 2 [7], was $(f_{cm,x}/f_{cm,ref})^{1/3}$, where $f_{cm,x}$ is the concrete strength in the beam studied, and $f_{cm,ref}$ the concrete strength in the control beam.

Table 2. Ultimate shear strength

Beam	f_{cm} [MPa]	Ultimate shear [kN]			Rise in strength [%]
		Long span (L)	Short span (S)	Mean of L and S	
Control	27.97	104.76	123.17	113.97	-
B90-3a	22.84	103.81	131.22	117.52	7.60
B90-3b	26.02	114.60	120.56	117.58	
B90-6a	26.69	160.06	180.98	170.52	49.72
B90-6b	24.09	164.90	161.97	163.44	
B45-3a	29.11	177.68	133.64	155.66	53.17
B45-3b	23.91	183.48	194.90	189.19	
B45-6a	22.98	173.20	188.77	180.99	75.66
B45-6b	28.48	232.67	193.05	212.86	
S90-3a	22.84	111.08	123.05	117.07	13.58
S90-3b	26.02	124.59	138.75	131.67	
S90-6a	26.69	177.24	198.79	188.02	50.34
S90-6b	24.09	137.07	157.63	147.35	
S45-3a	29.11	172.83	174.29	173.56	68.49
S45-3b	23.91	209.03	203.39	206.21	
S45-6a	22.98	180.91	186.73	183.82	80.47
S45-6b	28.48	225.99	216.02	221.01	
Mean	25.66	161.99	166.29	167.27	-

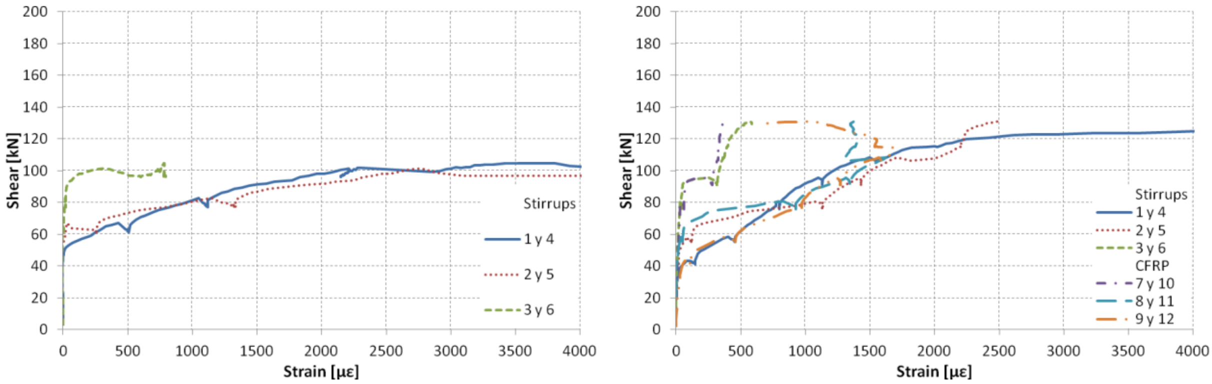
Although the long and short span findings for any given beam differed by around 10%, the mean value for all the long span trials combined was approximately equal to the short span mean. That was interpreted to be an indication that the two trials were equivalent, with the differences in each beam being attributable to the natural randomness inherent in this kind of tests. Consequently, the last column lists the mean rise in strength for the four tests in each series. Figure 3 shows the shear load vs mid-span deflection for all the long (a) and short (b) span trials.



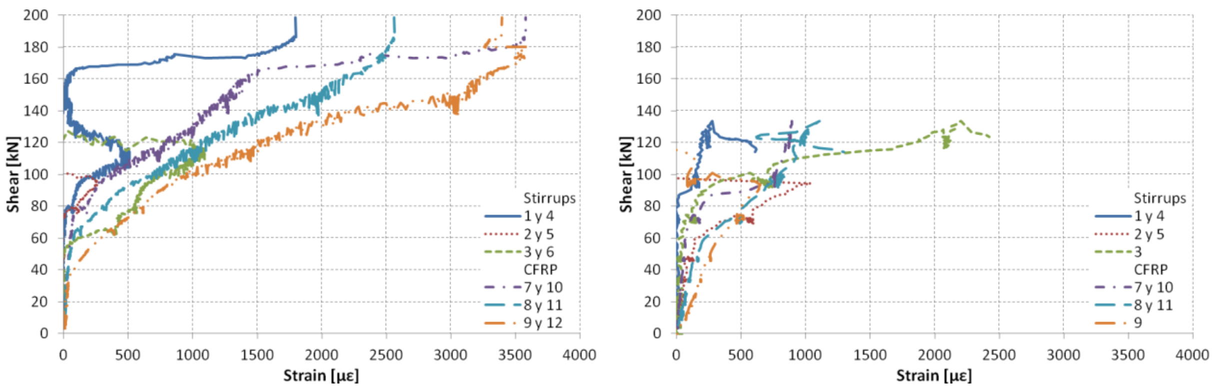
(a) Shear load vs mid-span deflection (long span) (b) Shear load vs mid-span deflection (short span)

Figure 3. Shear load vs mid-span deflection for long (a) and short (b) beams

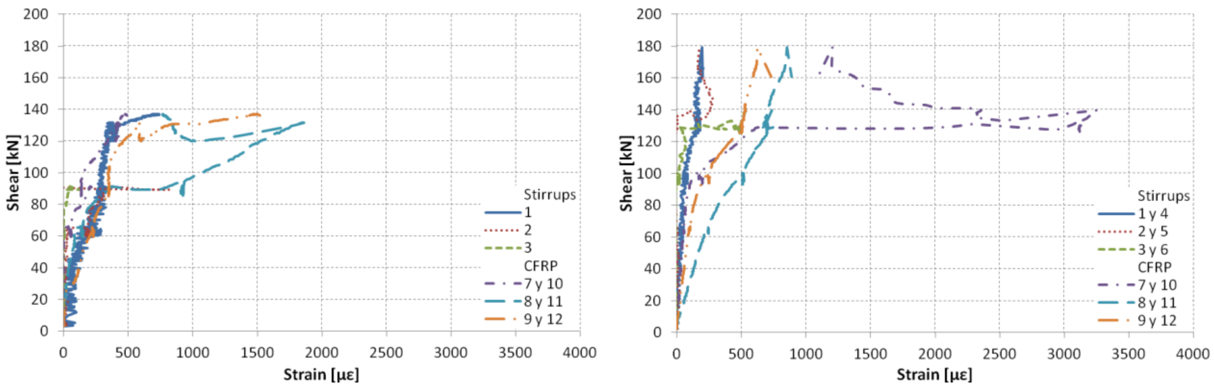
The shear strain-shear stress diagrams for the stirrups and FRP are plotted in Figure 4. These diagrams are shown for a few selected beams only for greater clarity, since the ones not shown exhibited similar patterns.



(a) Control beam (L) (b) Beam B90-3a(S)



(c) Beam S45-3b(L) (d) Beam B45-3a(S)



(e) Beam S90-6b(L) (f) Beam B45-6b(S)

Figure 4. Shear strain-shear stress diagrams for stirrups and FRPs

As the figure shows, no strain was recorded in either the stirrups or the FRP until the stress induced a nearby crack. The strain value observed depended on the proximity of the crack to the position of the strain gauge.

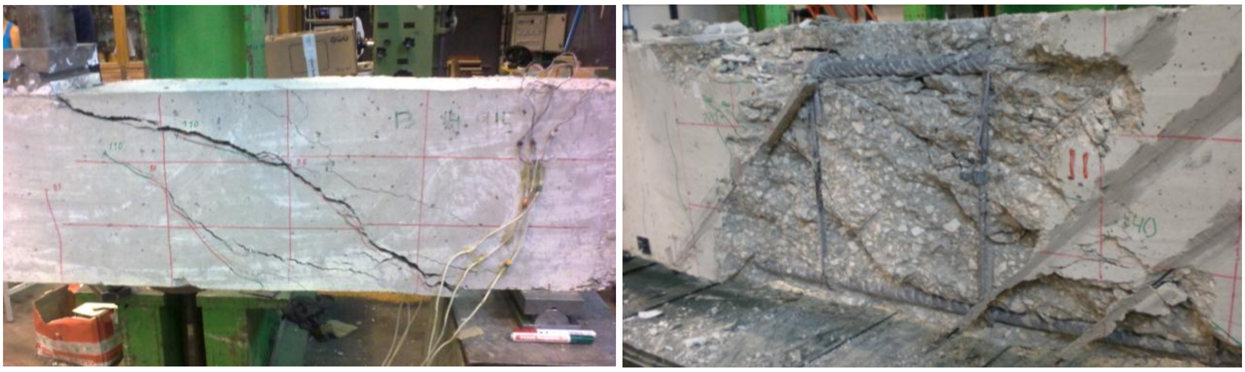
4.2 Failure mode

The failure mode observed depended largely on the amount of FRP used and its angle.

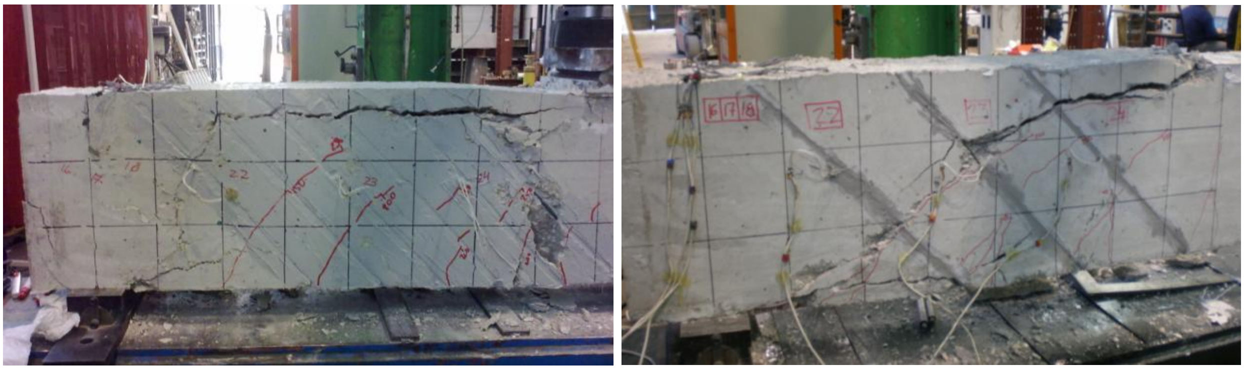
For the (unstrengthened) control beam, failure was caused primarily by a large shear crack that ran from a point near the support to the load point. Several smaller cracks appeared alongside the main crack that were observed to progress at a slower rate (Figure 5 (a)).

The failure mode observed in the FRP-retrofitted beams followed three main patterns: 1) failure due to detachment of the concrete cover (Figure 5 (b)); 2) failure due to separation of the concrete at the top of the beam (Figure 5 (c)); and, 3) failure due to severe shear cracking along one or several fronts (Figure 5 (d)).

Failure modes 1) and 2) were observed primarily in beams more heavily strengthened with elements placed at a 45º angle. In all the other strengthening arrangements studied, i.e., lighter retrofitting at a 45º angle and both more and less intense strengthening at a 90º angle, failure was predominantly due to severe shear cracking on one or more fronts.



(a) Control beam (b) Beam S45-6b(L)



(c) Beam S45-6a (L) (d) Beam S45-3b(S)

Figure 5. Failure modes

More generally, beams failed due to any one or a combination of the aforementioned modes. Moreover, beam failure occasionally concurred with other types of local failure such as stirrup rupture or the detachment of the bottom concrete cover.

Another aspect of the failure modes that merits mention is the path of the main crack. As a rule, but especially in the beams more heavily retrofitted, that crack tended to find a pathway in-between the FRP elements, inducing mode 2 failure, i.e., separation of the concrete at the top of the beam.

5. Conclusions

The main conclusions to be drawn from the experimental findings described here are summarised below.

- By applying the load at three times the beam depth from each end, two equivalent tests can be conducted on each beam. This yields twice the experimental data with nearly the same effort as in conventional four-point testing.
- The increase in shear strength afforded by NSM FRP depends primarily on the reinforcement angle and amount of material used. The mean rise in shear strength with respect to the control for each type of strengthening is listed below:

All beams with bars:	46.5%
All beams with strips:	53.2%
All beams with elements at a 90º angle:	30.3%
All beams with elements at a 45º angle:	69.4%
All beams with 3 bars/strips:	35.7%
All beams with 6 bars/strips:	64.0%

  - Strips performed better than bars because their (34%) smaller cross-section and (40%) greater perimeter afforded more effective bonding to the concrete. The advantage of using bars is that they can be housed in shallower grooves.
  - NSM FRPs positioned at 45º were twice as efficient as the 90º elements, even though the total length in the former was only 40% greater. The reason may be that in beams strengthened at a 90º angle, cracks can propagate parallel to, i.e., without crossing, the FRP.

    - Using six instead of three elements nearly doubled strength.

- No perceptible rise in beam strength was observed in members retrofitted with three bars or strips of FRP positioned at a 90º angle.
- The mode failure in beams with six bars or strips positioned at 45º, i.e., detachment of the side cover, is an indication that those amounts of FRP were very close to reaching the optimum, beyond which more FRP would have no further effect on strength.

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