



Behaviour of large FRP ties for seismic strengthening of concrete diaphragms

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ABSTRACT

Externally bonded fibre reinforced polymer (EB-FRP) techniques have been widely recognized as an excellent seismic retrofit strategy for structures. Despite the extensive research and practical implementation of EB-FRP, premature debonding at strain levels significantly below the rupture strain remains one of the biggest problems. Implementing FRP anchor(s) in EB-FRP systems is an effective method to provide post-debond capacity and ensure the continuity of the load path and improve the deformation capacity. Extensive research on the behaviour of EB-FRP systems has been undertaken over the years, but the research was limited to short and thin FRP strips with small and shallow FRP anchor(s). Recent experimental testing of thicker and longer FRP ties on concrete has shed light on the debond strain capacity, the post-debond deformation capacity (ductility) and the efficiency of anchor detailing to provide redundancy and deformation capacity beyond that of fully debonded FRP.

INTRODUCTION

Fibre reinforced polymer (FRP) materials, typically carbon fibres and epoxy resin, have been increasingly used in the field of seismic retrofitting of existing buildings due to their high strength-to-weight ratio, corrosion resistance, and ease of application. Externally bonded FRP (EB-FRP) technique has become popular for enhancing the structural performance and increasing the seismic resistance of concrete structures among various retrofit strategies. One of the major challenges associated with EB-FRP systems is the problem of premature debonding, which occurs when the FRP detaches from the concrete substrate at strain levels significantly below the rupture strain, resulting in a loss of load-carrying capacity and reduced deformation capacity. Researchers have proposed various methods to prevent or delay debonding to address this issue, including the use of FRP anchors (Ozbakkaloglu 2017; Muciaccia 2022)

FRP anchors, which are made of bundles of fibres soaked in epoxy, can be embedded into the concrete substrate and bonded to the FRP, thus improving the load transfer between the FRP and concrete and increasing the deformation capacity of the system (del Rey Castillo 2019a). The addition of anchorage devices enables the FRP-to-concrete bond to increase in both strength and ductility (Smith 2011; Zhang 2012). A myriad of experimental and numerical studies on the behaviour of EB-FRP systems have been undertaken, but they focused on short and thin FRP strips and small and shallow FRP anchors. Limited research on the behaviour of

larger FRP ties with more extensive anchorage systems has been completed to date (del Rey Castillo 2022). In collaboration with Simpson Strong Tie, we recently completed a round of experimental testing of thicker and longer FRP ties. The objective of this research was to investigate the behaviour of long and thick ties, be able to develop design models to calculate debond capacity, and provide insights on anchor detailing for redundancy. This paper is just an interim, reporting provisional analysis on the results, and further work will be completed in the coming months – the content of this paper is not to be taken as design recommendations.

METHODOLOGY

The cylinder compressive strengths were obtained at the time of testing following ASTM C-39 standard, resulting in 19.24 ± 1.32 MPa, 19.53 ± 1.17 MPa and 36.14 ± 3.03 MPa. A total of 8 cylinders per mix were tested. The mechanical properties of the FRP material were evaluated through 42 coupon tests following ASTM D3039, the properties are elastic modulus (105.4 ± 8.83 GPa), tensile strength (1363.5 ± 136.9 MPa) and elongation at break (1.39 ± 0.17 %).

Rectangular reinforced concrete blocks with dimensions of 1372 mm or 1524 mm x 457 mm x 152 mm were used as the substrate for the single lap shear tests, where the FRP was bonded onto the concrete. Large FRP ties were tested by Simpson Strong-Tie Inc. company (SST) Tyrell Gilb Research Laboratory, with a total of 36 specimens tested without anchors and 24 specimens with anchors, including 12 single-anchored and 12 double-anchored specimens. The typical specimens used in the testing are shown in Figure 1, with an unbonded area equal to 152 mm being applied to prevent breaking the edge of the concrete. Three lengths were tested, 12, 24 and 36 inches (305, 610 and 914 mm), while the thickness (stiffness) of the [FRP tie](#) was varied from 1 to 4 layers of a typical 11 oz./yd.² (370 g/m²). The concrete strengths were 2500, 3000 and 5000 psi (17, 21, 34 MPa). The [FRP anchors](#) had a cured dowel diameter of either 0.5, 0.75, 1-inch (12.7, 19.1 and 25.4 mm), with the fan being 8, 12 and 16 inches (203, 305 and 406 mm) long. The holes were always 4 inches (102 mm) deep. Concrete surface and holes were prepared according to supplier and contractor specifications, aligned with best practice. Concrete block movement was measured using three LVDTs along the direction of loading. Strain patterns were captured using DIC (Digital Image Correlation). Considering the space constraints, these results are not included in this section.

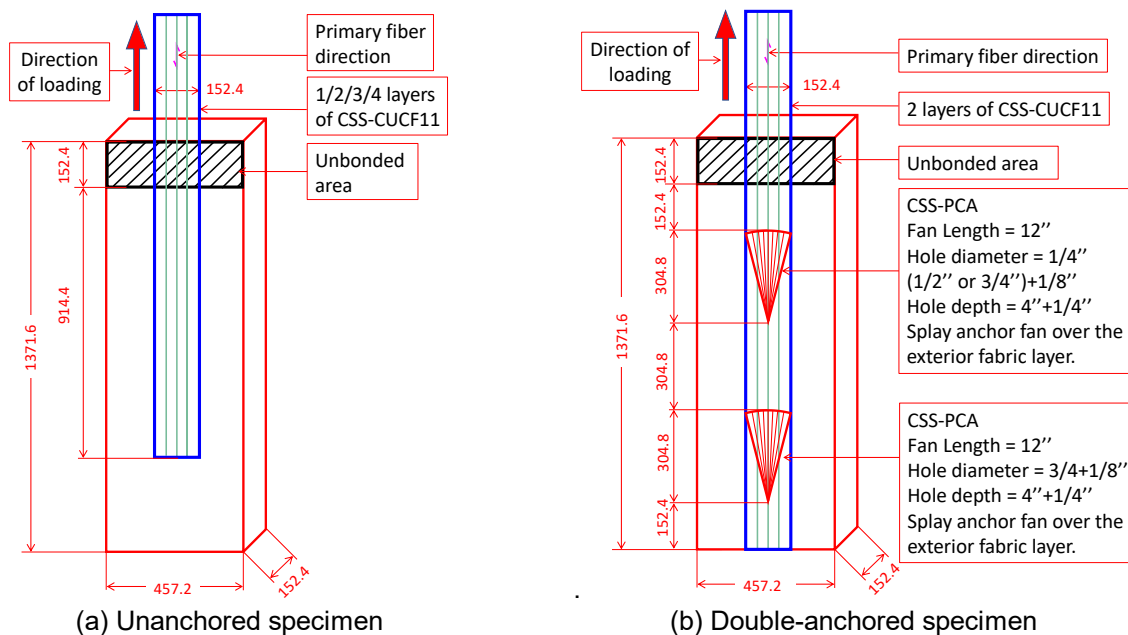


Figure 1: Typical configuration of specimens, with two block lengths of (a) 1524 mm and (b) 1372 mm

RESULTS

The experimental results are summarized below, first for unanchored ties and second for anchored ties. In the subsequent analysis, the significance of findings and their implications further discussed, examining the behaviour of the FRP-concrete interface in unanchored and anchored specimens separately.

Unanchored ties

The failure mode of all unanchored ties was the debonding of the FRP from the concrete, which is actually related to the tensile strength of the concrete as the resin tears off a thin layer of concrete. All three tested lengths showed some post-debond deformation capacity, depending on the bonded length, the concrete properties and the stiffness of the FRP. The increase in post-debond deformation capacity when longer FRP bonded lengths were used is significant, as shown in Figure 2, but this deformation capacity also depends on stiffness. For example, the one layer thick tie showed a larger deformation capacity than the 4 layers thick ties for same bonded length. Discussion on concrete properties are below.

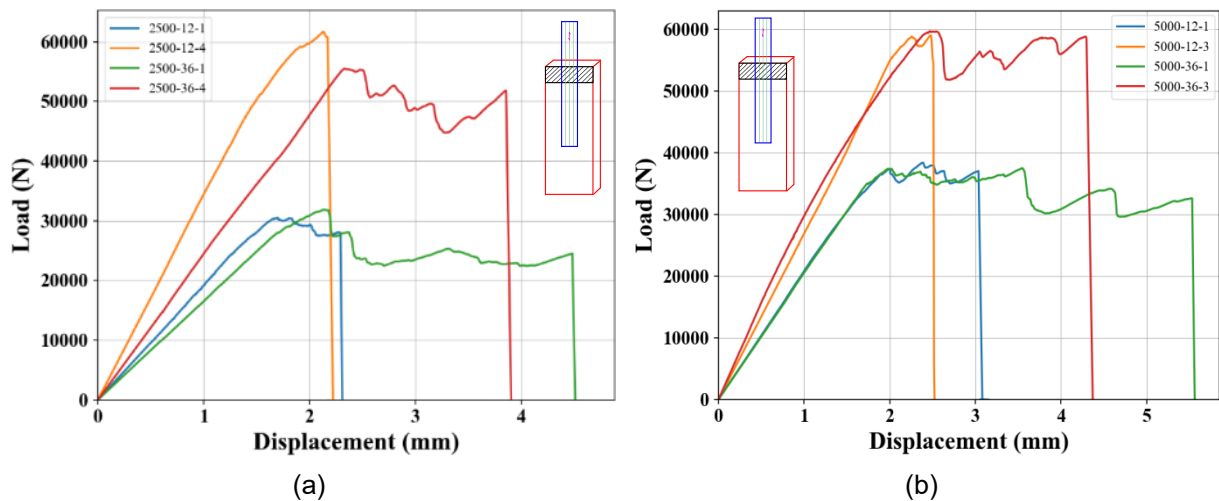


Figure 2: Unanchored tests L-D curves with concrete strength of (a) 17 MPa and (b) 34 MPa

A summary of the test results is presented in Table 1, which includes the nomenclature and calculated debond strain (N_d/E_fA).

Table 1: Summary of results of unanchored test.

Specimen*	ϵ_d (%)	Specimen*	ϵ_d (%)	Specimen*	ϵ_d (%)	Specimen*	ϵ_d (%)	Specimen*	ϵ_d (%)
2500-12-1	0.41	2500-36-1	0.43	3000-12-4	0.22	3000-36-4	0.20	5000-24-4	0.21
2500-12-3	0.26	2500-36-2	0.29	3000-24-1	0.4	5000-12-1	0.51	5000-36-1	0.50
2500-12-4	0.21	2500-36-3	0.20	3000-24-2	0.28	5000-12-2	0.34	5000-36-2	0.31
2500-24-1	0.35	2500-36-4	0.19	3000-24-3	0.24	5000-12-3	0.26	5000-36-3	0.27

2500-24-2	0.32	3000-12-1	0.51	3000-24-4	0.21	5000-24-1	0.49	5000-36-4	0.22
2500-24-3	0.18	3000-12-2	0.27	3000-36-2	0.33	5000-24-2	0.35		
2500-24-4	0.19	3000-12-3	0.26	3000-36-3	0.25	5000-24-3	0.28		

*Labelled specimens indicate concrete compressive strength, bonded length, and number of FRP layers. For example, "3000-12-4" represents 3000 psi (21 MPa) strength, 12-inch (305 mm) length, and 4 layers (2 mm) of FRP.

Figure 3(a), (b) and (c) illustrates the behaviour of unanchored specimens, highlighting the relationship between debond strain, stiffness ($t_f n_f E_f$), bonded length of FRP ties and concrete compressive strength. Thicker FRP ties decrease the debond strain (Figure 3a) but result in a larger debond load as the ties have a larger cross-sectional area. Longer FRP bonded length has a negligible impact on bond capacity for ties at least 300 mm long (Figure 3b), but longer lengths significantly increase the post-debond deformation capacity, as discussed above. Concrete compressive strength shows no substantial influence on the system capacity (Figure 3c). Through the analysis of the results, we found that the relative stiffness of the FRP tie with respect to the stiffness of the concrete has a significant influence on debond strain. Thus, the k_f/E_c (where k_f is the FRP stiffness and E_c is the concrete elastic modulus) was created, which follows a non-linear power relationship. Figure 3d provides valuable insights on the FRP-concrete interface behaviour and will inform future design guidance development.

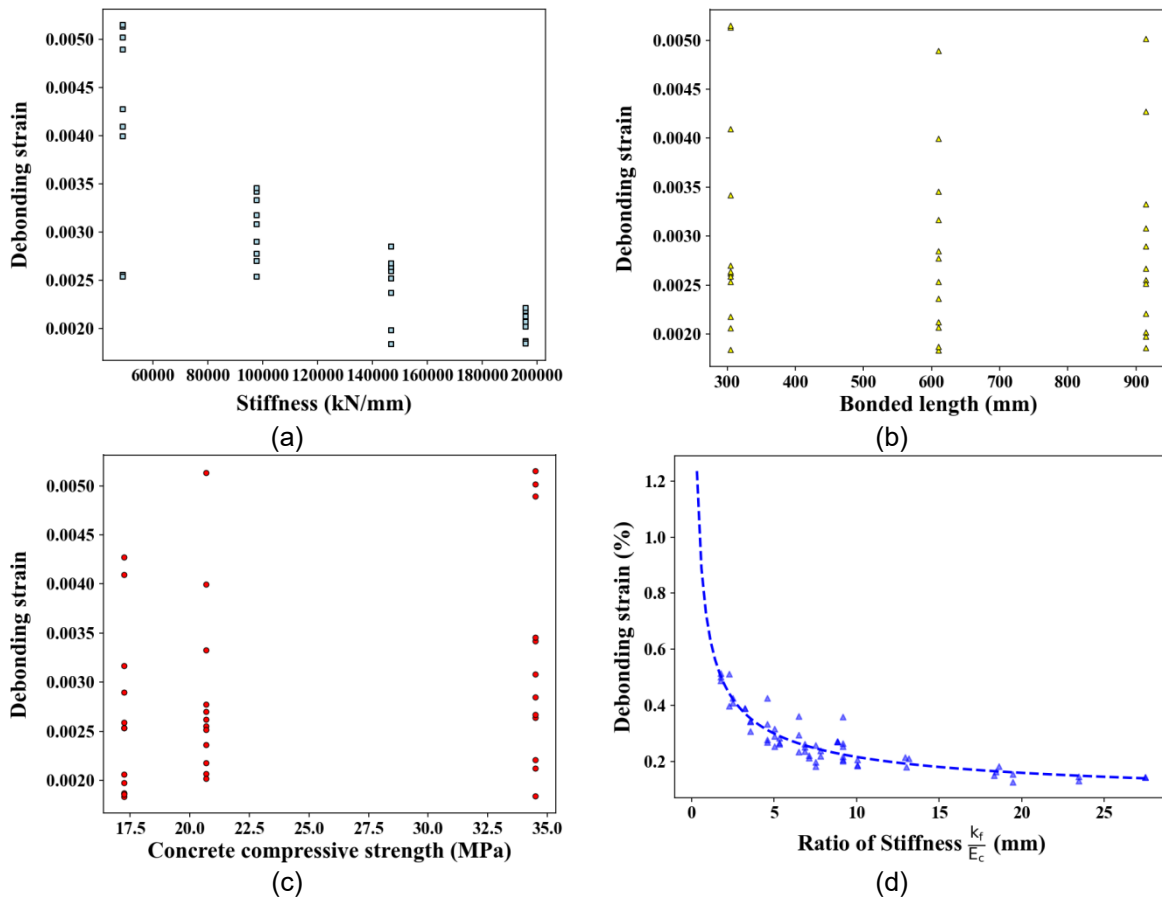


Figure 3: Relationship of debond strain with (a) FRP stiffness, (b) FRP bonded length, (c) concrete compressive strength and (d) ratio of FRP stiffness and concrete modulus of elasticity

Anchored ties

Table 2 provides a summary of the anchored test results, including nomenclature, calculated debond strain, and failure modes. The key observations are that longer fans do not affect the failure capacity, that anchor size and anchor capacity are not linearly related (del Rey Castillo 2019b; del Rey Castillo 2019c), and that installation quality has a huge effect on performance (del Rey Castillo 2021), as some of the specimens failed prematurely due to installation errors.

Table 2: Summary of results of anchored test.

Specimen*	N_d (kN)	Failure Mode ²	Specimen*	N_d (kN)	Failure Mode ²
2500-1-0-8-0.5	62.7	FD	5000-1-0-8-0.5	58.5	FR
2500-1-0-16-0.5	64.2	AR	5000-1-0-16-0.5	75.7	FR
2500-2-12-12-0.5	131.4	FR	5000-2-12-12-0.5	128.7	FR
2500-2-24-12--0.5	130.0	AR	5000-2-24-12--0.5	131.3	FR
2500-1-0-8-0.75	71.0	FD	5000-1-0-8-0.75	66.2	FR
2500-1-0-16-0.75	65.0	FD	5000-1-0-16-0.75	66.8	FD
2500-2-12-12-0.75	97.5	FR	5000-2-12-12-0.75	135.2	FR
2500-2-24-12--0.75	125.7	FR	5000-2-24-12-0.75	149.6	FR
2500-1-0-8-1	76.7	FR	5000-1-0-8-1	76.9	FR
2500-1-0-16-1	57.0	FR	5000-1-0-16-1	80.1	FR
2500-2-12-12-1	127.6	FR	5000-2-12-12-1	141.5	FR
2500-2-24-12-1	129.6	FR	5000-2-24-12--1	107.2	F

¹Labelled specimens indicate concrete compressive strength, number of fibre anchors, spacing between anchors, length of anchor fan and diameter of dowel. For example, "2500-2-12-12-1" represents 2500 psi (17.24 MPa) strength, 2 anchors, 12-inch (304.8 mm) spacing, and 12-inch (304.8 mm) fan length and 1-inch (25.4 mm) diameter of anchor dowel.

²FD means anchor fan debonding failure mode, FR means fabric rupture, AR means anchor rupture, F Failure mode including setup failure, installation failure, and premature failure, with less convincing results compared to other modes.

The analysis of the anchored specimens examined key parameters governing the behavior of fibre anchors. Figure 4(a) and (b) illustrate crucial aspects, such as the size of the fibre anchor and anchor spacing. The findings support the hypothesis that larger diameter of dowels and increased anchor spacing greatly enhance system and deformation capacity, but not in a linear manner. In other words, the 1-inch (25.4 mm) anchor does not have twice the capacity of the half inch anchor (Figure 4a). Further and more detailed analysis is required, but the results so far seem to indicate that the two anchors shared the load and transferred it to the concrete, regardless of whether they were 12 or 24 inches (304.8 mm or 609.6 mm) apart (Figure 4b). This is an important observation, as sometimes there is no space in the structure for installing a single anchor, and the anchoring load can be shared over a longer area.

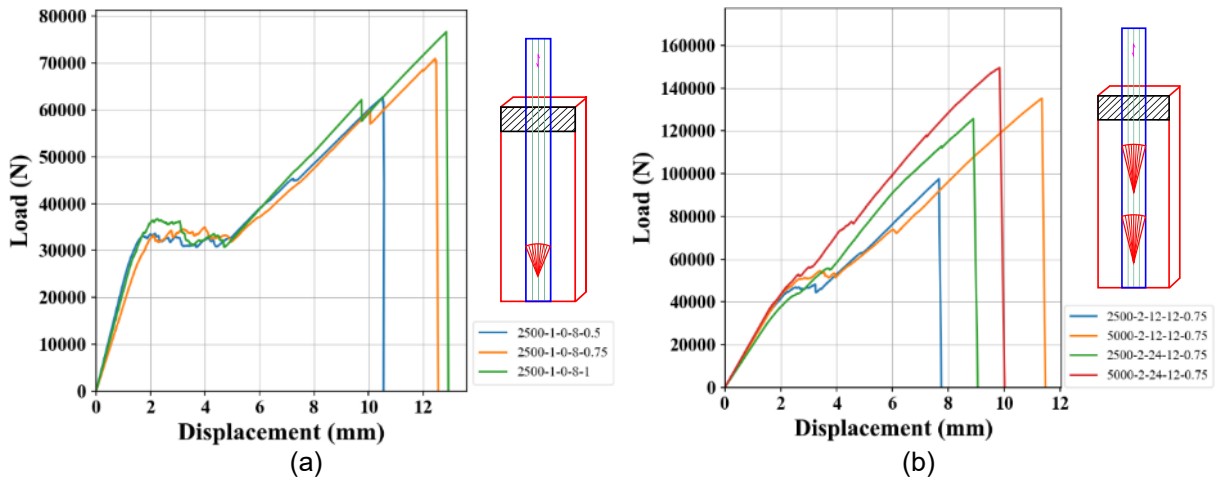


Figure 4: Relationship of debond load with (a) diameter of dowel and (b) spacing of anchors

CONCLUSIONS

This study aims to address the issue of premature debonding in EB-FRP systems used for seismic retrofitting. Single lap shear tests were conducted to explore the incorporation of different configurations of FRP ties (thicker and longer) with and without FRP anchors, as well as under varying concrete strengths. The objectives were to enhance load transfer continuity, improve post-debond deformation capacity, and evaluate anchor detailing effectiveness, with the final objective being to develop a future design guidance. The key observations are listed below:

- Unanchored specimens exhibited debonding failure, while anchored specimens experienced diverse failure modes: fan debonding, fabric fracture, and anchor rupture.
- Debond strain is correlated with FRP stiffness-to-concrete stiffness ratio, revealing a non-linear power relationship with potential future design implications.
- The debond strain in unanchored specimens was primarily influenced by the stiffness and length of the FRP. Thicker ties improved anchorage capacity, and longer ties exhibited greater post-debond deformation capacity, which depends on both the bonded length and the stiffness (thickness) of the tie.
- Larger anchors and increased spacing improved system capacity and enabled load sharing between two anchors up to a spacing of 24 inches (609.6 mm).

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