
Novel FRP-steel composite anchoring plate for seismic strengthening of concrete diaphragms

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ABSTRACT

The evolving understanding of seismic demands on reinforced concrete buildings has driven widespread assessment and strengthening of existing structures, particularly in the U.S. West Coast and New Zealand. Diaphragm upgrades are often required, as these elements transfer lateral forces and ensure structural integrity. Fibre reinforced polymers (FRP) are preferred for diaphragm strengthening due to their versatility and minimal disruption, though traditional FRP anchorage systems—especially FRP anchors—present challenges such as an inability to inspect them, the craftsmanship needed to install them, the required embedment depths, drilling damage due to the required hole sizes, bulkiness (leading to aesthetic concerns), and corrosion issues with metallic components. To address these limitations, a new FRP–steel composite anchorage plate was developed, improving load transfer, preventing corrosion, and enabling more efficient diaphragm retrofitting. The anchorage plates are also easily inspected, have reduced required embedment depths/hole sizes, have a straightforward and consistent installation process and have improved aesthetics. Five tests were conducted on tension/compression cycles of large-scale concrete slabs, with one slab having no FRP, one slab having FRP but no anchorage, and three slabs featuring different anchorage details. The force–displacement results show distinct behavioural stages in the FRP strengthened slabs: elastic response, cracking, and post debonding behaviour. Initially, the slabs exhibited narrow hysteretic loops, high stiffness, and no residual deformation. After cracking began, all FRP strengthened slabs developed multiple fine cracks, causing loop widening, stiffness reduction, and increased residual displacement as both steel and bonded FRP stretched across cracks. The post debonding stage varied significantly with anchorage type. The slab without anchorage failed in a very brittle manner after peak load, while all slabs with plates reached higher debonding capacities due to improved anchorage, which highlights the critical importance of using

anchorage in seismic environments. Each plate slab partially debonded at the main crack before prying out a concrete cone. Plate 1, with long screws, showed the greatest deformation but lowest strength due to screw elongation. Plate 2 achieved higher strength but lower deformation. Plate 3, with staggered screws and added glass fabric, reached slightly higher load but suffered the lowest deformation capacity due to its stiffer anchorage zone.

1 INTRODUCTION

Changes in seismic demands and/or understanding of RC structures have triggered a wave of seismic assessment and strengthening of existing building stock in many places in the world, specially US west coast and NZ (GNS 2022, ASCE/SEI 41 2023). This effort to improve the seismic resilience of building and cities often results in required seismic strengthening of existing diaphragms, as they act as important horizontal elements of the seismic force-resisting system that transmit lateral force from the floor system to the vertical elements and tie these vertical elements together (Moehle et al 2010, Salimian et al 2024, Yu and del Rey Castillo 2024).

FRP is typically preferred for diaphragm strengthening due to its versatility, ease of construction, and minimum invasiveness, which means it is a more cost-effective solution to traditional methods like steel plates or rebars in grooves, which are often not even feasible (del Rey Castillo et al 2022, Rogers et al 2024, Ormeno et al 2019). One of the key aspects of FRP for diaphragm strengthening is the anchorage, with FRP anchors being usually the default option (Kalfat et al 2013, del Rey Castillo et al 2019). FRP anchors are often not ideal, especially with large loads being involved, as they require extensive drilling or large holes, potentially damaging the structure and/or the internal steel, and are bulky on the floor, often requiring rebating and/or flooring compounds – all of which adds cost. Metallic anchors are easily corroded by carbon dielectric corrosion effect, as they are generally installed on FRP tie by metal fastened steel anchor fixed over the plate end (Wu and Huang 2008), and the stress difference when the force transferring from FRP composites to steel plate often results in premature failure of the FRP.

Due to these shortcomings, an FRP-steel composite plate was developed as a novel anchorage system to improve the seismic performance of concrete diaphragms retrofitted with FRP composites. This FRP-steel composite plate uses two layers of plates, an upper steel plate and a bottom FRP plate, to prevent the carbon dielectric corrosion and smooth the force transition from FRP to steel. Then, screw anchors are installed through the FRP composites into concrete diaphragm directly to improve the bonding effect.

2 EXPERIMENTAL PROGRAMME

2.1 Specimens and loading protocol

Five slabs were designed to replicate existing in situ concrete floors, as shown in Figure 1. Each slab has dimensions of 6000 mm × 1300 mm × 100 mm (length × width × height), with longitudinal reinforcement of 5 D10 and transverse reinforcement of D10@300. Additional longitudinal reinforcement of 10 HD16 and transverse reinforcement of HD16@125 were added to reinforce its two ends for loading purpose. The specified concrete strength of the slab is 21 MPa and the nominal yield strength of D10 and HD16 reinforcement is 300 MPa and 500 MPa, respectively. The FRP ties and FRP-steel composite plates were installed on the top of the slab in various configurations as discussed below.

The slab was secured to the strong floor by a foundation beam using 8 post-tensioned rods, and its loading end was subjected to a static cyclic loading by a horizontal actuator, as shown in Figure 1. The loading protocol was displacement-controlled, using force level as limits from the onset of elastic behaviour, and then turning to displacement level limits. The force control parameter in tension was the FRP debond strain

and the force level limit was set at 1/3, 2/3, 1.0, and 1.4 times the FRP debond strain, while after this point the displacement level limit was increased at 1.4 times intervals. In compression, all the force level was kept constant at 1/3 times the compression strength of the slab. Each force level was repeated for 2 cycles in both positive and negative direction

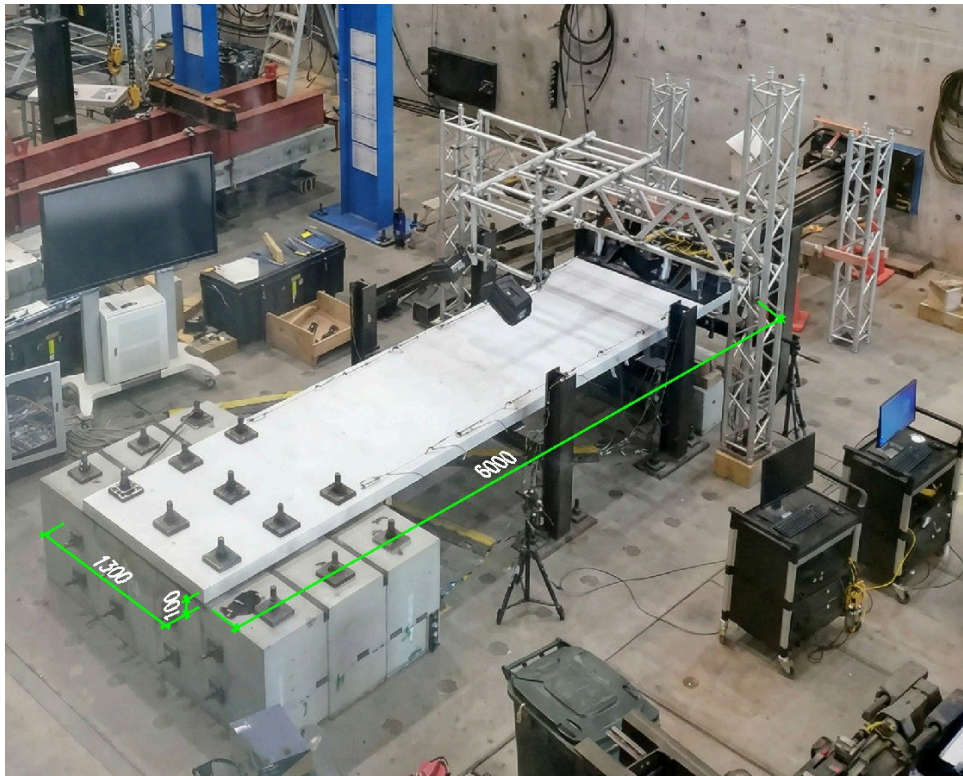


Figure 1 Test setup

2.2 Test matrix

FRP debonding is the primary failure of FRP-strengthened structures, governed by FRP debond strain and highly related to the FRP stiffness and concrete elastic modulus (Zhang et al 2024). This FRP debond strain is much lower than its rupture strain, resulting in a low level of FRP efficiency, and anchorages may be used to improve this efficiency and increase the strength, ductility and/or deformability of members. FRP-steel composite plates were used in three different configurations and to investigate their effect on the seismic performance of concrete slab retrofitted with FRP, particularly the post-elastic debonding deformation.

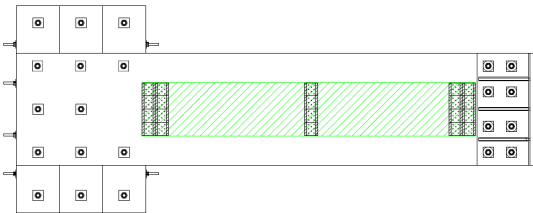
The FRP-steel composite plates consist of a 100x150mm steel plate with 8 staggered perforations that is bonded to an FRP plate 150x150 mm in dimensions, with the FRP protruding 25mm in each direction of the fiber. The plates are installed on the FRP fabric while the resin is still wet, and the 6 out of the 8 holes are used to install concrete screw anchors, as shown in Figure 2.

The anchorage failure mode is the critical factor for the post-elastic debonding deformation of the slab, with the failure mode being primarily governed by the length of the screw anchor (as the diameter is fixed at 6 mm), anchor grouping effects and concrete strength. Hence, screw anchor length of 60 mm and 80mm, and FRP-steel composite plates of double line pattern and staggered pattern were considered. The staggered pattern of FRP-steel composite plates was designed with an additional layer of bidirectional glass fabric to spread the load to a larger area (shown with a faint dash red line in Figure 2d), increasing the effective concrete cone, thus trying to prevent concrete cone failure. Five slabs tested at the University of Auckland

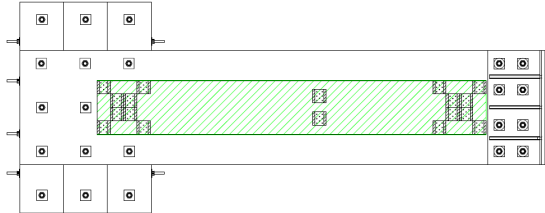
Structural Testing, are one slab without FRP tie, one slab with only FRP tie and no anchorage, and three slabs with the same FRP tie and three anchorage configurations, as summarized in Table 1.

Table 1: Slab test matrix

SLAB NO.	END PLATE		INTERMEDIATE PLATE		SCREW ANCHOR		
	PATTERN	NUMBER	PATTERN	NUMBER	ANCHOR TYPE	ANCHOR DIAMETER (MM)	ANCHOR LENGTH (MM)
NO FRP	-	-	-	-	-	-	-
FRP ONLY	-	-	-	-	-	-	-
PLATE 1	DOUBLE LINE	8	SINGLE LINE	4	WURTH W-BS/S 6X80	6	80
PLATE 2	DOUBLE LINE	8	SINGLE LINE	4	HILTI HUS3-C 6X60	6	60
PLATE 3	STAGGERED	8	SINGLE LINE	2	HILTI HUS3-C 6X60	6	60



(a) FRP-steel composite plates detail 1 and 2



(b) FRP-steel composite plates detail 3

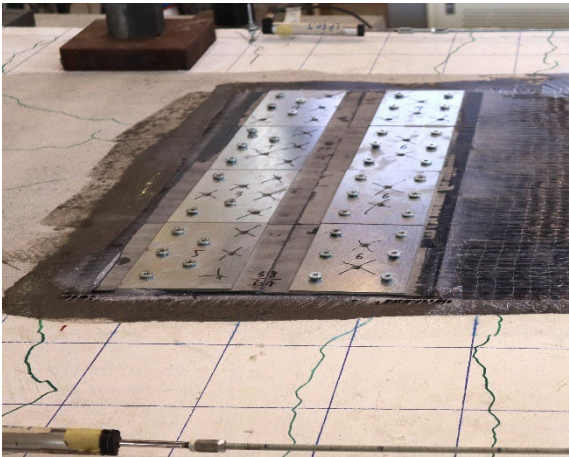


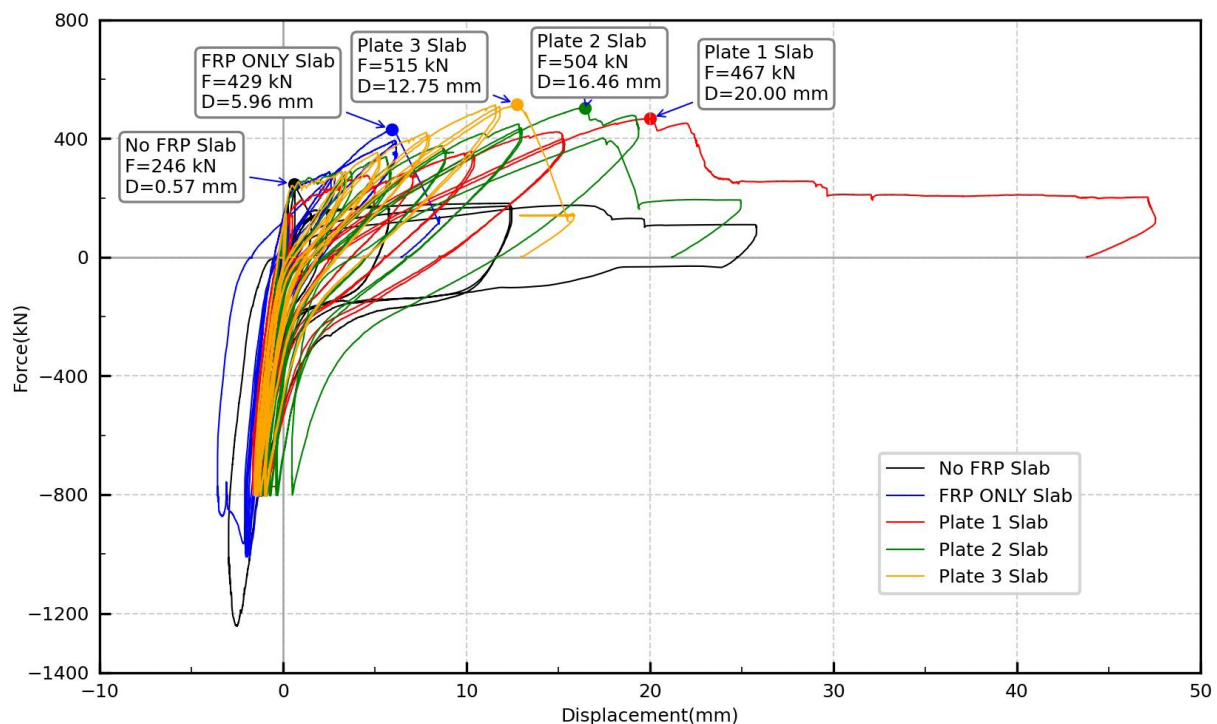
Figure 2 Details of FRP-steel composite plates in the slabs

3 EXPERIMENTAL RESULTS

3.1 Hysteretic behaviour

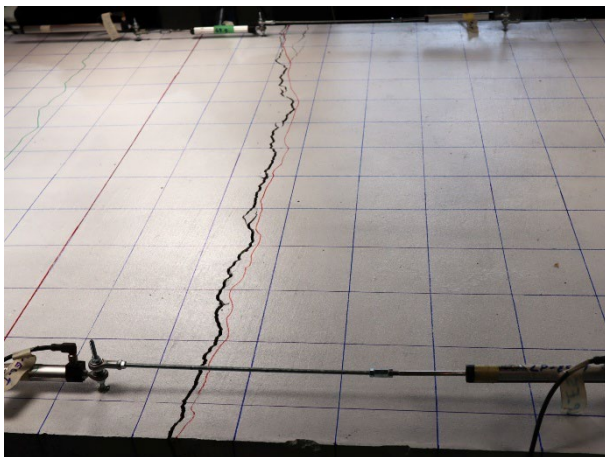
The force-displacement curves and corresponding peak points are plotted in Figure 3. The tension load is regarded as the positive direction and compression load is negative direction. The ultimate displacements between slabs are not the same, as they were loaded by the actuator until only the internal reinforcement steel was acting following composite plate failure, and the plates failed at different deformation levels. The FRP strengthened slabs featured three different behaviour stages, being (1) elastic behaviour, (2) cracking, and (3) post debond behaviour, with no distinct phenomenon being observed in their compression loading.

The elastic behaviour stage of force-displacement response spanned from the beginning of loading to the onset of slab cracking. This stage was marked by narrow hysteretic loop with high initial stiffness, no significant degradation observed at the second cycle, and no residual displacement recorded. The next stage, where the slabs experienced cracking but the FRP remained bonded, spanned from the start of the slab cracking to the start of the FRP-to-concrete debonding. The no FRP slab experienced a single crack at the drop of longitudinal reinforcement ratio at the loading end (Figure 4a), but all the other slabs exhibited multiple, thin cracks, spaced at 100 to 150 mm. The loop broadened while the stiffness reduced and the residual displacement increased, reflecting the progressive widening the cracks and the elongation of internal steel and bonded FRP, which spanned both lips of the cracks. The last stage, post debond behaviour, spanned from the initiation of FRP-to-concrete debonding to the end of the loading. This stage differed between the slabs depending on the anchoring detail, so further details are given below, but generally speaking the loops were broader, the peak strength was reached, and the as-built response was resumed for all slabs.

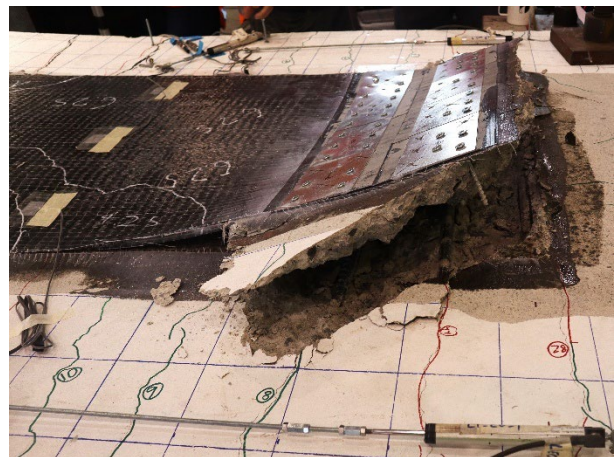


3.2 Post debond behaviour

The post-debonding behaviour was entirely dependent on the anchorage details. The slab with no anchorage exhibited a very brittle and sudden loss of capacity once it reached the peak load, after which point the as-built behaviour was resumed. This behaviour highlights the critical need to use anchors in seismic applications, as the debonding could happen at levels well below design due to uncertainties related to seismic loads, three-dimensional deformations often ignored in design, improper installation and/or deterioration of the installation over time. The debonding capacity of all plate slabs was higher than that of the no anchorage slab because the presence of anchorage in the vicinity of the debonding line increases the debonding capacity (CNR 2025, Flores et al 2020, Llauro et al 2017, Zhang et al 2026). The three slabs featured the same amount of FRP and very similar screws, but using more FRP and/or stronger screws would significantly increase this debonding capacity. All plate slabs featured a similar response, where the FRP partially debonded at the main crack location, where the longitudinal reinforcing steel ratio drops, and the plates were engaged before prying out a concrete cone. These debonded areas were marked with white marker and can be seen in Figure 4. Plate 1 slab with 80 mm long screws exhibited the largest deformation capacity but smallest force capacity. The reason is that the longer screws started deforming, allowing for a larger debonded area as can be seen by the white lines in Figure 4b, before finally engaging the full concrete cone and prying it out. Plate 2 slab with 60 mm screws resulted in a noticeably larger capacity than plate 1 slab (504 kN compared to 467 kN or 8% higher) but at the expense of a smaller deformation capacity (20mm compared to 16.46mm or 22% lower). The smaller white area but larger concrete cone in Figure 4c compared to Figure 4b qualitatively demonstrates these quantitative data. It is important to note that the post-peak deformation capacity of both samples was comparable. Plate 3 slab, which featured the staggered pattern and the additional bidirectional glass fabric, resulted in a slightly larger load but a significantly compromised deformation capacity (only 12.75 mm compared to 20 mm in Plate 1 slab). Figure 4d shows that the debonded area marked with white lines is almost nonexistent, and that the whole anchorage area remained in one stiff piece before prying out the concrete.



(a) NO FRP slab



(b) Plate 1 slab



(c) Plate 2 slab



(d) Plate 3 slab

Figure 4 Failure modes of slabs

4 CONCLUSIONS

This brief summary demonstrates the feasibility of a composite FRP-steel anchorage plate for seismic strengthening of concrete diaphragms using large-scale experimental testing. Five slabs were tested, including one with no FRP, one with no anchorage, and three different anchorage configurations. The results show that the force remains relatively similar regardless of the anchorage configuration due to the limited range of FRP and screws used in this preliminary study, but the deformation capacity is highly dependent on this detailing design and associated failure modes. The no FRP and no anchorage slabs had much lower force and deformation capacity, highlighting the critical need to anchor the FRP strips at relatively frequent intervals, especially in seismic environments which are highly uncertain. Further research will be completed by the team to provide more insight and design provisions, and to increase the capacity provided by both the FRP and the anchorage systems. These preliminary tests validated the use of the anchorage plates as an improved alternative to FRP anchors. The installation proved to be faster, more predictable and easy to inspect at any stage of the project.

5 ACKNOWLEDGEMENT

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