SESOC CONFERENCE 2023
CELEBRATING STRUCTURAL ENGINEERING
21-23 JUNE 2023 • TE PAE, CHRISTCHURCH
CONFER.NZ/SESOC2023

Design advice for FRP ties on diaphragms

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ABSTRACT

Concrete floor diaphragms of existing buildings are often inadequate to resist tension forces developed as the diaphragm spans between the lateral load resisting elements. A common strengthening method to provide additional tension capacity is through Fibre Reinforced Polymer (FRP) ties. However existing research is not applicable because it was conducted on thin and short FRP ties which are dissimilar to those typically required for diaphragm strengthening applications. This paper summarises the progress to date on an extensive research programme, including experimental testing on thick and long FRP ties, and a summary of the upcoming work. More importantly, specific FRP detailing advice is provided which is intended to prevent inadequate designs that may result in undesirable premature failure modes occurring during an earthquake. This advice is: a) **to use an FRP design strain significantly lower than the fracture strain of the FRP** and compatible with the deformation tolerance of the floor system, b) **to provide robustness and redundancy in the FRP detailing** to protect the building against unpredictable performance through FRP anchor detailing, and c) **to consider the expected ductility of the global structure**, specifically any damage that may be induced in the slab due to deformation incompatibilities and the corresponding impact on any FRP ties. This project is still underway, so this paper is not to be taken as specific design guideline – more content will be published in the coming months.

Introduction

The 2016 Kaikōura earthquake highlighted the seismic vulnerability of concrete floors in existing buildings, especially precast floors (Henry et al 2017). Based on the post-earthquake observations, one of the key aspects of the seismic vulnerability of existing precast floors was their performance as a diaphragm. Many factors influence this vulnerability, but arguably they could be summarised in two broad categories:

1) insufficient tension capacity to develop the strut and tie mechanisms that give the floor the diaphragm action needed to transfer forces between the lateral resisting elements, and,

2) deformation incompatibilities between often very flexible and ductile lateral systems (frames with ductility of 4 or 6) and extremely stiff and rigid precast floors (Puranam et al 2021).

Additional issues include the use of brittle mesh as reinforcement (typically 665 cold drawn mesh), inadequate (and often nonexistent) connections between the floor and the lateral system in the form of starter bars, changes to the structure over time including cracking caused by shrinkage, service loadings or settlement affecting integrity of non-ductile reinforcement, corrosion, degradation and myriad other minor issues. The two critical factors, insufficient tension capacity and deformation incompatibilities, are treated separately and in parallel in the seismic assessment guidelines (NZSEE et al 2017, 2018), but in reality, they interact significantly and are part of the same problem.

Multiple solutions exist for seismic strengthening of concrete floors. Extensive recent research has investigated how steel angles can be designed to prevent the collapse of precast units due to deformation incompatibilities, effectively extending the seating length (Bueker et al 2021, 2022). This aspect of seismic strengthening is critical to preventing collapse and therefore enabling the floor to function as a diaphragm, but is treated separately to the strengthening of the floor to resist diaphragm actions (i.e. strut and tie model), so no discussion on this topic is included in this paper.

Strengthening options to enhance the tension capacity of floor slabs to resist diaphragm actions include: steel bars embedded in grooves, steel plates bonded and/or bolted to the floor, post-tensioning of the floor and the use of FRP. FRP is a composite material, typically consisting of carbon fibres that are soaked into epoxy resin on site and then bonded to the concrete surface. The use of FRP has gained more and more attention, both in New Zealand and worldwide, due to its low weight and ease of retrofit installation, which typically results in reduced disruption for owners and tenants and lower costs when compared to other strengthening methods, as it’s also less obtrusive. However, there is no established design guidance that is directly relevant to seismic strengthening of floors with FRP, despite the extensive use of this material for this purpose both in New Zealand and around the World. Arguably, there is also very limited guidance on how to use steel rebars or plates for this purpose, but because FRP is a fundamentally different and relatively new material (compared to structural steel and reinforced concrete), the likelihood of inadequate designs that may lead to undesired outcomes during an earthquake is more significant.

A very extensive research programme, led by the University of Auckland and in collaboration with industry both in New Zealand and US, is being undertaken to directly investigate the use of FRP for diaphragm strengthening and, eventually, develop a design guideline. This paper aims to: a) provide insight into FRP and its behaviour as a material for providing tension capacity to floors, b) summarise the research undertaken to date, and c) briefly detail the future research. **This paper is not to be taken as design recommendations**, more work is being performed and future test results can potentially affect the final design procedure.

FRP behaviour as tension ties in diaphragms

Strut and tie and/or grillage modelling is typically used to obtain the tension demands on the floor diaphragm which results in an orthogonal grid of tension demands. FRP tension ties are detailed along these grids to satisfy the demands as shown in Figure 1 (del Rey Castillo et al 2019a). FRP is an anisotropic (strong in only one direction) material which is linear elastic until failure. As such, the force is directly proportional to the strain in the FRP and when the ultimate tensile strain in the FRP is reached it fails in rupture in a brittle manner which is generally undesirable in a seismic system. However, the design tension forces are achieved in the FRP at strains significantly lower than the ultimate tensile strain, and appropriate detailing of the FRP ties can allow for post-elastic behaviour to occur in the diaphragm slab while redistributing and limiting the strain in the FRP and thus preventing the FRP from approaching its ultimate tensile strain. As such, appropriately detailed FRP ties can provide a diaphragm strengthening system that has post-elastic deformation capacity. This is achieved by detailing the ties to allow debonding to occur when design strains are exceeded locally (i.e. where cracking occurs), and transferring the tension tie forces through effective mechanical anchorage of the FRP. This hypothesis was experimentally confirmed recently, and further discussion is below

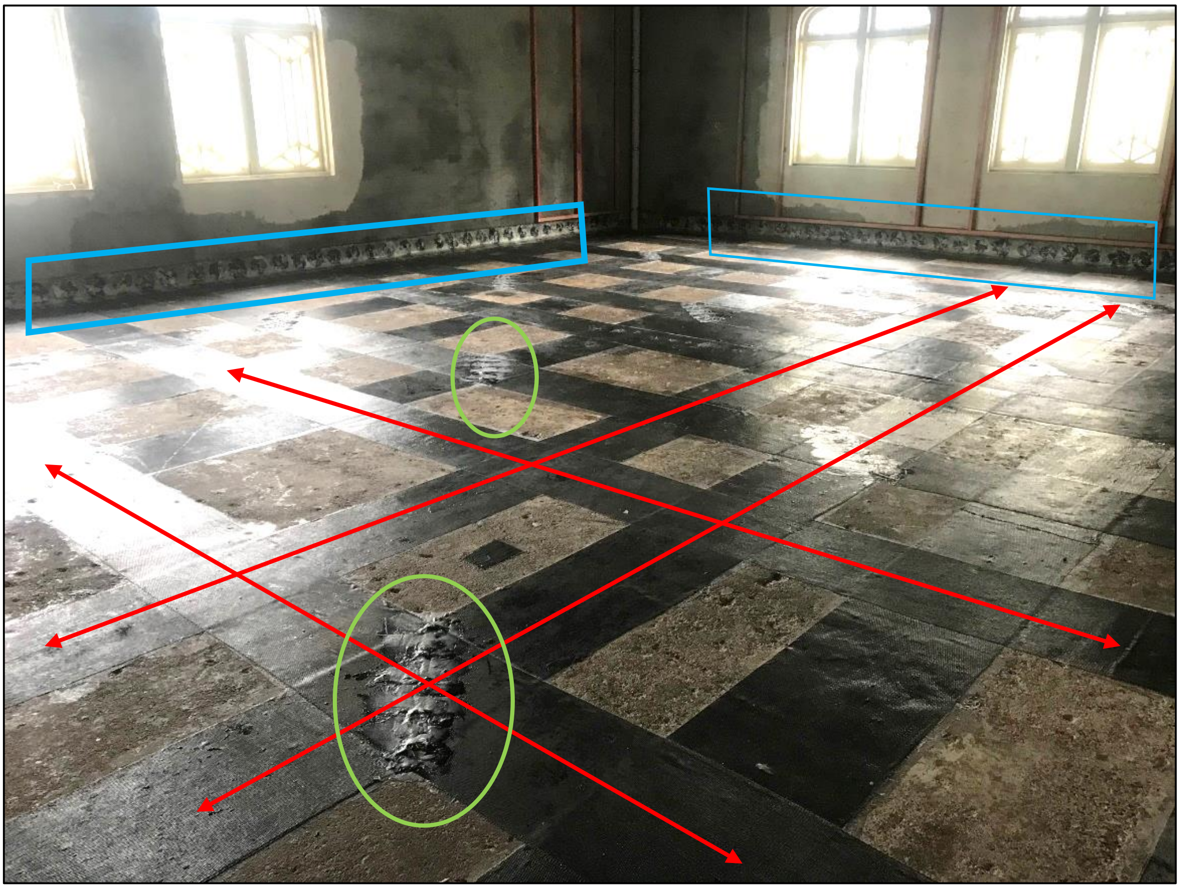


Figure 1 Typical FRP layout, with an orthogonal grid (red) and anchors in both the perimeter (blue) and within the floor (green)

A definition of ductility is controlled damage that dissipates the energy introduced into a system while maintaining an effective load path. An example of this is the yielding of steel reinforcement in Reinforced Concrete (RC). In an RC system the failure mode of concrete in compression is brittle, but RC as a system is ductile because the failure is controlled by yielding of the steel reinforcement which prevents compression failure of the concrete. A similar logic can be applied to FRP ties on diaphragms, where the brittle FRP ties can be detailed in such a way that protects against FRP tensile failure and results in a diaphragm system that can tolerate inelastic deformations while dissipating energy and maintaining the load paths required to provide diaphragm action. This approach results in a diaphragm structural system with post-elastic deformation capacity, or simply, ductility.

When debonding of an FRP tie initiates at a crack or a high strain location, adjacent areas of bonded FRP and strategically located FRP anchors maintain the load path required to enable diaphragm action. Progressive debonding of the FRP occurs, starting at the first unbonded crack and working towards the ends of the tie, dissipating energy and maintaining the load path. For example, in floors where a crack appears and is widening during an earthquake and the FRP tie is spanning the crack, each side of the tie will start debonding progressively away from the crack while maintaining force across the crack to resist further opening. As further deformation is introduced into the system the bonded lines progress away from the crack and the debonded length of FRP increases to maintain the FRP strain at the debonding strain but without increasing load-carrying capacity. This behaviour has been observed in recent testing, as further discussed below. The first obstacle is how to accurately calculate the debond strain for diaphragm ties, because all existing research has been carried out on thin and/or short ties while typical ties required for diaphragm strengthening are much thicker and longer. Recent research indicates that the existing design models for thin ties are unconservative when calculating the strain of thick ties, as shown in Figure 2 (del Rey Castillo et al 2022). Additionally, the existing models are based on test data generated from tests on very short ties which were dominated by end peeling effects, which is a comparatively brittle failure mode, and they did not capture the progressive debonding behaviour and post-debond deformation capacity. Thus, testing of long and thick ties is the first objective of this research, to confirm the progressive debonding behaviour of long ties and to allow the debond strain to be calculated. Thus, **existing models to calculate bond strain are unconservative and the fracture strain approach to calculate FRP debonding strain should not be used for design of FRP diaphragm ties**. The fracture strain approach is used by many FRP design guidelines to calculate FRP debonding strain.

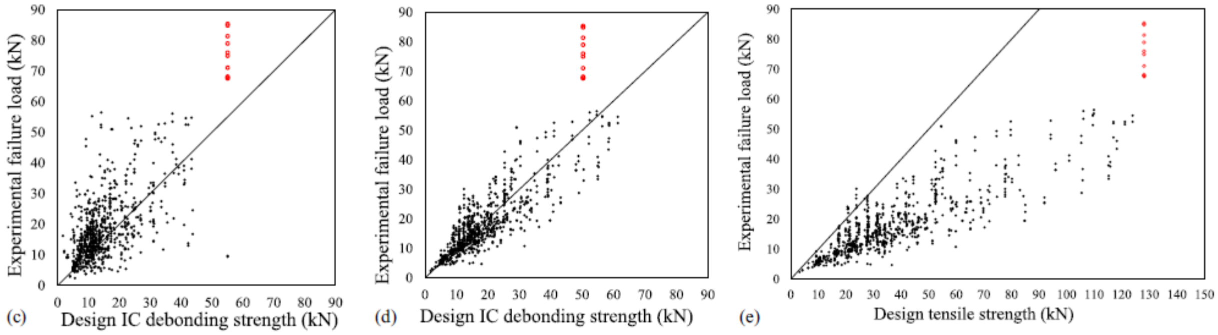
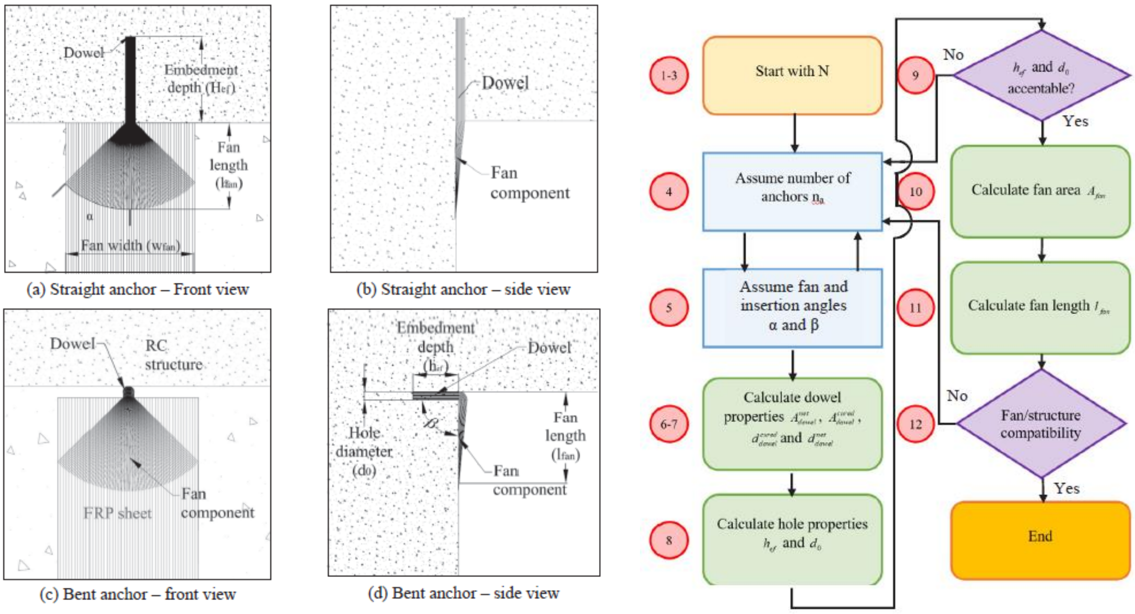


Figure 2 Comparison of experimental results and guide-prescribed equations on long ties for (c) fib bulleting 90 design, (d) CNR-DT 200 design, and (e) ACI 440.2R design, extracted from (del Rey Castillo et al 2022)

Earthquakes are unpredictable by nature, with seismic loads often being significantly higher than what the seismic hazard models predicted. Accurate prediction of crack patterns and the corresponding length of the FRP tie available for progressive debonding is typically unrealistic. Additionally, previous testing on RC columns (del Rey Castillo et al 2018) and recent diaphragm testing by our collaborators at Virginia Tech seem to indicate that debonding may initiate when the FRP is subjected to the compression cycle, rather than the tension cycle as is typically assumed in FRP design. As such, the FRP may already be debonded when it is subjected to its design tension load. For these reasons designing redundancy and robustness into the strengthening system is even more important than in typical seismic design – once an unanchored FRP tie is fully debonded from the concrete floor failure has occurred as there is no load path available for the diaphragm tension forces. **Redundancy must be provided through detailing of effective anchorage.** This is similar to detailing requirements for typical reinforced concrete or steel structures.

FRP anchors are particularly well suited to provide anchorage for FRP diaphragm ties as the design and installation processes are complimentary and a significant body of research exists to confirm their compatibility and effectiveness and to enable accurate design (del Rey Castillo et al 2021). These FRP anchors consist of bundles of fibres soaked into epoxy resin and embedded into the concrete as detailed in Figure 3. This FRP anchorage method has been extensively researched by the authors (del Rey Castillo et al 2019b, c) and the published design guideline has been successfully tested by several academic and professional teams around the world (del Rey Castillo et al 2019d).



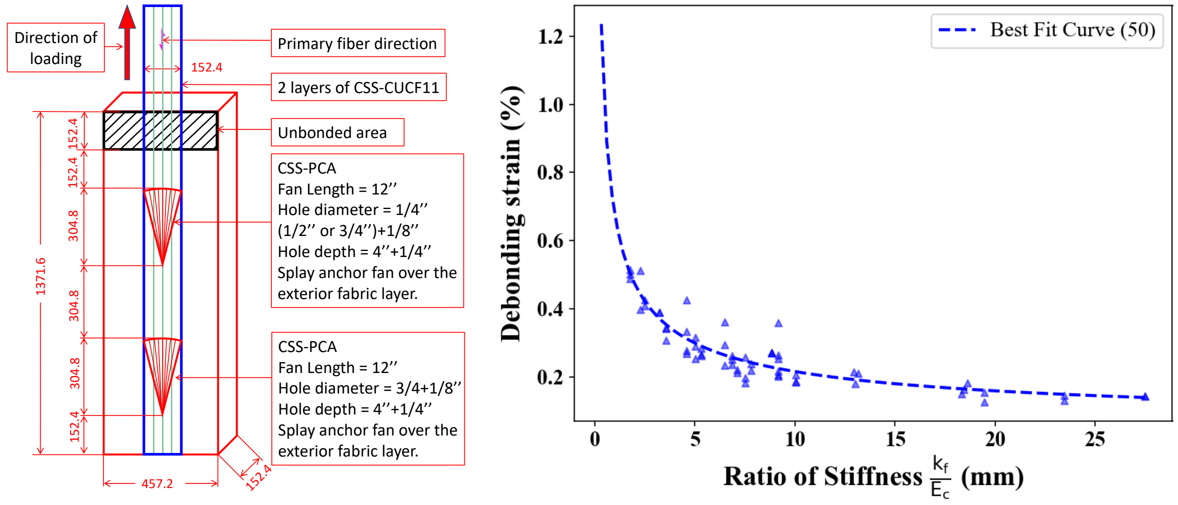
(a) Main properties of FRP anchors (b) Flowchart for FRP anchor design

Figure 3 FRP anchors properties and design flowchart, extracted from

Relatively small story drifts have been shown to result in significant slab damage in structures with precast flooring systems (Bueker et al 2022b). This slab damage could render poorly designed FRP diaphragm ties ineffective, so consideration of this issue is necessary even for structures analysed using an elastic or nominally ductile approach (i.e. where $\mu<=1.25$ for the global analysis). It is important to note that providing tension capacity through FRP ties is often part of a global strengthening strategy which includes separate interventions to increase the stiffness of the structure and reduce the drift and/or ductility requirements on structural elements, for example, installation of K braces or additional concrete shear walls. At this stage, engineers should be particularly cautious when specifying FRP diaphragm ties for use in structures designed using a ductile or limited ductile approach (i.e. $\mu >1.25$ in global analysis), and explicit consideration of expected slab crack patterns and magnitudes is likely warranted to inform the design and detailing of FRP ties for such structures. **The global effect of the FRP on the building's behaviour needs to be considered.** Further advice applicable to ductile and limited ductile structures will be developed through the course of this research.

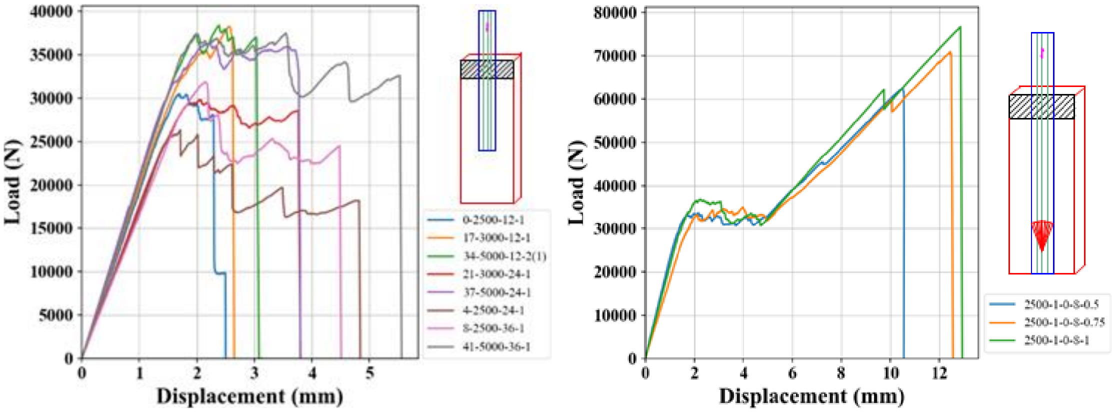
Summary of this FRP diaphragm research completed to date

A large database of experimental work on the debonding behavior of anchored and unanchored FRP tension ties has been compiled, with over 1500 individual data points from about 100 papers. However, the vast majority of these tests were on thin and short ties. Simpson Strong Tie (SST) has shared approximately 150 previous tests on more appropriately sized ties, and 42 tests on 2.8x1.3x0.1 m diaphragms. Analysis of all of these experiments is underway. A testing campaign consisting of 36 unanchored ties and 24 anchored ties was recently completed at SST's laboratory in California. These tests seem to indicate that the bond length and the concrete strength do not have a significant effect on the debond strain, and only the relationship between the FRP stiffness and the concrete stiffness plays an important role in the debond strain (Figure 4b). Additionally, the post-debond elastic deformation hypothesised in the previous section has been observed experimentally (Figure 4c) and the ability of FRP anchors to provide redundancy to the system has been confirmed (Figure 4c). More details on this recent testing are provided and discussed elsewhere (Zhang et al 2023).



(a) Typical testing setup with two anchors

(b) Relationship between debond strain and stiffness ratio



(c) Load-displacement graphs with the post-debond deformation

(d) Load-displacement graphs showing the redundancy provided by anchors

Figure 4 Observations from the first round of testing (Zhang et al 2023)

Research to come

More testing of FRP ties will be completed in the next 12 months at Simpson StrongTie's laboratory in California, until a more complete picture of FRP debonding behaviour of long and thick FRP strips is obtained. Other potential research questions to be investigated include the behaviour of FRP ties with intermediate ties including: post-anchor failure capacity, dowel pullout (especially if the dowel was to be inserted into a very thin topping), dynamic loading, cyclic loading, the behaviour of anchor groups (i.e. many smaller anchors). Testing of FRP ties on hollowcore precast units will be completed at the University of Auckland using a test setup similar to that shown in Figure 5 and using a methodology that is complimentary to previous hollowcore research campaigns (Courney et al 2021). The primary objective of the hollowcore testing is to verify that the out of plane deformation at the beam/unit interface does not compromise the FRP tie behaviour or initiate premature failure, and confirm that the tie testing performed at Simpson StrongTie is relevant to this application. Additionally, this testing will aim to investigate the deformation capacity of the hollowcore vertical support when an FRP tie is applied to assess whether the unit collapse is delayed when the crack opening is being restrained by the FRP tie. Funding for testing at Virginia Tech has been secured which will investigate the in-plane behaviour of FRP-strengthened diaphragms. Finally, extensive analysis and modelling are underway to understand the global behaviour of the whole diaphragm and the interaction with the global behaviour of the building.

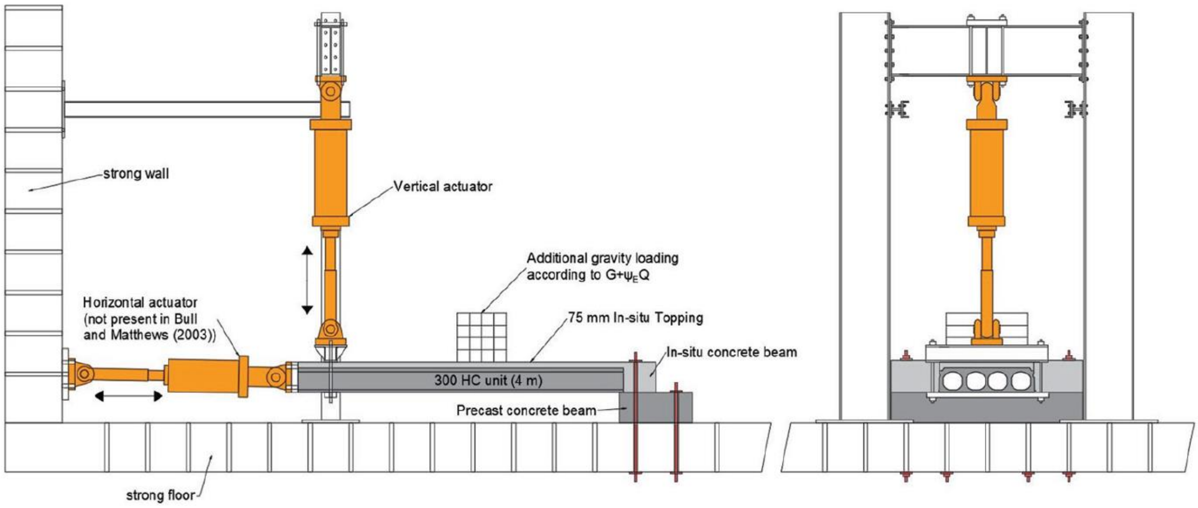


Figure 5 Testing setup from Courney et al 2021.

REFERENCES

- Bueker, F., Brooke, N.J., Elwood, K.J., Bull, D.K., Hogan, L.S. and Parr, M., 2021. Development and validation of retrofit techniques for hollow-core floors. In *The 2021 Structural Engineering Society New Zealand Conference, Hamilton, New Zealand*.
- Buker, F., Hogan, L.S., Brooke, N.J., Elwood, K.J. and Bull, D.K., 2022a. Design recommendations for seating angle retrofits. *SESOC Journal*, *35*(1), pp.55-68.
- Buker, F., Parr, M., De Francesco, G., Hogan, L.S., Bull, D.K., Elwood, K.J., Liu, A. and Sullivan, T.J., 2022b. Seismic damage observations of precast hollow-core floors from two full-scale super-assembly tests. SESOC Journal, 35(1), pp.125-147.
- Corney, S.R., Puranam, A.Y., Elwood, K.J., Henry, R.S. and Bull, D., 2021. Seismic performance of precast hollow-core floors: part 1-experimental data. *ACI Structural Journal*, *118*(5), pp.49-63.
- del Rey Castillo, E., Griffith, M. and Ingham, J., 2018. Seismic behavior of RC columns flexurally strengthened with FRP sheets and FRP anchors. *Composite Structures*, *203*, pp.382-395.
- del Rey Castillo E, Kanitkar RA, Smith ST. Floor diaphragm strengthening of concrete structures with FRP. InProc., 2019 Concrete New Zealand Conf 2019a (pp. 1-5).
- del Rey Castillo, Enrique, Dmytro Dizhur, Michael Griffith, and Jason Ingham (2019b). "Experimental testing and design model for bent FRP anchors exhibiting fiber rupture failure mode." Composite Structures 210: 618-627.
- del Rey Castillo, E., Griffith, M. and Ingham, J., 2019c. Straight FRP anchors exhibiting fiber rupture failure mode. *Composite Structures*, *207*, pp.612-624.
- del Rey Castillo, Enrique, Ravi Kanitkar, Scott T. Smith, Michael C. Griffith, and Jason M. Ingham (2019d). "Design approach for FRP spike anchors in FRP-strengthened RC structures." Composite Structures 214: 23-33.
- del Rey Castillo, E. and Kanitkar, R., 2021. Effect of FRP spike anchor installation quality and concrete repair on the seismic behavior of FRP-strengthened RC columns. *Journal of Composites for Construction*, *25*(1), p.04020085.
- del Rey Castillo, Enrique, Kent A. Harries, Rhys Rogers, and Ravi Kanitkar (2022). "FRP Tension Ties: State-of-the-Art Review of Existing Design Guidance for Debonding Capacity

and Applicability to Concrete Diaphragm Seismic Strengthening." Journal of Composites for Construction 26, no. 2: 04022014.

- Henry, R.S., Dizhur, D., Elwood, K.J., Hare, J. and Brunsdon, D., 2017. Damage to concrete buildings with precast floors during the 2016 Kaikoura earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, *50*(2), pp.174-186.
- NZSEE, MBIE, EQC, NZGS, & SESOC. (2017). The Seismic Assessment of Existing Building: Technical Guidelines for Engineering Asessments. Wellington, New Zealand.
- NZSEE, MBIE, EQC, NZGS, & SESOC. (2018). Concrete Buildings Part C5 - Technical Proposal to Revise the Engineering Assessment Guidelines. Wellington, New Zealand: Ministry of Business, Innovation and Employment (MBIE).
- Ormeno, M., Jing, J., Rogers, R. and Del Rey Castillo, E., 2019, April. Capacity of diaphragm strengthened with FRP: Comparison between ACI 440.2 R and in-situ tests. In *Proceedings of the 2019 Pacific Conference on Earthquake Engineering (NZSEE/PCEE), SkyCity, AK, New Zealand* (pp. 4-6).
- Puranam, A.Y., Corney, S.R., Elwood, K.J., Henry, R.S. and Bull, D., 2021. Seismic Performance of Precast Hollow-Core Floors: Part 2--Assessment of Existing Buildings. *ACI Structural Journal*, *118*(5).
- Junrui Zhang, Enrique del Rey Castillo, Aniket D Borwankar, Ravi Kanitkar, 2023, Behaviour of large FRP ties for seismic strengthening of concrete diaphragms. SESOC Conference