Fulfilling a concrete need

Extensive research at the University of Auckland on carbon fibre-reinforced polymers (CFRP) helps understand how this material can be used for seismic strengthening, increasing existing buildings' resilience.

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THE BUILDING ACT was amended in 2016 to include a national system for managing earthquake-prone buildings, including strict timelines for repairing and strengthening them.

Seismic issues make for challenging projects

This comes as our growing knowledge of the seismic behaviour of structures has highlighted numerous issues with our current building stock, including notably thin and unconfined walls and deficient diaphragms.

The seismic hazard model governing the seismic demand on buildings is also being revised following the work of GNS and the Resilience to Nature's Challenges National Science Challenge. Seismic demand is likely to be will be increased, especially in areas such as Wellington.

National and international commitments to reduce our carbon footprint also require a change in mentality from having disposable buildings to forever ones.

Because of these changes, owners, builders, architects and engineers have their hands full with unique and challenging projects. While New Zealand has developed comprehensive guidance on completing the seismic assessment of existing buildings, there is nothing about how to repair and strengthen buildings to comply with the new building standard.

Change to fibre-reinforced polymers

Engineers here and overseas have typically resorted to materials and structural systems that are well understood and familiar to them, such as adding new steel frames or new concrete walls. The current environment, however, often precludes this practice as there is too much added weight, too much valuable real estate lost and too much construction and disturbance.

As a result, the use of fibre-reinforced polymers (FRP) has taken off in the last few years. This is a composite material consisting of fibres - usually carbon - and a matrix - usually epoxy. The use of FRP was pioneered in the 1990s in California, but it is only in the last 10 years that use of this versatile material for many applications has exploded.

Many applications are very well researched, and design guidance exists both in the US and in Europe. Typical examples are the confinement of isolated columns and flexural - that is, gravity - strengthening of beams.

However, reality is very different from these highly simplified design models. For example, columns are rarely isolated in buildings, and it is common to find obstructions that prevent the column being fully wrapped.

In seismic environments, we also need to provide a level of redundancy that is rarely needed in gravity-based interventions, but international guidelines are notoriously silent on seismic provisions.

I have been working to develop easy-to-apply design solutions for seismic strengthening of concrete buildings in a variety of applications. This research has been supported by

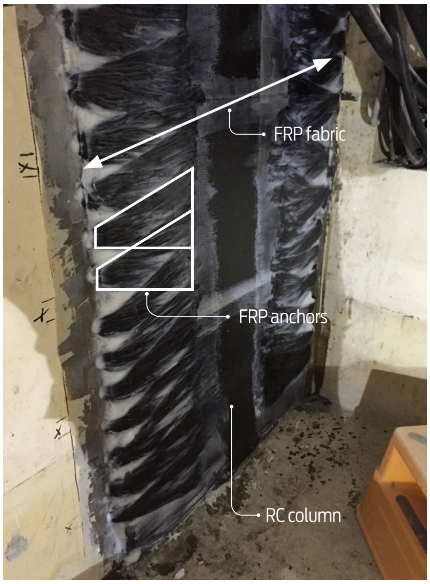

Figure 1: Examples of the use of fibre-reinforced polymer (FRP) anchors.

industry stakeholders including Concrete New Zealand, BBR Contech and Concrete Solutions as well as EQC and MBIE.

Understanding FRP anchors

FRP anchors are bundles of fibres that can be introduced into the structure to ensure load path continuity between the FRP fabric and the concrete structure (see Figure 1). This provides the necessary redundancy should the FRP fabric fail prematurely or if the load is larger than expected.

The FRP anchors are critical in seismic environments, but our understanding of how they work was inadequate when I began researching them in 2014.

A set of equations was developed through a 3-year project and dozens of laboratory tests. These allow an engineer to calculate the capacity of the FRP anchors for all possible failure modes. This is not too different to how post-installed steel anchors are designed. The equations are being used in design and will be implemented in the next iteration of ACI 440.2R *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*.

Seismic flexural strengthening

A notable gap in design guidelines and research was how to use FRP to increase the moment capacity of structural members when the forces need to be transferred into the foundation or into/through the joints. This is a particular concern in old buildings without sufficient longitudinal reinforcement, as these were typically only for gravity loads, and insufficient development length.

By testing, it was found that the typically assumed bilinear behaviour is not applicable to FRP-strengthened structures. In this situation, three distinct branches exist:

- The elastic branch, which concludes at the point where the steel yields or the FRP debonds - usually very close together.
- The inelastic hardening caused by the progressive debonding of the FRP from the point of maximum moment demand towards the point(s) of zero moment.
- The inelastic softening as the FRP progressively ruptures until the as-built behaviour is resumed. This behaviour can be predicted using section analysis and calculating the FRP debond and FRP rupture strain from existing guidelines.

Prisms and wall confinement with FRP anchors

Columns are not always isolated. Sometimes, obstructions prevent all sides from being fully wrapped with FRP (see Figure 1). Research on prisms confined with FRP anchors has resulted in a yet to be published design methodology to calculate the stress-strain curves.

One of the applications of the confinement of prisms is confinement of boundary elements of walls to prevent out of plane failure and inadequate confinement. It was possible to prevent out-of-plane failure, extending the drift capacity without gravity load loss from 1% to 4.5% (see Figure 2).

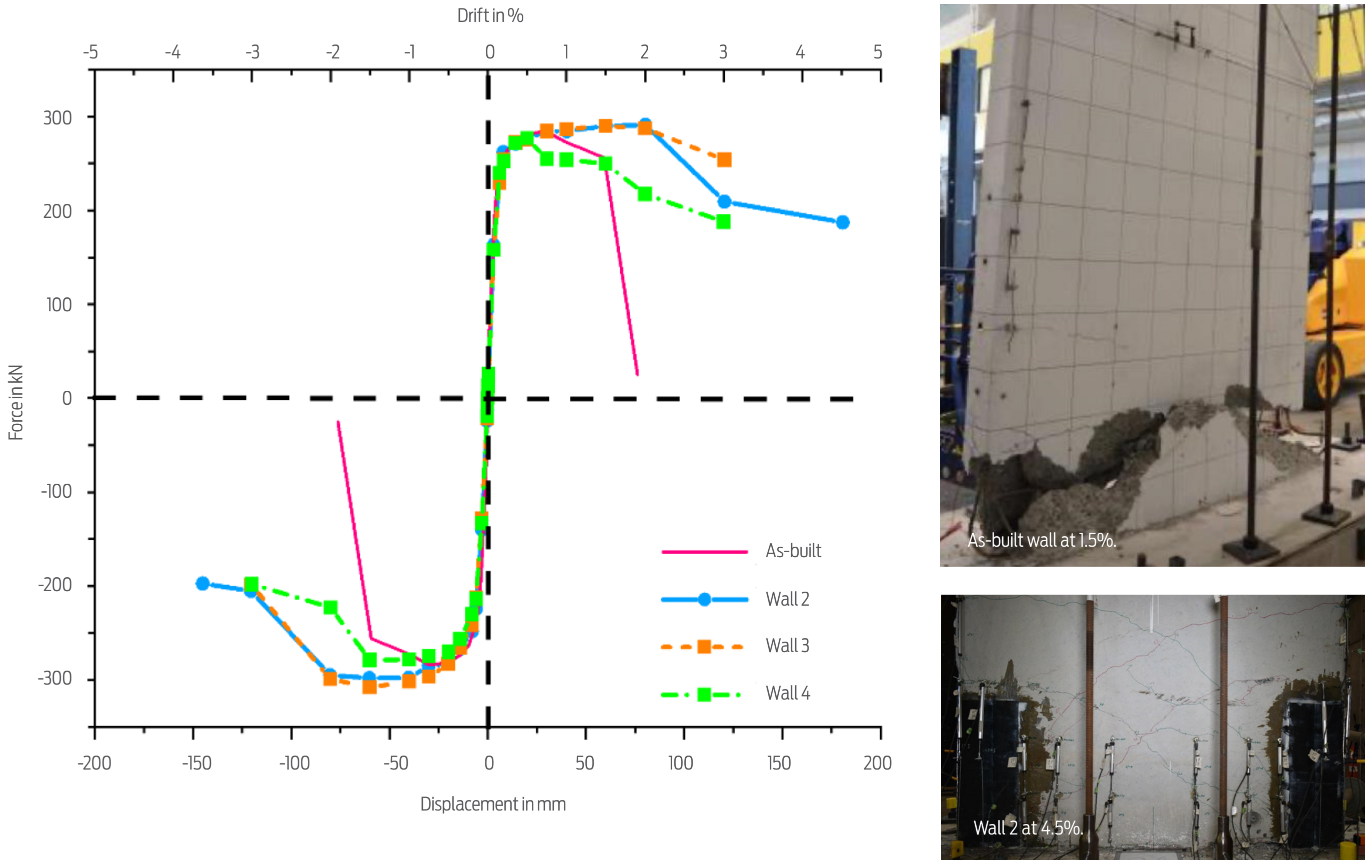

Figure 2: Out-of-plane failure and inadequate confinement of thin walls (courtesy of Zhibin Li).

Walls 2, 3 and 4 had different variations of FRP strengthening to optimise the design for different seismic demands.

Figure 2 also shows the catastrophic failure of the as-built walls, with the whole section shearing out of plane, compared to the FRP-strengthened wall that only presents minor cracking and rebar fracture.

Diaphragm strengthening

Concrete diaphragms are often designed in New Zealand using the strut and tie or grillage method. These analysis methods provide the demand as compression struts, which the concrete typically can satisfy, and the tension ties, which the steel reinforcement cannot always satisfy.

The ties have various levels of demand depending on the location within the floor - for example, higher demand close to openings. The resulting layout of FRP is an orthogonal grid that must satisfy that demand.

However, the design force that the ties can sustain cannot be calculated with any degree of certainty. Recent research demonstrated that, while international codes can successfully predict the force capacity of short (<300 mm), narrow (<150 mm) and thin (1-2 mm) ties, they are incapable of predicting the force capacity of ties of the size typically used in floor diaphragms (several metres long, 500-600 mm wide and 4-10 mm thick).

In addition to in-plane loading, floor diaphragms need to sustain the gravity loads and are subjected to significant deformations, both in-plane and out-of-plane. These include:

- the differential rotation between the floor and the perimeter beams
- the differential vertical displacement of walls as they grow during the earthquake compared to the floor
- the differential deformation between precast units and between units and the lateral system.

The FRP ties must be able to accommodate and survive these deformations while providing the needed extra tension capacity to the floor. Redundancy must also be built in to the design in case of a larger than expected event, construction errors or long-term issues arise.

MBIE Endeavour Funding was recently awarded to provide a solution for FRP strengthening of diaphragms.

For more Those who are interested are welcome to join our practice advisory group by contacting Enrique at edelrey@auckland.ac.nz.