Mechanical Anchor Supplementary Shear Reinforcing as a Retrofit Technique for Hollowcore Floors

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ABSTRACT

Hollowcore floor systems have been prevalent in New Zealand construction since the 1980s. The susceptibility of these elements to fail under seismic action has been highlighted through numerous post-earthquake observations, particularly those made after the 2016 Kaikoura earthquake. Recent full-scale testing of hollowcore floor panels has revealed previously undocumented failure mechanisms that render commonly adopted retrofit techniques inadequate. As a result, the engineering industry requires new, verified, retrofit techniques for the effective seismic strengthening of hollowcore floors to assist structural engineers with developing and maintaining a safe, seismically resilient building stock. This paper presents a proof-of-concept testing regime with supporting finite element (FE) analysis of a new, purpose-built mechanical fixing for use as supplementary shear reinforcing in hollowcore floors. This retrofit technique offers a practical and cost-effective alternative to other currently proposed techniques. Subsequently, the availability of this retrofit technique has the potential to increase the accessibility of hollowcore retrofits to building owners across New Zealand, thereby facilitating a safer and more seismically resilient national building stock.

1 INTRODUCTION

When first brought to market, prestressed hollowcore (HC) flooring units provided a long-spanning and lightweight alternative to traditional reinforced concrete construction. Coupled with a building boom in the 1980s, this resulted in HC units being widely adopted across New Zealand. Observations from post-earthquake building inspections after the 2016 Kaikōura earthquake suggest that over 60% of multistorey commercial floor space in Wellington consists of prestressed hollowcore flooring (Henry et al. 2017). Given the extent of the 1980s building boom, it is reasonable to assume that other commercial hubs in New Zealand contain similar proportions of prestressed hollowcore flooring in their commercial multistorey buildings.

The 1994 Northridge earthquake and subsequent research by the University of Canterbury highlighted the poor performance of hollowcore flooring under seismic actions (Norton et al, 1994; Matthews, 2004). An early and widely adopted retrofit was the installation of equal angle (EA) or rectangular hollow section (RHS) steel profiles below hollowcore flooring units to provide additional seating (Büker et al, 2021c). Observations from the 2016 Kaikōura earthquake indicated several previously unconsidered failure mechanisms (Henry et al, 2017) that were later reproduced in full-scale laboratory testing (Büker et al, 2021a). During the same testing campaign, it was also shown that EA and RHS, while effectively addressing loss of seating concerns, were not sufficient for collapse prevention.

The majority of hollowcore floors in New Zealand have been produced using the extrusion method which does not facilitate the inclusion of transverse shear reinforcing. Subsequently, flexural shear loading in hollowcore floors is primarily resisted by the tensile capacity of the concrete webs (Pisanty, 1992). In addition to this, the pre-stressing strands not being fully developed at the ends of the section leaves them susceptible to web shear failure under seismic loading and deformation demands (Broo et al., 2007). The possibility of initial end slip of the prestress strands in the fabrication process can exacerbate this effect, as well as adding uncertainty around the web shear capacity of the slab (Palmer et al, 2011).

Outlined herein is an experimental and modelling campaign which was executed to provide proof-of-concept evidence for using PYTHON HC fixings as supplementary shear reinforcing in hollowcore floors. The development of this retrofit method could provide a cost and space efficient option for consideration by design engineers when looking to strengthen existing hollowcore flooring.

2 EXPERIMENTAL PROGRAMME

Two full-scale shear tests were performed on 200 mm deep hollowcore specimens with a 75 mm thick mesh reinforced concrete topping produced using the extrusion method by a local precast company in Auckland, New Zealand. The units had seven low relaxation type 12.7 mm diameter pre-stressed strands with an ultimate tensile capacity of 1860 MPa. The strands were stressed to 67% of their ultimate capacity (1240 MPa jacking stress) prior to casting the concrete. Three concrete cube compression tests were performed following the standard C39/C39M (ASTM International, 2021) and an average compression strength of 50.6 MPa was recorded. The concrete cubes were obtained from 400 mm deep hollowcore flooring units from the same manufacturing line, as the 200 mm deep hollowcore specimens do not have sufficient web height to extract appropriate samples.

The hollowcore specimens were tested in a three-point bending configuration using the test setup shown in Figure 1. A shear span of 500 mm (1.8D) was maintained for all tests. Pinned supports consisting of 25 mm diameter round bars and 10 mm thick steel plates were used to support each end of the specimen. The same round bar and steel plate arrangement was used for load application. The hollowcore specimen was 4000 mm long and was therefore able to be utilised for two tests by testing once at each end of its length with the previously tested area left outside the supporting span. The distributed load along the width of the hollowcore specimen was applied using a hydraulic actuator with a loading limit of 1000 kN and measured using a calibrated load cell as seen in Figure 1. The hydraulic actuator was controlled by a manual pump which increased the applied force in intervals between 10 kN and 25 kN until shear failure was observed. After failure, data collection was maintained and loading of the specimen was continued to investigate the post failure behaviour. Six digital displacement gauges with accuracies of between 0.002mm and 0.02mm were used to measure the vertical displacement of the hollowcore specimen (arranged as seen in Figure 1). These gauges are described in the format DX-Y where D = displacement gauge, X = longitudinal distance from the applied load and Y = lateral location (A = edge 1, B = edge 2, C = central).

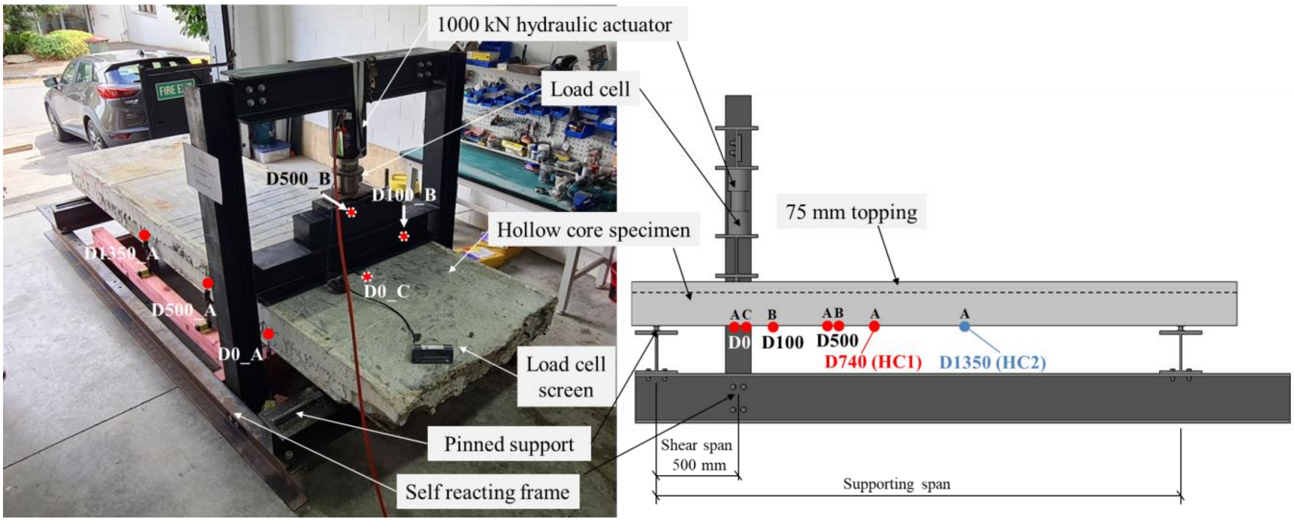

Figure 1: Testing setup

A total of two shear tests were performed: one tested the specimen in its as-built state (HC1) with a 2040 mm supporting span and one was tested after it had been strengthened using high strength fixings designed specifically for use in New Zealand hollowcore floors (PYTHON HC) with a 3220 mm supporting span. The PYTHON HC fixing has a nominal shank diameter of 10 mm and is threaded such that it only grips to the thickness of the hollowcore and topping slab above the hollowcore voids (see Figure 2). This design prevents premature and exposed failure in the section of concrete below the hollowcore voids and the nonlinear behaviour that fully threaded mechanical fixings in hollowcore can exhibit.

The PYTHON HC fixings were installed from the underside of the specimen through the centre of the voids as is typical in such units due to the strands of the hollowcore flooring preventing fixings from being installed through the webs. Three rows of fixings were installed which were spaced longitudinally at 200 mm (0.7D), resulting in a total of 18 fixings (see Figure 2). The results of the experimental campaign provided data for the calibration of a finite element (FE) analysis model, refer Section 3.

Figure 2: PYTHON HC fixing, strengthening configuration, and tested HC2 specimen

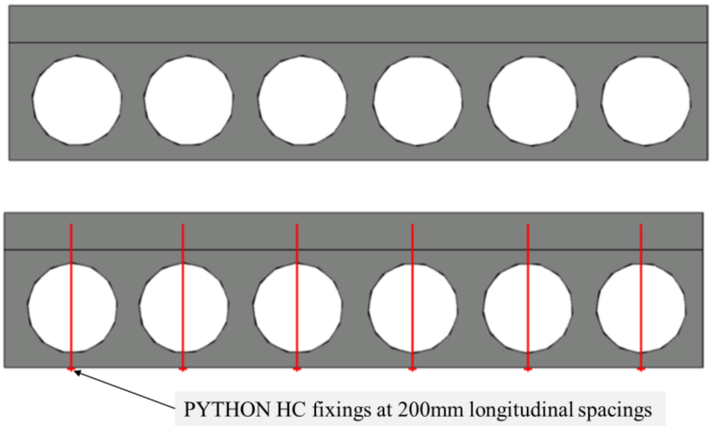

Figure 3: As-built hollowcore specimen cross section, and hollowcore specimen retrofitted with PYTHON HC fixings cross section

3 FINITE ELEMENT ANALYSIS

The hollowcore slab was numerically modelled adopting a FE modelling approach using nonlinear layered shell elements with edge constraint properties implemented in the software package SAP2000. Three main parts were included in the model to simulate the hollowcore slab: the web, the upper flange, and the lower flange. A co-axially rotating smeared crack material model (Darwin & Pecknold, 1974; Vecchio & Collins, 1986) was assigned to the web elements to account for crack opening due to the interaction between bending and shear. Because the model does not account for the tensile strength of concrete, a fictitious layer was added to the web layered shell element to simulate concrete behavior under tensile stress.

The prestressing strands were modelled using tendon elements. To account for the effect of the transfer length, separate tendon objects were placed at the end of every strand. These tendon objects were pretensioned from the extremity located closest to the middle of the unit and friction loss values were specified along the tendon length so that the force reduced to zero at the extremity located closest to the hollowcore flooring unit's end.

Finally, nonlinear layered shell elements were also used to simulate the concrete topping. To avoid any load transfer to the topping when the prestress is applied, these elements were added to the model via staged construction. A full interaction between the topping and the unit was assumed.

The numerical model was first validated using data from previous testing on bare hollowcore flooring units available in the literature. The first reference specimen was selected from the specimens tested by Nguyen et al. (2019). The stiffness and peak strength obtained from the numerical model matched the experimental data with sufficient accuracy (see Figure 4a). The numerical model also exhibited a failure mode that is consistent with what was observed during experimental testing (see Figure 4b).

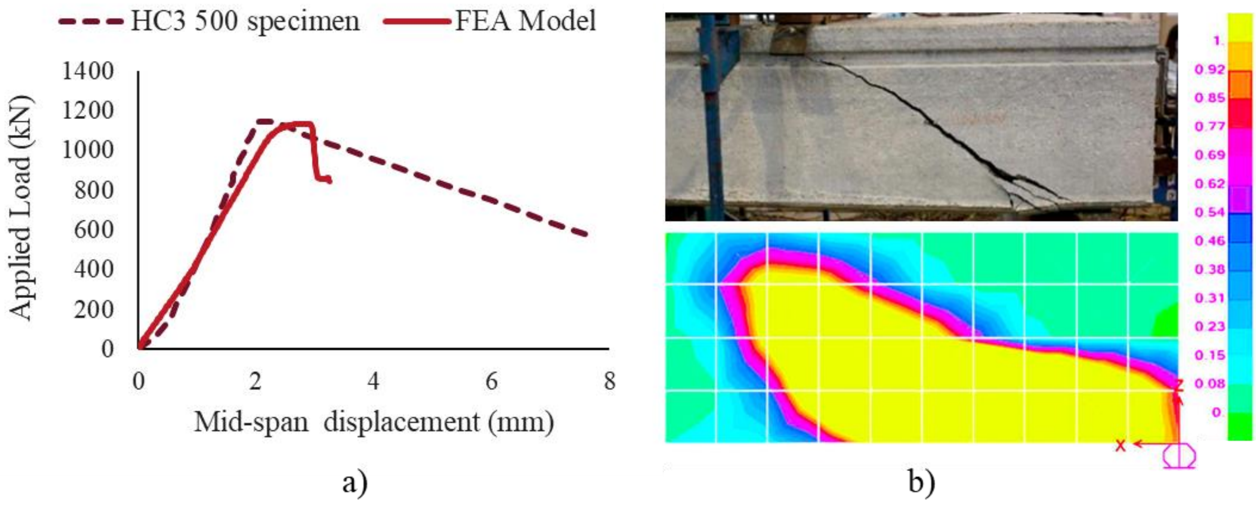

Figure 4: FE model validation based on Nguyen at al. (2019) test on 500 mm depth Hollow-core units. a) Comparison between force-displacement curve. b) Comparison between web crack after collapse in the tested specimen and tensile strain of the nonlinear layered shell element.

The retrofit technique described in Section 2 was numerically investigated to study the effectivity of different fixings layouts applied to the aforementioned 200 mm deep hollowcore slab, and hence providing a rational for future physical testing. The installed PYTHON HC fixings were modelled using *link* elements connecting the lower to the upper flanges and characterized by a two-branch behaviour with linear softening (see Figure 5b). The resultant force-displacement curves are shown in Figure 5.

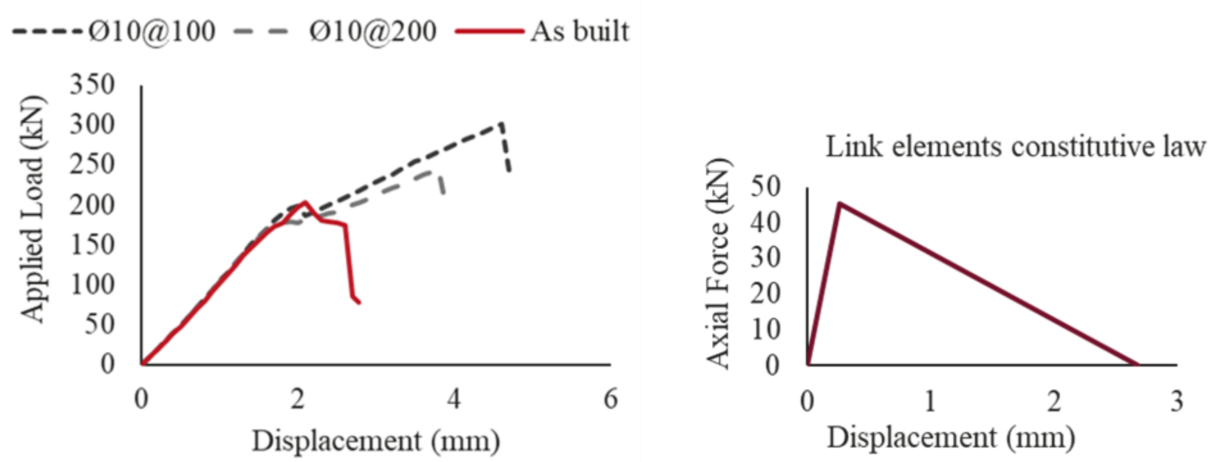

Figure 5: Force-displacement curves resulting from (a) modelling different fixing layouts applied to a 200mm deep bare hollowcore flooring unit, and (b) link elements constitutive law assigned to link elements to simulate PYTHON HC fixings.

4 RESULTS AND DISCUSSION

Figure 7 shows the shear force versus displacement graphs for the tested HC specimens with Table 1 providing a data summary and Figure 6 showing the crack pattern at failure. For clarity, only D0 and D500 were reported and D0 was averaged from D0_C, D0_A and D100_B to account for any rotation of the hollowcore specimen during testing. Test HC1 provided a benchmark for comparison of the shear strength, displacement behaviour and post-failure behaviour of the subsequent retrofitted test.

HC1 exhibited a clear shear failure with a typical inclined crack starting close to the support and reaching the point of load application (see Figure 7). HC1 was observed to reach a maximum beam shear of 257 kN before failing in a brittle manner with a residual shear capacity of 126 kN (49% of peak). Residual capacity was observed to be provided primarily from strand pull out, as was typically observed in previous as-built hollowcore testing (Sarkis Fernandez, 2021).

Test HC2 showed a greater post-peak capacity as well as a significantly smaller displacement increase at initial failure, with an ultimate shear strength 23% greater than HC1 (317kN), a residual strength 70% that of its peak (214kN) and a displacement increase at initial failure 66% less than HC1. The PYTHON HC fixings in specimen HC2 appeared to effectively engage and behave as shear reinforcing, spanning the shear crack that developed and providing additional shear capacity. The horizontal portion of the shear crack seen for HC2 in Figure 7 is in line with the fixings location and is evidence of the engagement and contribution of the fixings across the shear plane.

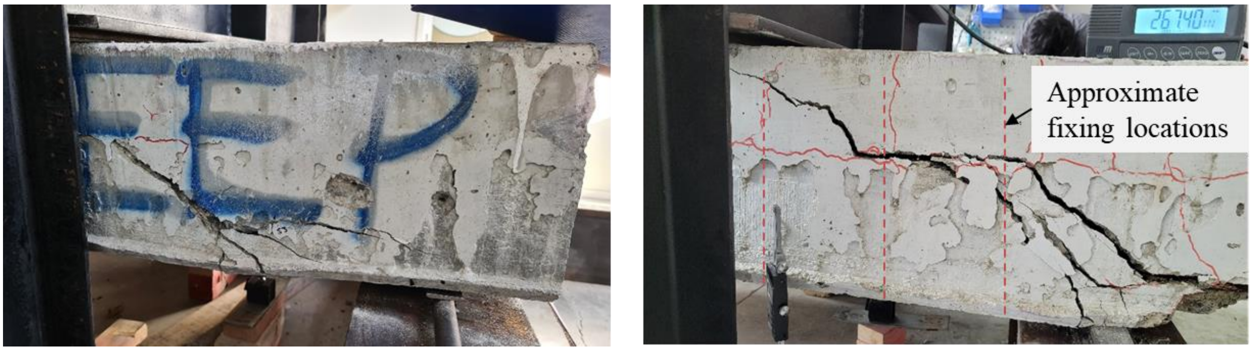

Figure 6 HC1 (as-built) crack pattern, HC2 (retrofitted) crack pattern

It is noted that the overhang length of test HC1 and HC2 were different (110 mm and 450 mm respectively). The overhang difference was a result of practical testing constraints. As a result, the local strand prestress across the shear spans in tests HC1 and HC2 was not consistent. Given the proof-of-concept scope of this campaign, the collaboration with a FE model and the planned future testing that will exclude this inconsistency, it is considered to be an acceptable variation for the goals of this study. As expected, the stiffness of the specimens was observed to be inversely proportional to the supporting span length, refer Figure 7.

Table 1: Experimental test results

Specimen	Ultimate Strength (kN)	1st residual strength (kN)	Final residual strength (kN)	Ultimate strength increase	Residual strength increase	Displacement increase at initial failure (mm)	Specimen overhang length (mm)
HC1	257	126 [49%]	126 [49%]	-	-	6.15	110
HC2	317	247 [78%]	214 [67%]	23%	70%	2.09	450

* Values in square brackets are percentages of ultimate strength of the same test

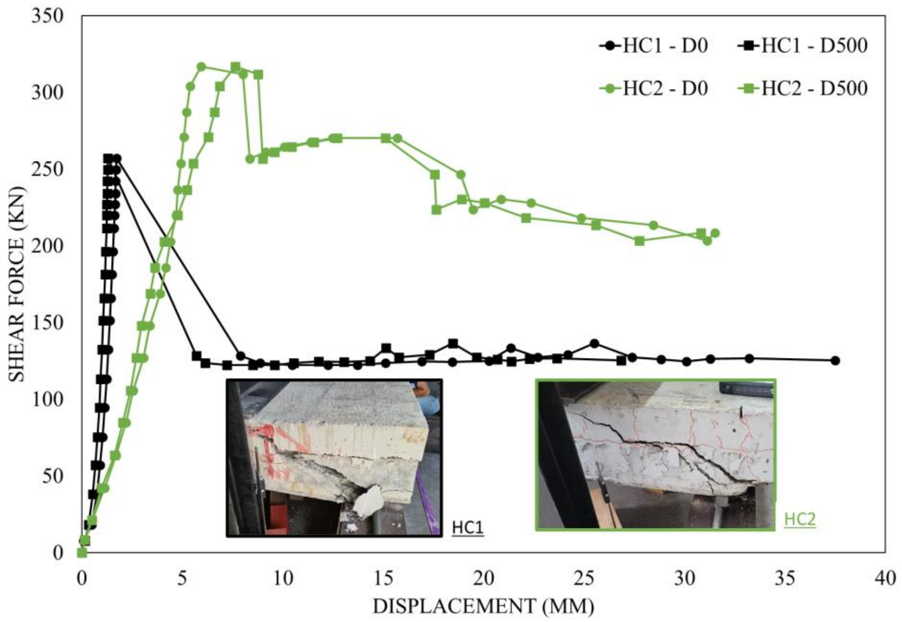

Figure 7: Experimental shear force versus displacement response of HC1 and HC2 including cracked specimens at the end of the test.

The model outlined in Section 3 was applied to replicate the HC1 test. Material properties assigned to the model were based on the specimen material characterization discussed in Section 2. A comparison between the HC1 test results and numerical prediction is shown in Figure 8. The load carrying capacity predicted by the model was in accordance with the experimental capacity. There is a good agreement between predicted and observed values of stiffness provided that the numerical capacity curve is shifted by +0.9 mm along the x-axis. The shape of the experimental curve exhibiting increasing stiffness (up to a displacement of 1.3 mm) has been previously reported on by Nguyen et al. (2019) who attributed it to the presence of initial slack.

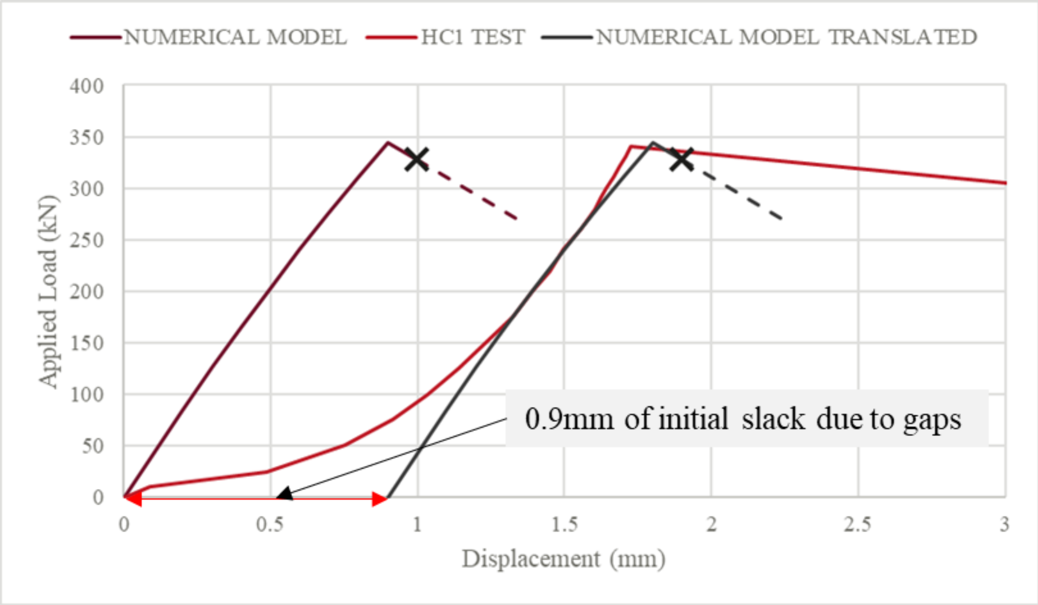

Figure 8: HC1 prediction based on the FE modelling approach

5 CONCLUSIONS

The shear response of hollowcore flooring units was experimentally tested in a three-point bending configuration to investigate the effect of PYTHON HC fixings installed as supplementary shear reinforcing on the hollowcore flooring units' behaviour. The following key observations were made:

- Test HC2 with PYTHON HC fixings installed at 200 mm longitudinal spacings (0.7D) had a shear strength 23% greater than the as-built test (HC1).
- Test HC2 with PYTHON HC fixings installed at 200 mm longitudinal spacings (0.7D) had a final residual shear strength of 78% (247 kN) of its peak shear strength compared to the as-built test (HC1) which had a final residual shear strength of 49% (126 kN) of its peak shear strength. This correlates to a 70% variance in final residual shear strength between as-built and retrofitted tests.
- Test HC2 with PYTHON HC fixings installed at 200mm longitudinal spacings (0.7D) had a displacement increase at initial failure 66% less than that of HC1.

A FE model was developed to reproduce the experimental testing as a mode of validation of the numerical model. It is intended that this model will be used in future research to explore different testing configurations and to design an efficient retrofit solution. The model was successfully calibrated with previous experimental testing data and with as-built experimental testing data from this testing programme. Further development of this model is required to reliably predict the behaviour of hollowcore flooring when retrofitted with mechanical anchors as supplementary shear reinforcing

Further investigation is required to sufficiently quantify the impact of mechanical anchors as supplementary shear reinforcing in hollowcore flooring for design guidance to be developed. A continuation of this testing programme is currently underway to investigate the impacts of overhang length, longitudinal and transverse fixing spacings, washer size, and prestressing of fixings, and to quantify the performance improvement by using these fixings in conjunction with the strong back retrofit as outlined in *Draft design recommendations for strongback retrofits* (Büker et al. 2021b).

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