Finite element analyses of hollow-core units subjected to shear and torsion

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ABSTRACT

A building boom in the 1980s allowed pre-stressed hollow-core floor construction to be widely adopted in New Zealand, even though the behaviour of these prefabricated elements within buildings was still uncertain. Inspections following the Canterbury and Kaikōura earthquakes has provided evidence of web-splitting, transverse cracking and longitudinal splitting on hollow-core units, confirming the susceptibility of these floors to undesirable failure modes.

Hollow-core slabs are mainly designed to resist bending and shear. However, there are many applications in which they are also subjected to torsion. In New Zealand, hollow-core units contain no transverse reinforcement in the soffit concrete below the cells and no web reinforcement. Consequently, their dependable performance in torsion is limited to actions that they can resist before torsional cracking occurs.

In previous work by the present authors, a three-dimensional FE modelling approach to study the shear flexural behaviour of precast pre-stressed hollow core units was developed and validated by full-scale experiments. This paper shows how the FE analyses have been extended to investigate the response of HC units subjected to torsional actions. Constitutive models, based on nonlinear fracture mechanics, have been used to numerically predict the torsional capacity of HC units and have been compared with experimental results. The results indicate that the numerical approach is promising and should be developed further as part of future research.

1 INTRODUCTION

The use of precast prestressed hollow-core (PPHC) units for floors is common in buildings. In New Zealand cities, buildings with precast concrete floors comprise a large percentage of the commercial building stock. Anecdotal evidence, based on post-earthquake inspections of buildings, suggests that over 60% of commercial floor area in Wellington falls into this category (Henry et al., 2017).

The partial collapse of precast concrete flooring components in Statistics House during the Kaikōura earthquake, together with several other buildings in Wellington damaged beyond economical repair, triggered serious concerns about the seismic performance of precast floors (Cubrinovski et al., 2020). Of particular importance was the presence of damage to the floors that were inconsistent with the failure modes identified during previous research. This has brought into question the seismic assessment of buildings with these floors, the residual capacity of the floor once the damage had been sustained, and the effectiveness of the existing retrofitting techniques.

To help address these concerns, a comprehensive campaign of three-dimensional finite element (FE) analyses into PPHC floors is underway. Special consideration has been given to local displacements and structural actions induced into the individual floor units, as it is these that are likely to cause brittle failure. Accordingly, the modelling approach presented herein aims to improve our understanding of the initial web cracking behaviour of PPHC units when subjected to flexural and torsional shear forces that lead to brittle failure mechanisms. For this purpose, detailed solid 3D FE models of the units have been calibrated against existing shear test results for PPHC units, both in New Zealand and internationally. In this paper, test results are compared with initial obtained by FE analysis predictions using constitutive models, based on nonlinear fracture mechanics. The shear strength capacity, the evolution of shear stress distributions and crack patterns of single-span PPHC units are examined.

2 VULNERABILITY OF HOLLOW-CORE FLOORS

Owing to the manufacturing extrusion process, hollow-core units in New Zealand contain no transverse or vertical reinforcement. This, in combination with the cross-section geometry, with large voids to save material and reduce self-weight, makes the units inherently vulnerable to web cracking when subjected to torsional or flexural shear actions (Broo et al., 2007). There are, however, many applications in which PPHC units are subjected to combined shear and torsion, for example in floors supported on three edges, in floors with openings, and in floors with skew ends (Broo et al., 2007).

Torsion on a PPHC unit generates shear stresses that act mainly around the perimeter of the cross section. In the outermost webs, these stresses act upwards in one web and downwards in the other. A vertical shear force, on the other hand, produces shear stresses that are uniformly distributed over all webs. When vertical shear and torsion act simultaneously on one hollow core unit, the stresses from these influences interact. This means that one of the outermost webs in the cross-section receives much higher stresses than the others (Broo et al., 2007).

Containing no reinforcement in the soffit concrete below the cells and no web reinforcement, the dependable performance of PPHC units in torsion is considered limited to actions that they can resist before torsional cracking occurs (Fenwick et al., 2010). Once torsional cracking develops, torsional resistance decreases rapidly. In addition, this torsional cracking reduces the flexural and shear strengths (Broo et al., 2005; Broo et al., 2007). There are many situations where torsional actions are induced in PPHC units due to differential displacement of supports; for example, where one end of a unit is supported on a beam, which remains relatively straight as the building sways in an earthquake, while the other end is supported by a structural wall that flexes due to the in-plane bending moments earthquake shaking induce.

3 NONLINEAR SOLID FINITE ELEMENT ANALYSES

3.1 Experimental test database

A detailed discussion of all available experimental tests is beyond the scope of this paper; nonetheless, a summary of the experimental database formed, and the key test results used for the development of the FE models are presented below.

To assess the shear strength of PPHC units under web-shear and flexural-shear actions, six full-scale tests were performed on 200 mm deep PPHC units fabricated by a local precast company using the extrusion method. The 200 mm deep units were selected since this has been the most widely used precast floor unit in New Zealand. All specimens were tested in a three-point bending test, where all geometric properties remained the same across the tests apart from the shear span. Table 1 summarizes the test results, which have been used to calibrate the material properties and fracture mechanics of the FE model for the PPHC units.

Table 1: Summary of 3-point shear bending test results.

Specimen	Shear span (mm)	Aspect ratio*	Failure load (kN)	Deflection at failure (mm)	Failure mode
HC1	300	1.5	245	2.2	Web-shear
HC2	300	1.5	248	2.1	Web-shear
HC3	500	2.5	199	3.4	Web-shear
HC4	500	2.5	190	3.3	Web-shear
HC5	700	3.5	203	6.5	Flexural-shear
HC6	700	3.5	204	7.1	Flexural-shear

* The aspect ratio here refers to the distance between the point of load application and the support, to the unit depth,

To expand the numerical model to capture torsional cracking, results from full-scale tests carried out by Pajari (2004) have been used. Pajari (2004) conducted four full-scale experiments on PPHC slabs to document pure torsion without bending moment, shear force or contributions from neighbouring slab units. The tests provide a lower limit for the maximum angle of twist and torque when an isolated slab unit is twisted. The support conditions and loading arrangements are approximately depicted in Figure 1, and the main test characteristics and results are summarized in Table 2. The active end of the slab was free to rotate around an axis parallel to the longitudinal axis of the slab, whereas the passive end was able to move longitudinally only.

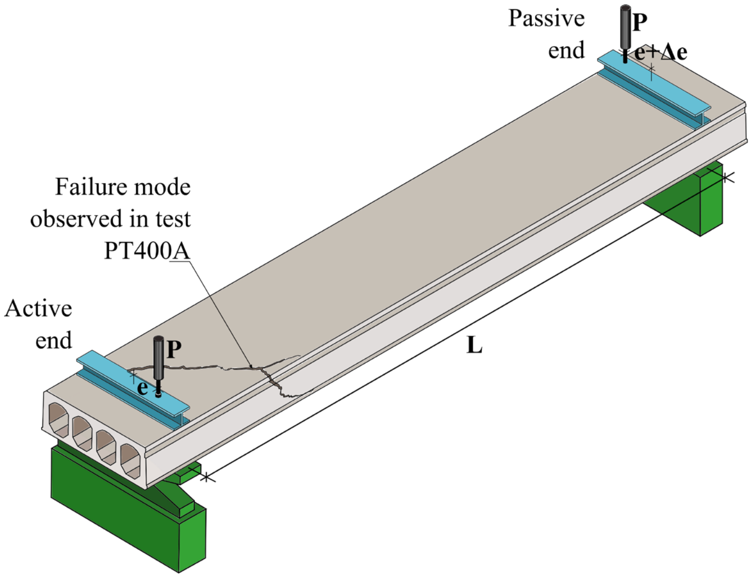

Figure 1: Conceptual pure-torsion experimental test set-up (Adapted from: Pajari (2004)).

Table 2: Summary of pure torsion tests for case study (Pajari, 2004).

Test	Thickness H (mm)	Span length L (mm)	Resistance against torque (kNm)	Angle of twist before cracking (mrad)
PT200A	200	5000	37.45	4.86
PT200B	200	5000	39.38	5.35
PT400A	400	7000	92.96	4.17
PT400B	400	7000	87.38	3.92

3.2 Proposed modelling approach

To investigate the behaviour of PPHC units, three-dimensional FE models have been created using the software Midas FEA (MIDAS Information Technology, 2016), and then calibrated against full-scale test results for both shear and torsion. Mean material properties are obtained from material characterization testing into the extruded concrete, as well as from the material properties reported by Pajari (2004). Figure 2 shows the detailed solid FE model for a 200 mm thick specimen in both longitudinal and transversal directions. Concrete has been modelled employing 6-node brick elements.

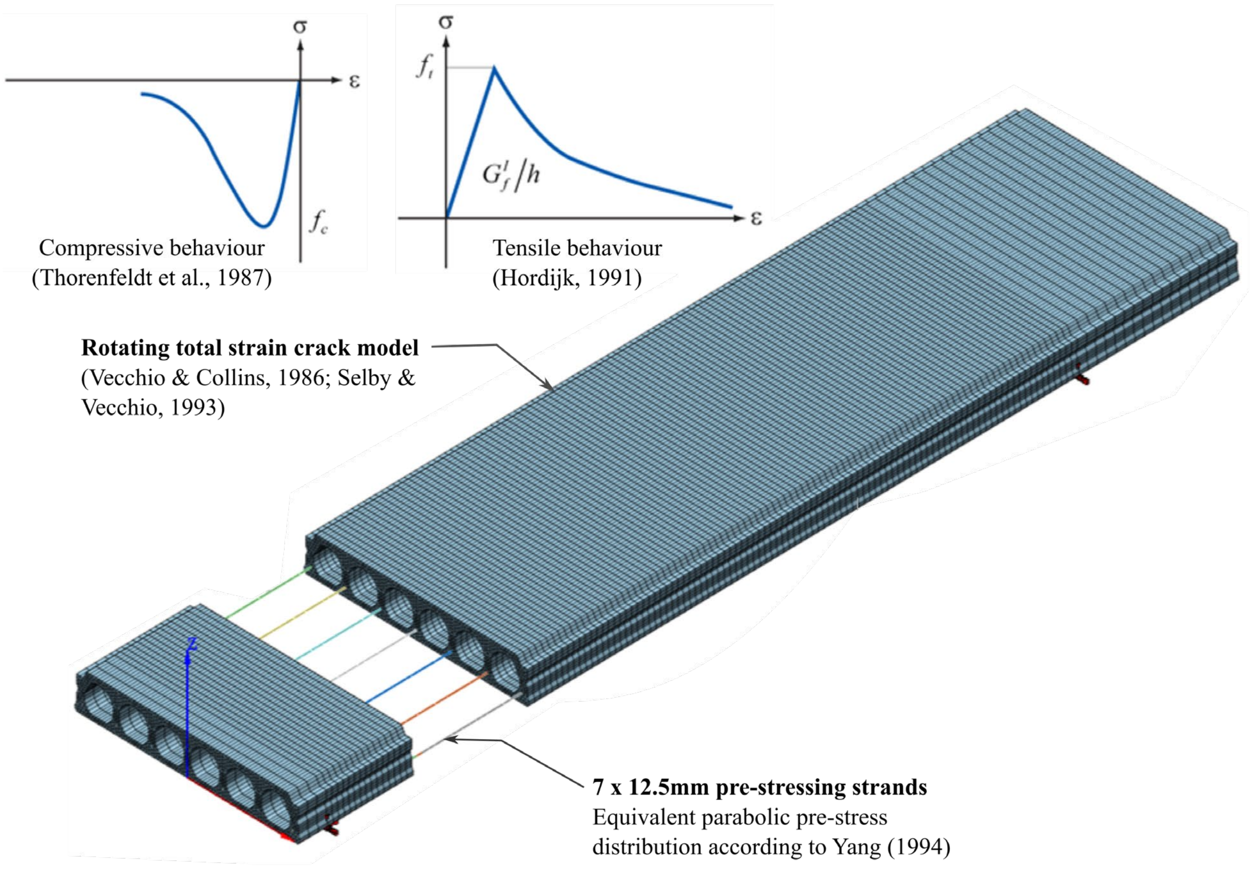

Figure 2: Example of detailed solid FE model developed for hollow-core units.

The total strain crack model, developed along the lines of the modified compression field theory, originally proposed by Vecchio and Collins (Vecchio & Collins, 1986) and then extended to the three-dimensional case by Selby & Vecchio (1993), was adopted to allow the development of a brittle web-shear failure mechanism. A rotating total strain cracking constitutive model was assumed, in which the directions of the cracks are presumed to continuously rotate depending on the changes in the axes of the principal strains. The algorithm for the rotating crack model is simpler than for its counterpart, a fixed crack model, providing improved convergence since, at each loading step, this model is unrelated to the previous cracking conditions (Vecchio & Collins, 1986).

The total strain crack model used is classified under the smeared crack model. Therefore, only one stress-strain relationship for tensile behaviour including cracks and one for the compressive behaviour is considered. In the case of the extruded concrete, the constitutive model was assumed to adopt the Hordijk & Reinhardt (1991) and the Thorenfeldt et al. (1987) model for uniaxial tensile and compressive behaviour, respectively (Figure 2). Confinement effects were neglected, while full shear retention and lateral crack effects (Vecchio & Collins, 1993) were allowed for through the selected rotating strain crack model.

The classical Von Mises yielding criterion with strain hardening was used for the pre-stressed steel strands, represented as embedded elements. To represent the strands-concrete interaction an equivalent parabolic pre-stress distribution was selected according to the work presented by Yang (1994). Therefore, no interface elements were introduced to represent strands-concrete interaction, since it is implicitly captured by the equivalent pre-stress distribution.

When the tendons are tensioned and released, inward slippage at the wedges takes place thus allowing the tendons to slacken. According to the experimental measurements, an average slippage of 2mm is considered to happen in the model, provoking tension losses in the tendons in the vicinity of the anchorages.

4 RESULTS AND DISCUSSION

4.1 Shear actions on PPHC units

The proposed numerical approach is first validated by focusing on a single PPHC unit, and for this purpose, specimens HC1 and HC2 (Table 1) have been taken as a reference. The accuracy of the unit FE model predictions is then tested for the remaining specimens and analysed in comparison with the experimental data. The adopted modelling approach provides a consistent match with experimental test results. The principal tensile and compressive strains, crack pattern and shear stress distribution at failure are all in close agreement with the collapse mechanism observed by the experimental damage pattern at the shear span of the unit tested in bending. An inclined crack emerges from both principal tensile strains and numerical crack patterns. Simultaneously, an inclined compressive diagonal strut arises, resulting in diagonal cracking and the failure mode that finally developed, also confirmed by a cut-off in the shear stress flow. Figure3a displays the shear force-displacement relationship from the testing of specimens HC1 and HC2 as well as the results from the FE prediction, together with the flow of shear strains in the shear span of the member under ultimate conditions in Figure3b.

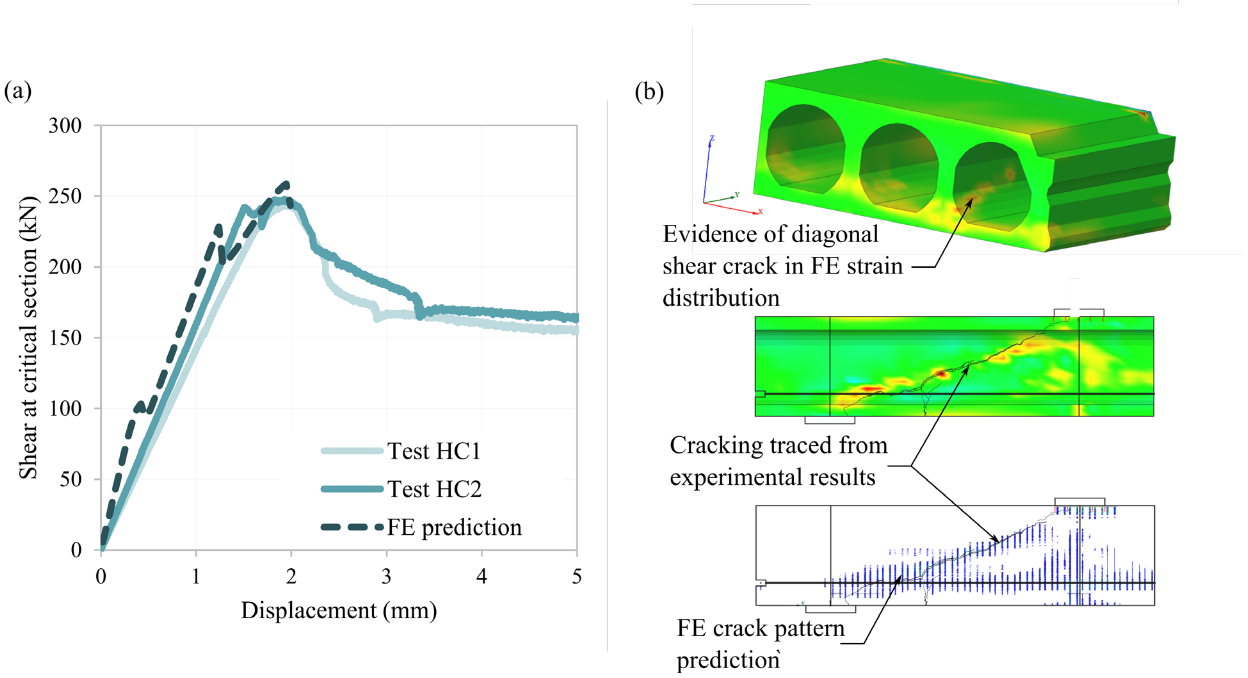

Figure 3: Comparison of FE predictions and experimental results for shear actions on hollow-core units.

The effectiveness of the FE models developed, accounting both for geometrical and material nonlinearities, is considered satisfactory. An accurate agreement with experimentally observed shear strength and displacement capacities has been achieved. For these models, mean values for the material properties were assumed. A variation of these properties in the actual specimens could have an influence on the difference between numerical and experimental results, especially considering that PPHC units are characterized as having a large variability in their material properties. Sensitivity studies were conducted for the shear strength and displacement capacity of the PPHC units, showing that the model is sensitive to the values of tensile strength of the concrete and elastic modulus of the concrete, whereas parameters such as the level of pre-stress and compressive strength of the concrete have a small influence on the shear strength and peak displacement of the units.

4.2 Pure torsion on PPHC units

The FE model applications have been expanded to include torsion failure by first validating the model against specimen PT400A (Table 2) and then, testing it for the remaining specimens. The proposed numerical approach offered a close agreement between the predicted failure mechanism and the experimental observations. Figure 5 shows a comparison of the principal shear strain on the PPHC unit after failure, compared against the cracking traced from the experimental observations. Ongoing analyses, on pure torsion and shear-torsion interaction on PPHC units, are aiming to analyse the effect of parameters that influence the shear and torsion response and load carrying capacity.

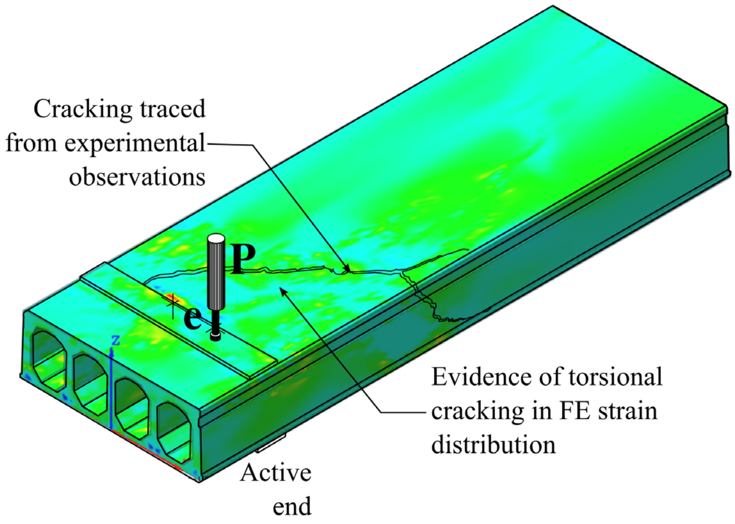

Figure 4: Comparison between FE predictions and observed torsional cracking in test PT400A.

5 CONCLUSIONS

The recent Kaikōura earthquake has raised again concerns about the general lack of understanding of the behaviour of PPHC floor systems and instigated the need for the vulnerability of these floors to be further investigated. For this reason, a numerical investigation, organized into a campaign of nonlinear FE analyses, has been initiated.

Three-dimensional FE models of HC units were developed and verified by non-linear finite element analyses of full-scale experiments on PPHC units subjected to shear and torsion. Overall, the FE analyses of the experiments could describe the general behaviour, failure mode, and crack pattern.

The outcomes from the FE analyses into PPHC units are being included in global models to enable modelling of the web-cracking behaviour. This work is thus considered a valuable contribution to the development of more complex FE models for PPHC slab connections and diaphragms.

6 ACKNOWLEDGEMENTS

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