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STRATEGIES FOR MODELLING THE NONLINEAR BEHAVIOUR OF PRECAST PRE-STRESSED HOLLOW-CORE FLOORS

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ABSTRACT

A building boom in the 1980s allowed precast pre-stressed hollow-core (PPHC) 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 2010-2011 Canterbury and 2016 Kaikōura earthquakes have provided evidence of web-splitting, transverse cracking, and longitudinal splitting on hollow-core units, confirming the susceptibility of these floors to undesirable failure modes. Moreover, post-earthquake observations evidenced inconsistencies between the observed damage conditions and the damage states identified by past research, bringing into question the seismic assessment of buildings with this type of floor system, the residual capacity of the floors once the damage has been sustained, and the effectiveness of existing retrofit techniques.

The work presented here aims to build on previous findings to further advance our understanding of the seismic behaviour of PPHC floors. In previous work by the present authors, a detailed three-dimensional finite element approach for the modelling of PPHC units was developed and validated by full-scale experiments. This paper summarizes the modelling criteria considered key to analyzing the nonlinear behaviour of PPHC floors. Comparisons of the numerical predictions with experimental results show that the proposed model can capture shear and torsional failure mechanisms. Lastly, the modelling approach has been advanced towards a sub-system model, developed to investigate the bending behaviour of PPHC slab-to-beam connections. The results indicate that the numerical approach is promising and should be developed further as part of future research. The outcomes from this research are helping inform methods for assessing the seismic performance of PPHC floors in New Zealand.

Keywords: finite element modelling, hollow-core slab, prestressed concrete, precast concrete, fracture mechanics, nonlinear behavior

INTRODUCTION

The use of precast concrete floor units with a thin in-place topping is a common construction technique used in buildings around the world. In New Zealand cities, due to an economic boom and the ease of construction, the use of precast pre-stressed hollow-core (PPHC) floors skyrocketed in the 1980s and dominated the construction market [1] to such an extent that, as anecdotal evidence suggests, about 60% of commercial floor area in Wellington falls into this category [2]. Observations suggest the proportion in Christchurch would have been similar until the earthquakes of 2010 and 2011, and there is no reason to think the situation is any different in Auckland and other major centres. New Zealand's extensive use of precast floors in regions of high seismicity is unusual, with in-situ floors more commonly used internationally. Consequently, and in contrast to most other deficiencies found in existing buildings, limited international research appears to be available regarding the adequacy of existing precast floors. Conversely, the recent earthquakes in New Zealand have prompted increased concern about the seismic performance of PPHC floors, and consequently, few new buildings are being constructed with hollow-core floors.

Past experimental research efforts sought to improve the detailing of beam-to-floor seating connections [3], helped to identify the vulnerabilities of PPHC floors and suggested improved connection details capable of accommodating earthquake demands [4]. Nonetheless, the partial collapse of precast concrete flooring components in Statistics House during the 2016 Kaikōura earthquake, together with several other buildings in Wellington damaged beyond economical repair, sparked serious concerns about the seismic performance of precast floors [5]. Of particular importance was the presence of damage to the floors that was 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.

PPHC units manufactured through the extrusion process, as is the case in New Zealand, contain no transverse or shear reinforcement. Furthermore, the pre-stressing strands will not be fully developed near the end of the units and may present initial end slip caused during the cutting of the units in the fabrication process [6]. All these features significantly affect the shear capacity of the units and make them prone to transverse and web cracking under deformation demands [4]. Transverse cracking close to the supports of hollow-core units was observed during the 2010/2011 Canterbury earthquake sequence [7]. However, it was more predominant during the 2016 Kaikōura earthquake, in which, an estimated 22% of the damaged buildings presented transverse cracking to hollow-core units [5]. In this situation, units may be close to a sudden brittle failure and, therefore, it is considered that the gravity load support has been compromised.

The 2016 Kaikōura earthquake highlighted the urgency to advance the understanding of the performance of existing buildings with PPHC floors. While the vulnerability of precast floor construction had been studied in past research, engineers lacked reliable assessment procedures and inspection methods that would facilitate the detection of damage, the estimation of the residual capacity of the floor, and a rapid recovery [8]. Subsequently, a national research program named ReCast Floors [9] was started in 2018 aimed at expanding the current knowledge of the seismic behavior of PPHC floors. To reach this goal, experiments and real-world observations are being combined with finite element (FE) modelling of PPHC units, connections, and diaphragms. The research presented in this paper is part of this program, and its main objective is to improve understanding of the cracking of PPHC units through nonlinear FE modelling.

As part of the ReCast research program, research has been undertaken to test and develop FE modelling techniques for PPHC floors. The work presented herein aims to summarize the findings and, in particular, the criteria that are considered critical for the FE modelling of PPHC floors. The presented modelling strategy could be used as part of a nonlinear analysis framework to reproduce and predict different cracking mechanisms for PPHC slabs. 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. Results obtained for 200 mm deep slabs failing in shear and torsion are shown, and the influence of key modelling parameters is highlighted. Finally, advances towards a sub-assembly model, developed to investigate the bending behavior of PPHC slab-to-beam connections, are presented. Results from the FE models should help improve our understanding of the likely behavior of PPHC floors during earthquakes.

FE MODELLING FOR HOLLOW-CORE UNITS

Experimental 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 [6]. The 200 mm deep units were selected since this has been the most widely used precast floor unit in New Zealand [2]. All specimens were tested in a three-point bending test, as illustrated in Figure 1, where all geometric properties remained the same across the tests apart from the shear span.

In addition, to expand the numerical model to capture torsional cracking, two 200 mm deep PPHC units tested under pure torsional actions [10], and four shear-torsion interaction tests [11] were selected. Figure 1 schematically shows the torsion test set-up used. 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. Table 1 summarizes some characteristics of the test specimens, as well as the dominant failure mode observed and the corresponding reference where more details about the experiments can be found.

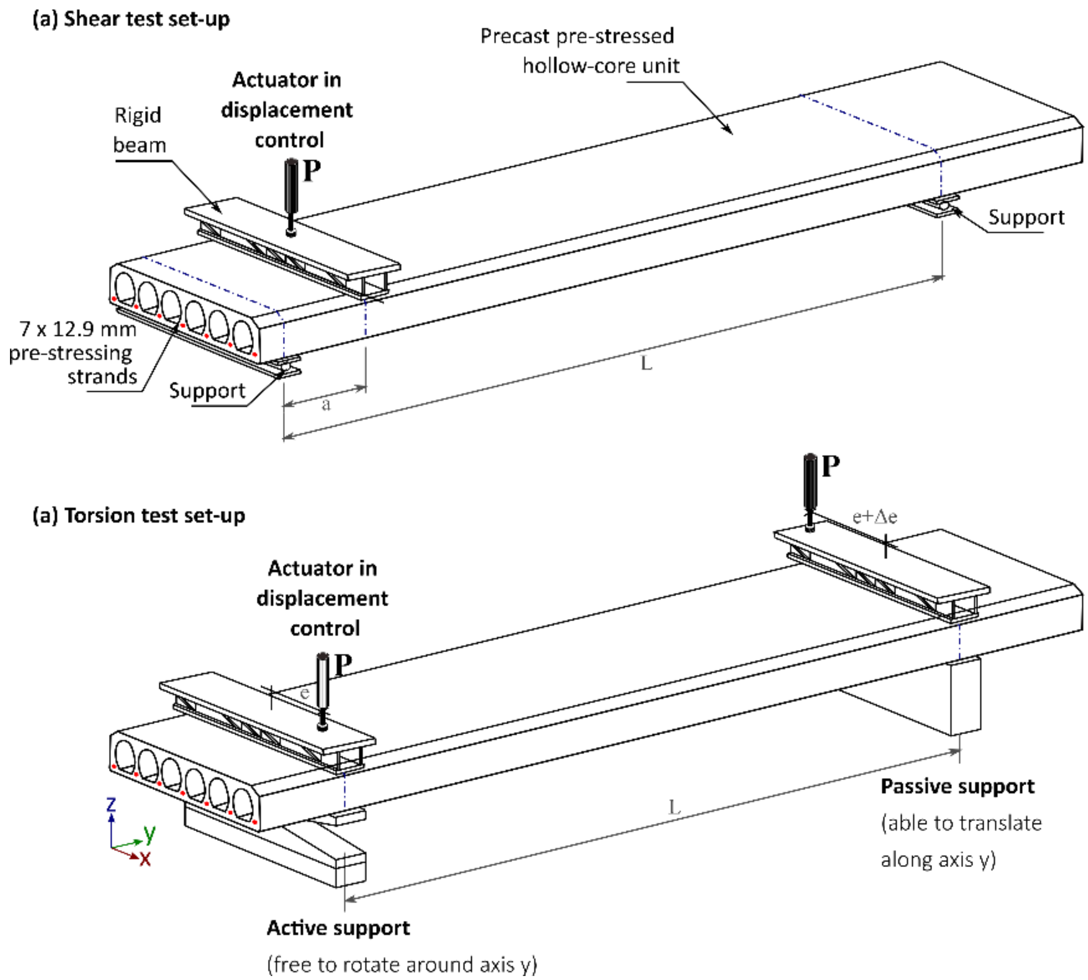

Figure 1. Illustration of the test set-up used for the PPHC slabs failing in shear and torsion.

Table 1. Summary of experimental test results on bare PPHC units employed for the validation of the FE model developed.

Test ID	Slab depth H (mm)	Span length L (mm)	Shear span a (mm)	Eccentricity of the applied load e (mm)	Failure mode	Reference
1.5H-A	200	4000	300	0	Web-shear	[6]
1.5H-B	200	4000	300	0	Web-shear	
2.5H-A	200	4000	500	0	Web-shear	
2.5H-B	200	4000	500	0	Web-shear	
3.5H-A	200	4000	700	0	Flexure-shear	
3.5H-B	200	4000	700	0	Flexure-shear	
PT200A	200	4000	0	300	Pure torsion	[10]
PT200B	200	4000	0	300	Pure torsion	
ST200C	200	7000	0	0	Web-shear	[11]
ST200E1a	200	7000	500	187	Shear-torsion	
ST200E1b	200	7000	500	187	Shear-torsion	
ST200E2	200	7000	500	384	Shear-torsion	

Modelling strategy

Different FE modelling and analysis trials have been undertaken using the software Midas FEA [12], which allows both mechanical and geometrical non-linearity to be considered. The FE modelling approach has been first developed by the authors to study PPHC slabs failing in shear [13], calibrated against full-scale three-point bending tests [6], and then extended to study the effect of torque and twist in the slabs [14] and the effect of bending moments in the slab-to-beam seating connections [15].

Table 2 summarizes the key parameters used for the definition of the FE model. The total strain crack model, developed along the lines of the modified compression field theory, originally proposed by Vecchio and Collins [16], and then extended to the three-dimensional case by Selby & Vecchio [17], was adopted to allow the development of the brittle failure mechanisms. The Hordijk model [18], [19] and the Thorenfeldt [20] model were adopted to define the uniaxial tensile and compressive behavior of the concrete, respectively.

The concrete has been modelled via 6-node solid/brick elements (see Figure 2), whereas the pre-stressing strands are represented as embedded line elements. No interface elements were introduced to represent the strands-concrete interaction, since it is implicitly captured by an equivalent parabolic pre-stress distribution

Table 2. Key modelling parameters employed in the FE modelling studies of PPHC slabs.

	Parameter	**Set value**
Mesh (see Figure 2)	Element type:	6-node brick elements
	Cross-sectional size, x/z (mm):	15
	Extrusion size, y (mm):	30
Loading	Type of vertical loading:	Displacement
	Loading rate (mm/step):	0.02
Convergence criteria	Iteration scheme:	Newton-Raphson
	Energy norm:	5x10-3
Constitutive model concrete	Smeared crack model:	Rotating
	Tensile behaviour:	Hordijk [18]
	Compressive behaviour:	Thorenfeldt [20]

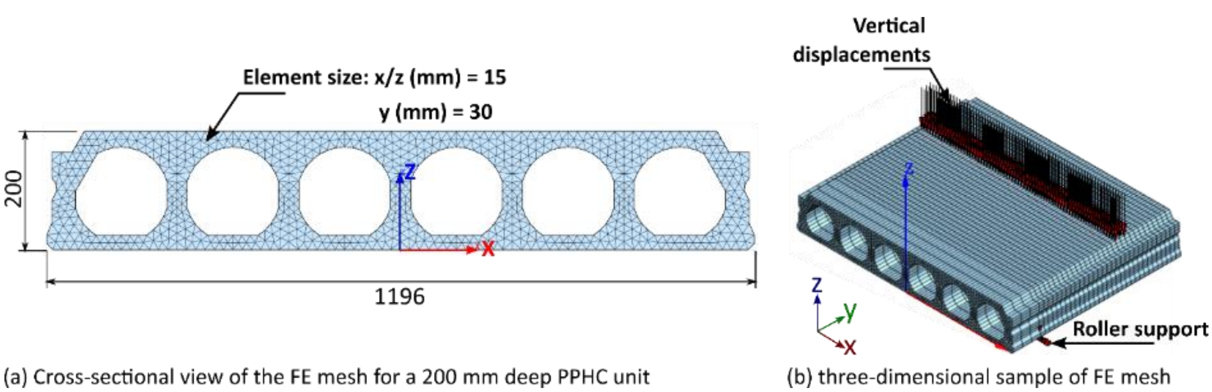

Figure 2. Mesh example of detailed solid FE model developed.

Material model and calibration

Care must be taken to identify and specify suitable material properties for the analyses, as research has found that common design values are not suitable [6]. Table 3 summarizes the material properties finally employed for the modelling of PPHC slabs. The mean compressive strength f_c, and the modulus of rupture f_r, of the hollow-core extruded concrete were obtained through material characterization testing [6]. The fracture energy G_f and the crack bandwidth h, required to define the tensile behavior of the concrete, were deterministically estimated following the equations shown in Table 3.

The stress in the pre-stressing strands can be represented as an equivalent parabolic pre-stress distribution, according to the work presented by Yang [23], where the strand stress is postulated to be zero at the free ends of the slabs and to achieve the full effective stress at the end of the transfer length of the strands. Final pre-stressing, after losses, as well as the corresponding transfer length to be used in the finite element model can be calculated according to NZS3101:2006-A3 [24].

Table 3. Summary of recommended material properties

	Parameter	Set value	Reference
Extruded concrete	Compressive strength, f_c (MPa)	60.5	Mean value from material testing [6]
	Modulus of rupture, f_r (MPa)	6.5	Mean value from material testing [6]
	Tensile fracture energy, G_f (N/mm)	0.16	$G_f = 73 f_c{}^{0.18}$ [21]
	Crack bandwidth, h (mm)	25	$h = 2.1 d_{agg}$ [22] d_{agg} = maximum aggregate size
Pre-stressing strands	Pre-stress losses	12%	Estimated according to NZS 3101:2006-A3 [24]
	Transfer length strands (mm)	635	Estimated as $50d_b$ based on NZS 3101:2006-A3 (SNZ, 2017)
	Anchorage slip (mm)	2	[25]
	Pre-stress distribution	Parabolic	[23]

The manufacturing process of extruded hollow-core slabs makes use of a dry concrete mix capable of meeting specific requirements such as instantaneous ability to maintain the required shape without any formwork, and to assure high early strength of the concrete and low rheological strain. The consistency of this dry mix makes it difficult to obtain cylinders to determine the compressive and tensile strength of the extruded hollow-core concrete. Furthermore, the presence of thin-walled elements on PPHC slabs, which at the width of their cross-section can include only a few coarse aggregate grains, might cause a significant difference between the real strength of concrete and the value given by standards for the corresponding concrete class [26]. Hence, it is important to note that the values observed for the compressive strength of the concrete and the modulus of rupture are significantly higher than design values for the same concrete class. Thus, if design values were adopted (fc = 45MPa and associated modulus of rupture), the shear capacity of the slabs would be significantly underestimated.

MODEL VALIDATION AND RESULTS

Unit model: shear and torsional response

The adopted modelling strategy (i.e. the FE models developed in line with the assumptions in Table 2 and the material characteristics listed in Table 3) was found to provide a consistent match with experimental test results for PPHC slabs failing in web-shear or flexure-shear. Figure 3 shows the comparison between the experimentally traced crack pattern and the principal tensile stress distribution and predicted crack pattern at failure. Numerical results are in close agreement with the damage mechanism experimentally observed (Figure 3). In both cases, an inclined crack emerges from both principal tensile strains and numerical crack patterns. Simultaneously, an inclined compressive diagonal strut develops, resulting in diagonal cracking and the failure mode that finally occurs, which resulted in a cut-off in the shear stress flow. Figure 5a shows the shear displacement response for specimens 1.5H-A and 1.5H-B (refer to Table 1) and compares it against the numerically predicted curve. The numerical curve reveals a good match with the test results and adequately simulates the brittle shear failure of the slabs. Numerical failure is assumed to happen in correspondence with two criteria: the attainment of a strain limit value in concrete, 0.003, and a drop on the shear capacity of at least 20% (which in many cases was accompanied by non-convergence of the model).

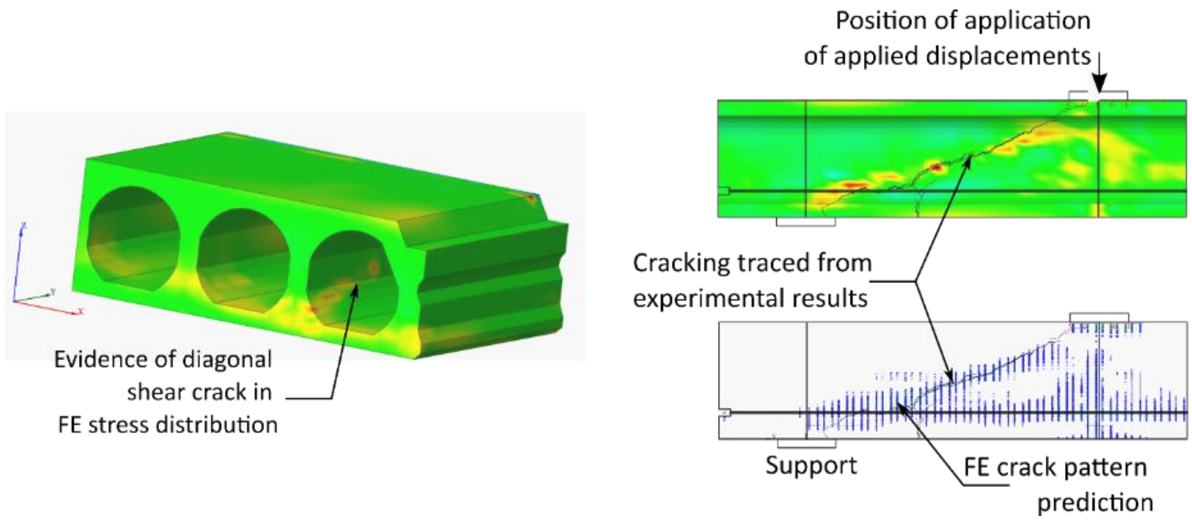

Figure 3. Principal tensile stress distribution and predicted crack pattern for a 200 mm deep PPHC unit failing in shear (the experimental testing is described in [6]*).*

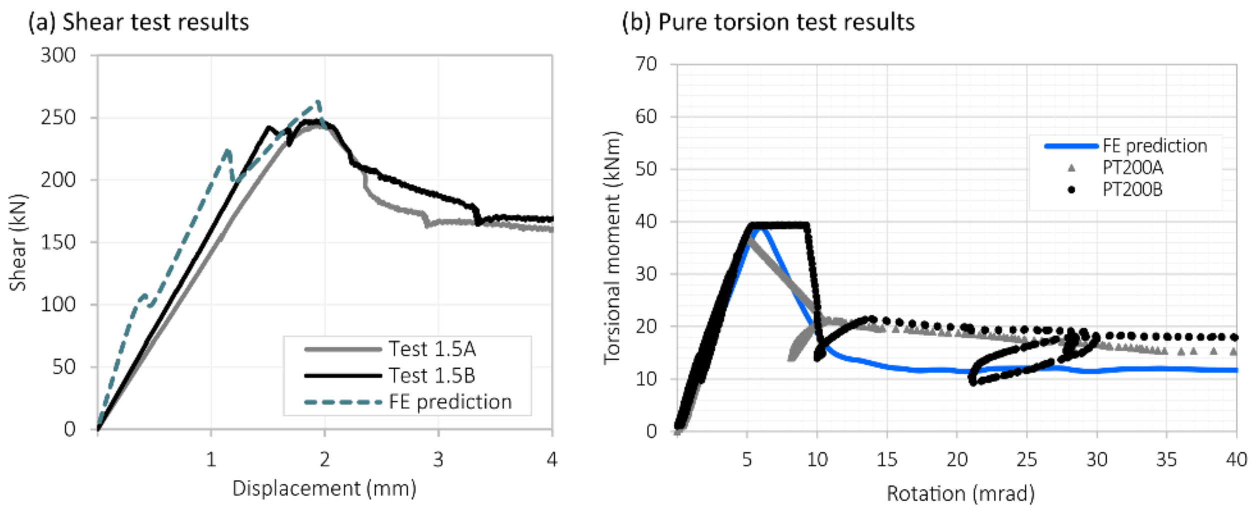

Figure 4. Comparison of numerical and experimental results: (a) shear displacement curve (specimens 1.5H-A and 1.5H-B); and (b) torque and relative angle of twist (specimens PT200A and PT200B).

The proposed FE modelling strategy was then validated for the cases of pure torsion and shear torsion interaction. Figure 4b presents the torque versus rotation relationship observed for specimens PT200A and PT200B. The FE model provided a reasonable approximation of the initial torsional stiffness, peak torsional moment and rotation, and overall response of the PPHC slabs. Figure 5 provides a comparison of the principal tensile stresses on the PPHC unit at failure due to pure torsion. The numerical observations show that the cross-sectional deformations in PPHC slabs under torsion are three-dimensional and that the flow of shear stresses around the perimeter of the cross-section is non-uniform. Results have shown that the proposed FE modelling approach was able to capture the elastic response of the PPHC slabs and torsional cracking, as well as the nonlinear behavior of the slabs at higher displacement demands.

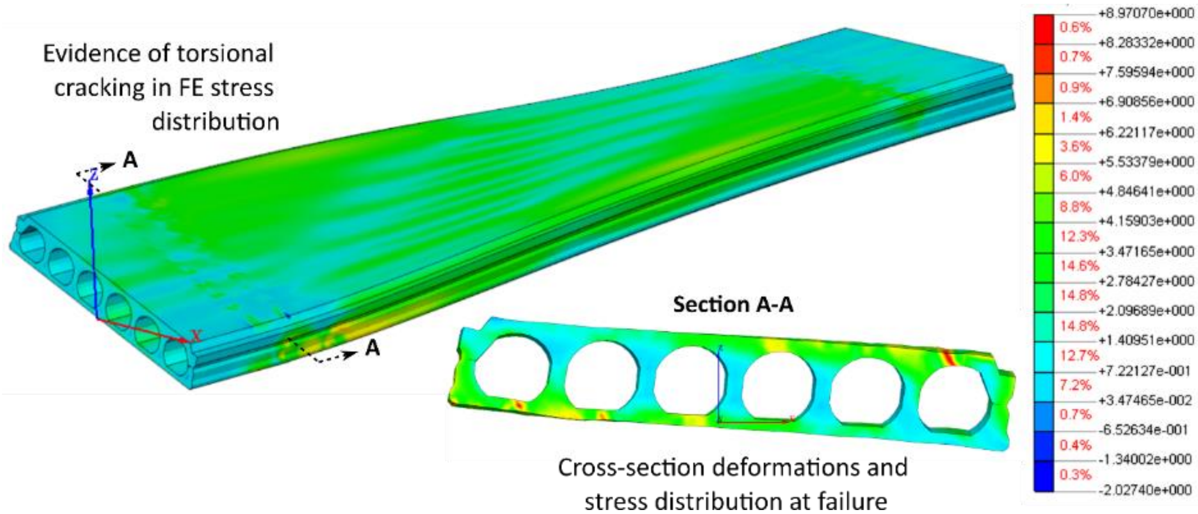

Figure 5. Principal tensile stress distribution for a 200 mm deep PPHC unit failing in pure torsion.

Influence of key parameters

A detailed sensitivity study was conducted to determine the relative significance of each modelling parameter on the numerical predictions of the strength and deformation capacity. For this purpose, uncertain variables grouped into three main features of the FE model were selected: the size of the solid element mesh, the material properties and the modelling approach. It is observed that the modulus of rupture and the crack bandwidth of the concrete and the cross-sectional size of the solid mesh element are the most important variables to be considered in reliability studies [13].

Figure 6 graphically shows the impact of varying the most significant modelling parameters on the force-displacement response of the PPHC slabs in shear. The three plots show the FE predictions for a 200 mm deep PPHC unit with a shear span of 300 mm. The solid black lines show the results from the model with the recommended parameters and material properties shown in Table 2 and Table 3 respectively. The dashed blue and orange lines show alternative values for the modulus of rupture, crack bandwidth and mesh size tested during the sensitivity analysis. It can be observed that varying the modulus of rupture of the concrete resulted in greater variations in the shear strength and deformation capacity predictions.

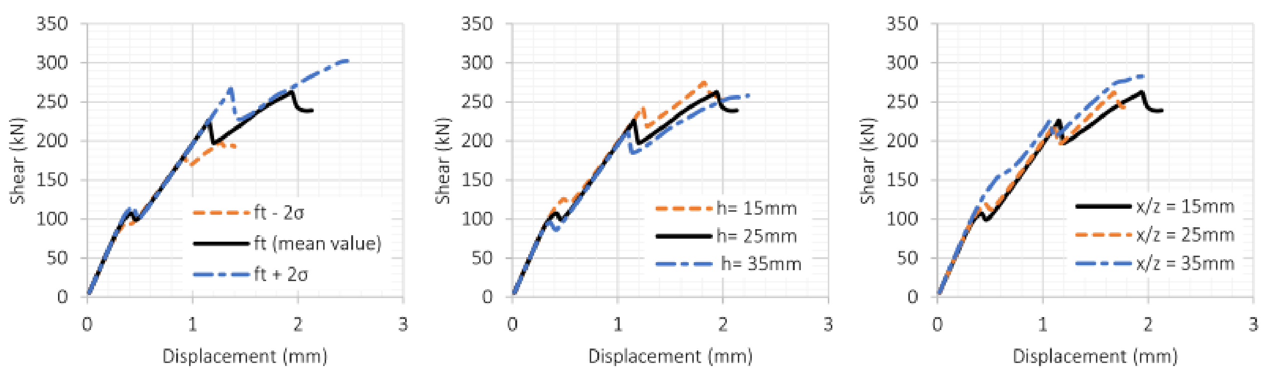

Figure 6. Impact of most significant modelling parameters on the force-displacement response: (left) modulus of rupture, (center) crack bandwidth, and (right) mesh size.

Sub-assembly model applications

In seismic areas, the upper surface of precast slabs is usually covered with a cast-in-situ concrete topping to enhance the strength and stiffness of the floor and its structural performance under lateral loads [4]. So, even if PPHC slabs are commonly designed as simply supported members, the presence of the concrete topping and reinforcement prompts continuity between the units and the supporting structure. Consequently, during an earthquake, significant bending moments can be induced in the PPHC units, close to the supports. Recent research efforts have also been looking to expand the proposed FE modelling strategy to consider the effect of these bending moments on the seismic performance of PPHC floor-to-beam seating connections, or PPHC sub-assemblies [15].

A model has been initially calibrated against existing test data to predict the failure of a PPHC slab under negative bending moments. Figure 7 shows the principal tensile stresses and predicted crack pattern against the cracking traced from the experimental testing conducted by [27]. When rotations were induced in the PPHC connection, cracks appeared at the end of the starter bars, at the top of the slab, and then propagated vertically down the webs of the hollow-core unit before extending horizontally at the top of the bottom flange of the unit, forming a full negative moment failure (NMF) mechanism at less than 1% drift. The FE analysis results obtained allow the moment-drift response, principal tensile stresses, and crack progression during loading to be compared. It is apparent from Figure 7 that good correlation was observed between the FE model predictions and the experimental crack patterns.

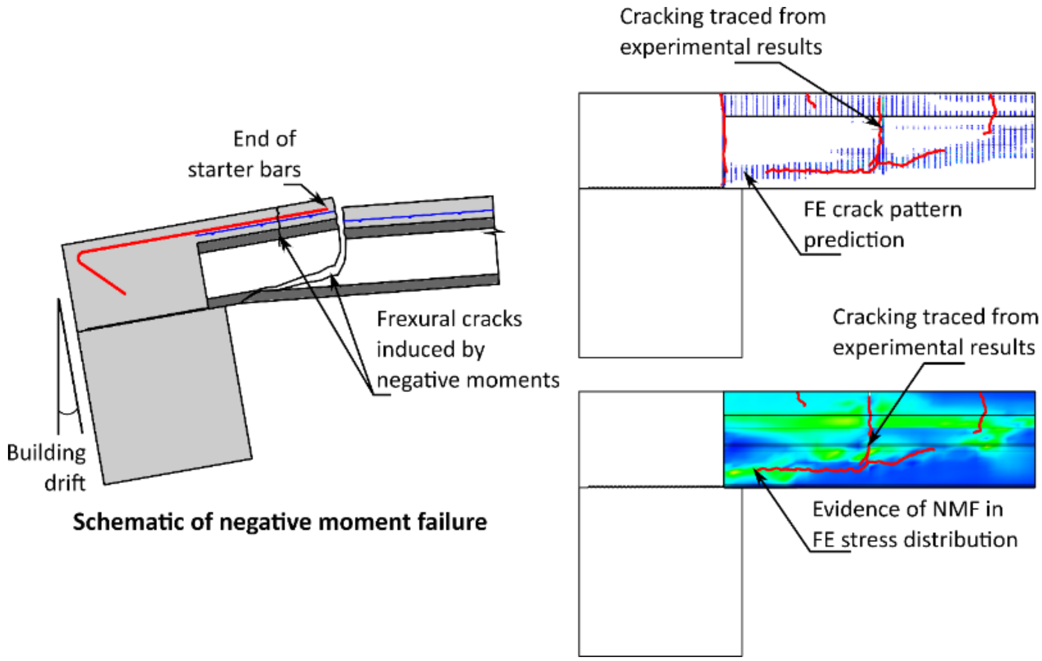

Figure 7. Preliminary results into the modelling of PPHC sub-assemblies

The FE modelling approach developed to date should permit future studies to exhaustively investigate all aspects of precast floor behavior by varying the properties and geometry of PPHC seating connections. This work also illustrates the potential value of the FE modelling and analysis approach in gauging the impact of retrofit efforts for precast hollow-core flooring systems.

CONCLUSIONS

This paper summarizes the key modelling criteria employed for the FE modelling of PPHC floors. A detailed nonlinear FE modelling strategy has been developed to represent the behavior of PPHC slabs under imposed deformations. The model has been calibrated against experimental data, and then used to undertake parametric studies by varying the dimensions, properties, loading conditions, and other aspects of the FE model. Results show that the model successfully predicts the PPHC floor brittle failure mechanisms. The following recommendations and conclusions can be drawn from the results presented:

- The reliability of FE modelling predictions can be greatly affected by the modelling assumptions made and the diverse user-defined input variables.
- The developed FE model can capture the damage patterns associated with the shear-deflection and twist-torque response of PPHC slabs. Results suggest that the FE model is capable of predicting the capacity of PPHC slabs with and without eccentricity.

- Sensitivity analysis results reveal that the modulus of rupture and the crack bandwidth of the concrete and cross-sectional size of the solid element mesh, are the most important variables that need to be considered in reliability studies of PPHC slabs.
- The modulus of rupture of the concrete plays a dominant role in the strength and deformation capacity of the PPHC slabs, in particular, for brittle fracture mechanics.
- It is recommended that characterization of the extruded concrete properties be carefully identified (e.g. through experimental testing) and defined since actual values (obtained from experimental testing) can be significantly higher than nominal design values, and capacity predictions of PPHC slabs are greatly affected by the properties adopted.
- An apparent post-peak capacity has been observed in the shear and torsion tests examined in this research. This post-peak capacity has been attributed largely to the bond behavior of the strands. The FE model developed is unable to fully capture the post-peak behavior observed during the tests, in particular, for the highly brittle web-shear failures. Further research is needed into capturing the complex bond properties of the prestressing strands into the modelling approach suggested.

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REFERENCES

[1] R. Park, "Seismic design and construction of precast concrete buildings in New Zealand," *PCI J.*, vol. 47, no. 5, pp. 60–75, 2002.

[2] A. Puranam *et al.*, "A detailed inventory of medium-to high-rise buildings in Wellington's central business district," *Bull. New Zeal. Soc. Earthq. Eng.*, vol. 52, no. 4, pp. 172–192, 2019, doi: 10.5459/BNZSEE.52.4.172-192.

[3] S. R. Corney, A. Y. Puranam, K. J. Elwood, R. S. Henry, and D. Bull, "Seismic Performance of Precast Hollow-Core Floors: Part 1—Experimental Data," *ACI Struct. J.*, no. 118, pp. 49–63, 2021, doi: 10.14359/51732821.

[4] R. Fenwick, D. Bull, and D. Gardiner, *Assessment of hollow-core floors for seismic performance*, vol. 2010–02.;2. Christchurch, New Zealand: Department of Civil and Natural Resources Engineering, University of Canterbury, 2010.

[5] R. S. Henry, D. Dizhur, K. J. Elwood, J. Hare, and D. Brunsdon, "Damage to concrete buildings with precast floors during the 2016 Kaikoura earthquake," *Bull. New Zeal. Soc. Earthq. Eng.*, 2017, doi: 10.5459/bnzsee.50.2.174-186.

[6] A. I. Sarkis, F. Bueker, T. J. Sullivan, K. J. Elwood, E. Brunesi, and L. Hogan, "Aspects affecting the nonlinear behavior of precast pre-stressed hollow-core units failing in shear," *Struct. Concr.*, 2022, doi: 10.1002/suco.202100579.

[7] S. Corney, R. Henry, and J. Ingham, "Performance of precast concrete floor systems during the 2010/2011 Canterbury earthquake series," *Mag. Concr. Res.*, vol. 66, no. 11, pp. 563–575, 2014, doi: 10.1680/macr.13.00106.

[8] M. Cubrinovski *et al.*, "Wellington's earthquake resilience: Lessons from the 2016 Kaikōura earthquake," *Earthq. Spectra*, vol. 36, no. 3, pp. 1448–1484, 2020, doi: 10.1177/8755293020919426.

[9] N. Brooke *et al.*, "ReCast Floors - Seismic assessment and improvement of existing precast concrete floors," *SESOC J.*, vol. 32, no. 1, 2019.

[10] M. Pajari, "Pure torsion tests on single hollow core slabs," Finland, 2004.

[11] M. Pajari, "Shear-torsion interaction tests on single hollow core slabs," Finland, 2004.

[12] MIDAS Information Technology, "Midas FEA: Advanced Nonlinear and Detail Analysis System." 2016, [Online]. Available: https://www.cspfea.net/prodotti/midas-fea-nx/.

[13] A. I. Sarkis, T. J. Sullivan, E. Brunesi, and R. Nascimbene, "Critical modelling criteria for precast pre-stressed hollow-core slabs," *J. Build. Eng.*, vol. 54, p. 104545, Aug. 2022, doi: 10.1016/j.jobe.2022.104545.

[14] A. I. Sarkis, T. J. Sullivan, E. Brunesi, and R. Nascimbene, "Assessment of the torsional behavior of hollow-core slabs," *Bull. New Zeal. Soc. Earthq. Eng.*, 2023, doi: https://doi.org/10.5459/bnzsee.1572.

[15] A. I. Sarkis, T. J. Sullivan, E. Brunesi, and R. Nascimbene, "Investigating the Effect of Bending on the Seismic Performance of Hollow-Core Flooring," *Int. J. Concr. Struct. Mater.*, vol. 17, no. 1, p. 18, 2023.

[16] F. J. Vecchio and M. P. Collins, "The modified compression-field theory for reinforced concrete elements subjected to shear," *ACI J.*, vol. 83, no. 2, pp. 219–231, 1986.

[17] R. G. Selby and F. J. Vecchio, "3D constitutive relations for reinforced concrete," Tech, Rep. 93-02, Department of Civil Engineering, Toronto, Canada, 1993.

[18] D. A. Hordijk, "Tensile and tensile fatigue behaviour of concrete; experiments, modelling and analyses," *Heron*, vol. 37, no. 1. pp. 1–79, 1992.

[19] H. A. W. Cornelissen, D. A. Hordijk, and H. W. Reinhardt, "Experimental determination of crack softening characteristics of normalweight and lightweight," *Heron*, vol. 31, no. 2, p. 45, 1986, [Online]. Available: internal-pdf://233.232.80.233/Hordijk_Model.pdf.

[20] E. Thorenfeldt, "Mechanical properties of high-strength concrete and applications in design," 1987.

[21] S. Federation internationale du beton, "fib model code for concrete structures 2010." Ernst & Sohn, a Wiley brand, Lausanne, Switzerland, 2013, doi: 10.1002/9783433604090.

[22] L. J. Malvar and M. E. Fourney, "A three dimensional application of the smeared crack approach," *Eng. Fract. Mech.*, vol. 35, no. 1–3, pp. 251–260, 1990, doi: 10.1016/0013-7944(90)90203-S.

[23] L. Yang, "Design of prestressed hollow core slabs with reference to web shear failure," *J. Struct. Eng.*, vol. 120, no. 9, pp. 2675–2696, 1994.

[24] NZS3101, *Concrete structures standard. Part 1: The design of concrete structures*. 2006.

[25] M. D. Brooks, K. H. Gerstle, and D. R. Logan, "Effect of initial strand slip on the strength of hollow-core slabs," *PCI J.*, vol. 33, no. 1, pp. 90–111, 1988.

[26] K. Flaga, W. Derkowski, and M. Surma, "Concrete strength and elasticity of precast thin-walled elements," *Red. Cem. Wapno Bet.*, pp. 310–317, 2016.

[27] F. Bueker, N. Brooke, K. J. Elwood, D. K. Bull, L. Hogan, and M. Parr, "Development and validation of retrofit techniques for hollow-core floors," 2021.