STRATEGIES FOR FINITE ELEMENT MODELLING OF PRECAST PRE-STRESSED HOLLOW-CORE FLOORS

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ABSTRACT

As part of the ReCast research programme, research has been undertaken to develop a finite element (FE) modelling approach for precast pre-stressed hollowcare (PPHC) floors. This paper summarises the modelling criteria that is considered key to analysing the behavior of PPHC floors. Comparisons of the numerical predictions with experimental results show that the proposed model is capable of capturing shear and torsional failure mechanisms. Lastly, advances towards a sub-assembly model, developed to investigate the bending behavior of PPHC slab-to-beam connections, are presented. The results indicate that the numerical approach is promising and should be developed further as part of future

1 INTRODUCTION

Extruded precast pre-stressed hollow-core (PPHC) units contain no transverse or vertical reinforcement and, given that their cross-sections contain large voids, are inherently vulnerable to brittle failure modes such as web cracking (Broo et al., 2005; Fenwick et al., 2010). Numerical and experimental research efforts have investigated the shear and torque behavior of PPHC slabs. Several previous studies have provided numerical predictions of the shear and bending behaviour of PPHC slabs at ultimate conditions based on finite element (FE) approaches, calibrated to experimental test results (Brunesi et al., 2015; Brunesi & Nascimbene, 2015; Michelini et al., 2020; Nguyen et al., 2019; Pachalla & Prakash, 2018). In addition, Pajari (2004b, 2004a) experimentally assessed the torsional behaviour of un-topped PPHC slabs under eccentric loading. The results from this experimental programme were then used by Broo et al. (2005, 2007) to numerically evaluate the shear-torsion interaction behavior in PPHC units.

While past research efforts have comprehensively studied the behaviour of PPHC slabs under gravity loads, research into the seismic performance of the slabs and the damage induced by imposed deformation demands is limited. There appears to be a need for assessment methodologies that provide estimates of the deformation capacity of the PPHC slabs. To this extent assessment methods based on numerical analysis could be useful, as it would be impractical to exhaustively investigate all aspects of precast floor behaviour in a laboratory given the expense and time required for physical testing and the difficulty of tightly controlling the properties of reinforced concrete test specimens.

As part of the ReCast research programme, research has been undertaken to test and develop finite element (FE) modelling techniques for PPHC floors. The work presented herein aims to summarise 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. 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.

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2 FINITE ELEMENT MODELLING OF PPHC UNITS

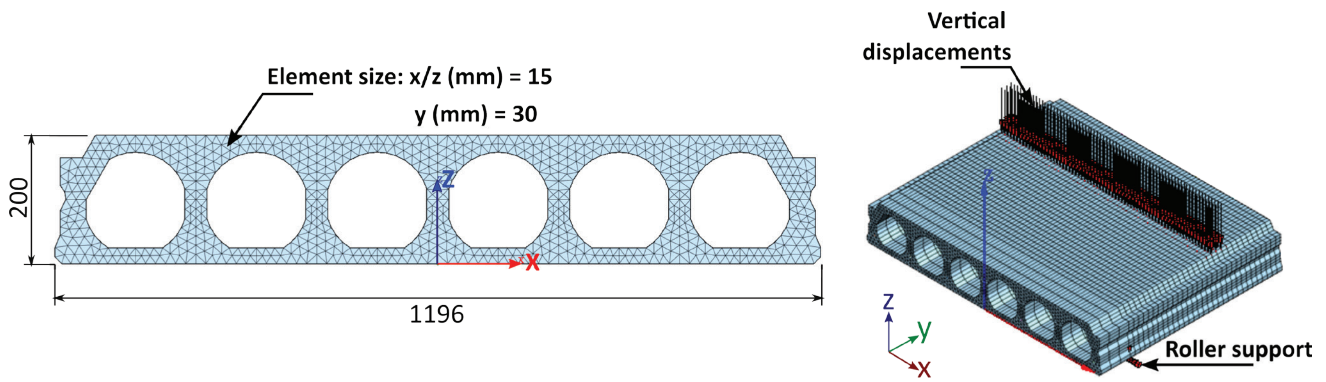
2.1 MODELLING STRATEGY

Different FE modelling and analysis trials have been undertaken using the software Midas FEA (MIDAS Information Technology, 2016), which allows both mechanical and geometrical non-linearity to be considered. 200mm deep cross-sections were considered with mean material properties typically used in New Zealand buildings. The FE modelling approach has been first developed by the authors to study PPHC slabs failing in shear (Sarkis et al., 2022b), calibrated against full-scale three-point bending tests (Sarkis et al., 2022), and then extended to study the effect of torque and twist (Sarkis et al., 2022a; Sarkis & Sullivan, 2021).

Table 1 summarises the key parameters used for the definition of the FE model. The constitutive model assumed for the concrete is the smeared total strain crack model (Selby & Vecchio, 1993; Vecchio & Collins, 1986). The Hordijk model (Hordijk, 1992; Reinhardt et al., 1986) and the Thorenfeldt (1987) model were adopted to define the uniaxial tensile and compressive behaviour of the concrete, respectively. The concrete has been modelled via three-dimensional solid/brick elements (see Figure 1), whereas the pre-stressing strands are represented as embedded line elements

Table 1: Key modelling parameters employed in the FE modelling studies of PPHC slabs.

	Parameter	Set value
Mesh (see Figure 1)	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 (1992)
	Compressive behaviour:	Thorenfeldt (1987)



(a) Cross-sectional view of the FE mesh for a 200 mm deep PPHC unit

(b) three-dimensional sample of FE mesh

Figure 1: Mesh example of detailed solid FE model developed

2.2 MATERIAL PROPERTIES

Care must be taken to identify and specify suitable material properties for the analyses as the research found that common design values are not suitable. Table 2 summarises 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 characterisation testing (Sarkis et al., 2022). Note that the values observed are significantly higher than design values and if design values were adopted (f_c = 45MPa and associated modulus of rupture) the shear capacity of the slabs would be significantly underestimated. The fracture energy G_f and the crack bandwidth h, required to define the tensile behaviour of the concrete, were deterministically estimated as shown in Equations 1 and 2 (Fib, 2013; Malvar & Fourney, 1990):

$$G_f = 73 f_c^{\,0.18} \quad (1)$$

$$h = 2.1 d_{agg} \quad (2)$$

where d_{agg} is the maximum aggregate size in mm

The stress in the pre-stressing strands can be represented as an equivalent parabolic pre-stress distribution, according to the work presented by Yang (1994), 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 (SNZ, 2017).

3 RESULTS

3.1 FINITE ELEMENT MODEL RESULTS

The adopted modelling strategy (i.e. the FE models developed in line with the assumptions in Table 1 and the material characteristics listed in Table 2) was found to provide a consistent match with experimental test results for PPHC slabs failing in shear. The principal tensile stress distribution and predicted crack pattern at failure are in close agreement with the damage mechanism experimentally observed (Figure 2). 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.

The proposed FE modelling strategy was able to capture the elastic response of the PPHC slabs and torsional cracking, as well as the nonlinear behaviour of the slabs at higher displacement demands. Figure 3 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.

3.2 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. 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 (Sarkis et al., 2022b).

Table 2: Summary of recommended material properties

	Parameter	Set value	Reference
Extruded concrete	Compressive strength, f_c (MPa)	60.5	Mean value from material testing (Sarkis et al., 2022)
	Modulus of rupture, f_r (MPa)	6.5	Mean value from material testing (Sarkis et al., 2022)
	Tensile fracture energy, G_f (N/mm)	0.16	(Fib, 2013)
	Crack bandwidth, h (mm)	25	(Malvar & Fourney, 1990)
Pre-stressing strands	Pre-stress losses	12%	Estimated according to NZS 3101:2006-A3 (SNZ, 2017)
	Transfer length strands (mm)	635	Estimated as 50db based on NZS 3101:2006-A3 (SNZ, 2017)
	Anchorage slip (mm)	2	(Brooks et al., 1988)
	Pre-stress distribution	Parabolic	(Yang, 1994)

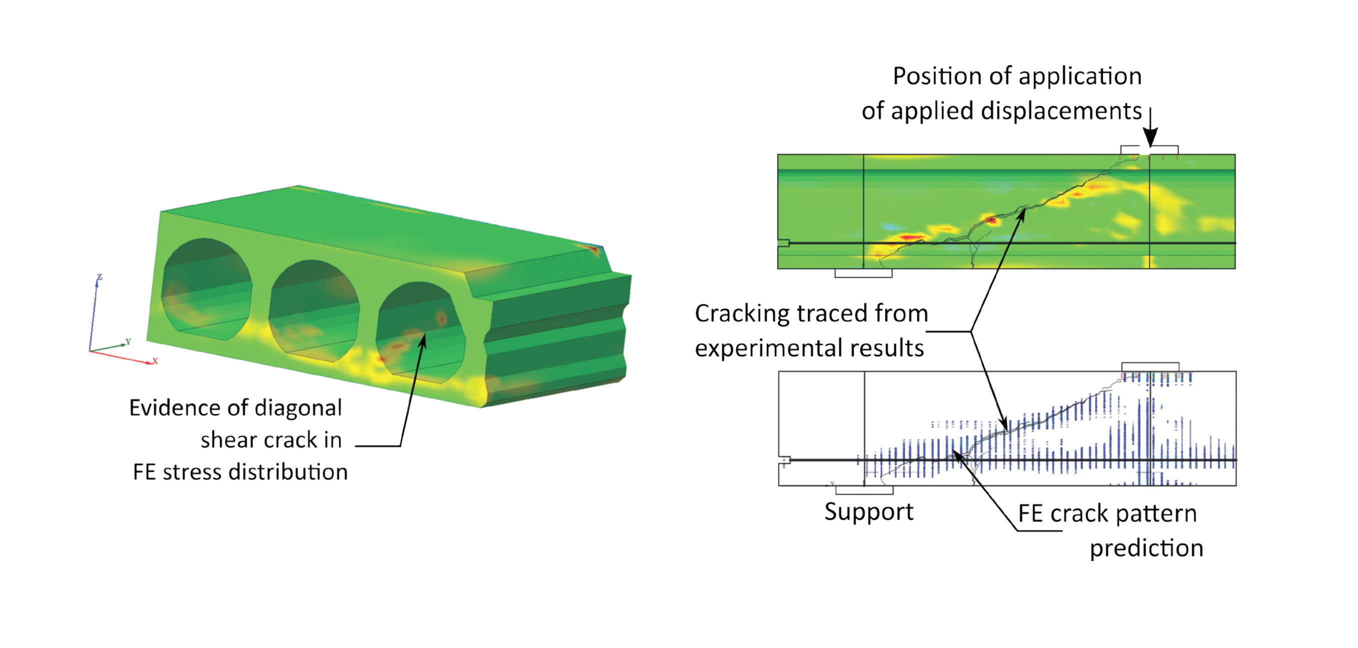


Figure 2: Principal tensile stress distribution and predicted crack pattern for a 200 mm deep PPHC unit failing in shear (the experimental testing is described in Sarkis et al. (2022)).

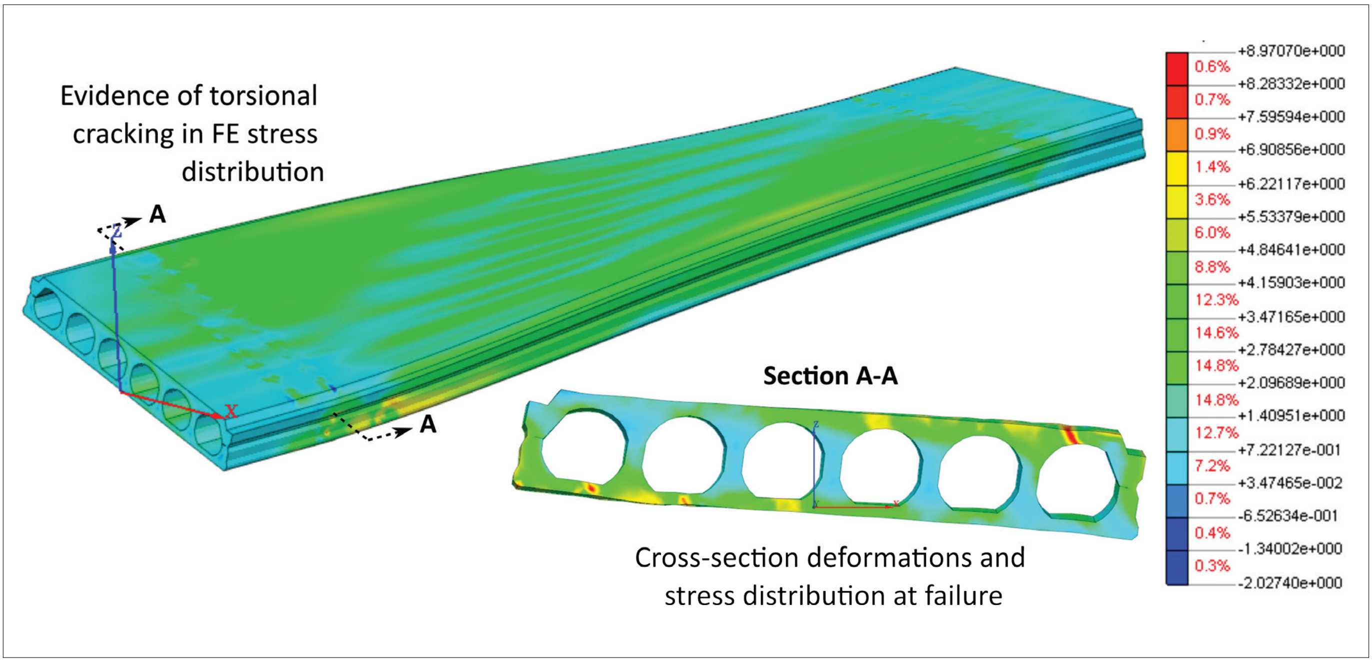


Figure 3: Principal tensile stress distribution for a 200 mm deep PPHC unit failing in pure torsion.

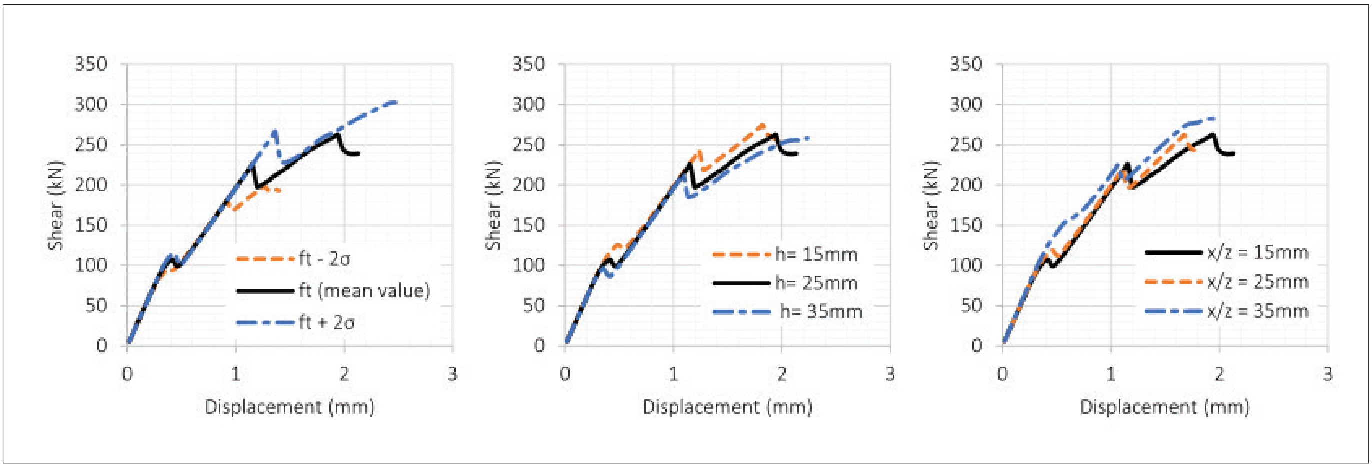


Figure 4: Impact of most significant modelling parameters on the force-displacement response: (left) modulus of rupture, (centre) crack bandwidth, and (right) mesh size.

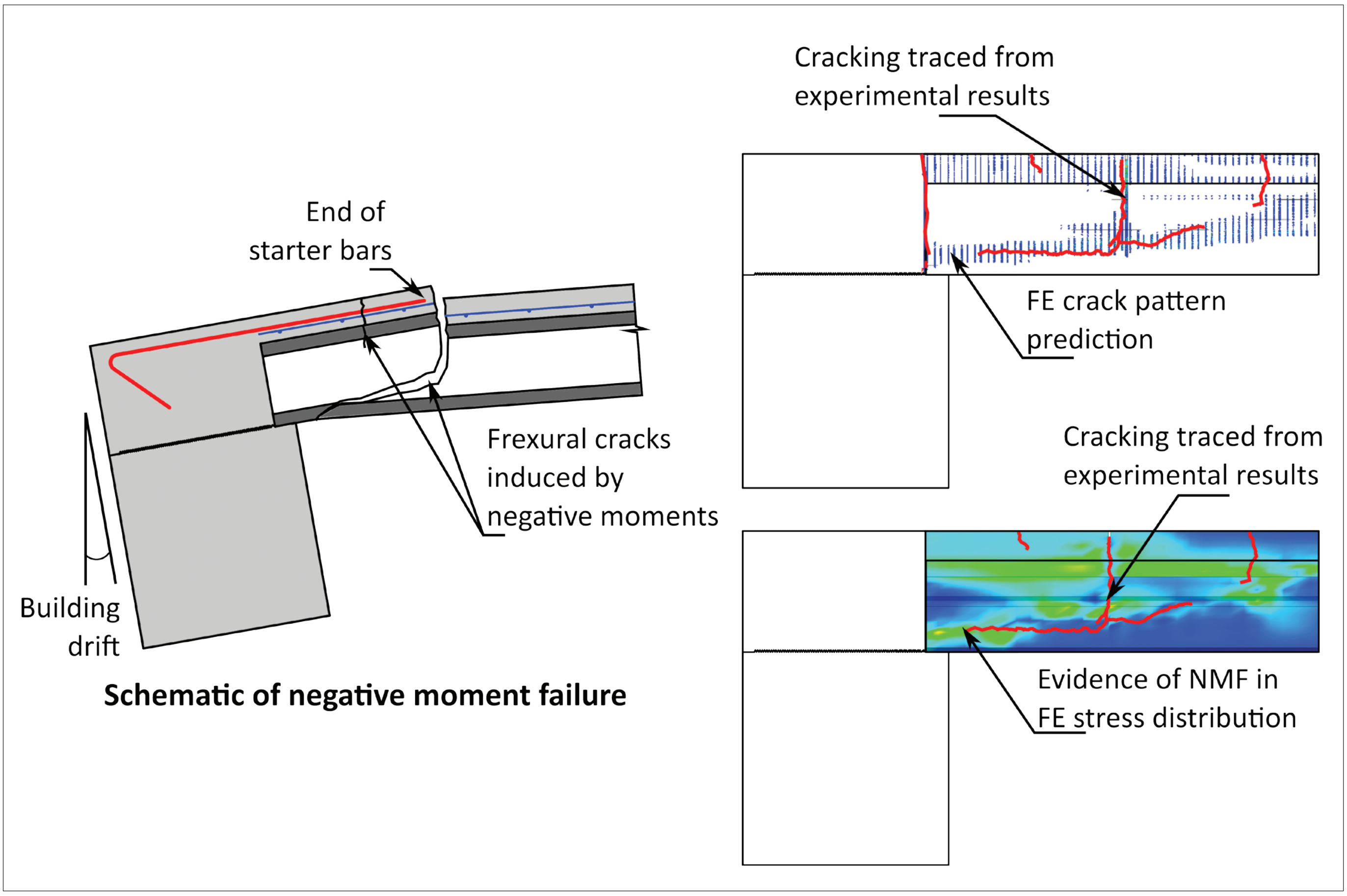


Figure 5: Preliminary results into the modelling of PPHC sub-assemblies

Figure 4 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 1 and Table 2 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.

3.3 TOWARDS A SUB-ASSEMBLY MODEL

Recent research efforts have also been looking to expand the proposed FE modelling strategy to consider the effect of bending moments on the seismic performance of PPHC floor-to-beam seating connections, or PPHC sub-assemblies. A model has been initially calibrated against existing test data to predict the failure of a PPHC slab under negative bending moments. Figure 5 shows the principal tensile stresses and predicted crack pattern against the cracking traced from the experimental testing conducted by Bueker, 2023.

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 5 that good correlation was observed between the FE model predictions and the experimental crack patterns.

The FE modelling approach developed to date should permit future studies to exhaustively investigate all aspects of precast floor behaviour 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.

4 CONCLUSIONS AND RECOMMENDATIONS

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.

This paper summarises the key modelling criteria employed for the FE modelling of PPHC floors. 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.
- 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 characterisation 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.

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