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# Structural Performance Assessment of Pace Modular Precast Slab Structure Systems

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**Abstract:** PACE building technology is an accelerated construction system involving prefabricated modular reinforced concrete elements of regular size, shape, and geometry, which are fabricated off-site and adjoined on-site using post-tensioned tendons. Due to the modularity and prefabrication of the building components, reductions in terms of project costs, construction times, and material requirements are achievable. Field experiences involving similar systems have demonstrated outstanding structural performance, making them a viable off-site construction alternative to cast-in-place slab systems employed in North America. However, the detailing of these modular connections is atypical to common building practice in that they rely on friction for transferring forces at connection interfaces. This paper presents numerical results from a series of nonlinear finite element analyses done to characterize modular connection gravity load resisting performance, lateral load/deformation resistance, and influences associated with connection detailing parameters. It was found that the friction-based connections do not control the gravity load resisting performance of the modular slab system. Under lateral loading scenarios that would arise from ground motions, the connections comprising the PACE system were estimated to provide sustained gravity load resistances that meet existing codified requirements. The system was also analyzed under extreme tendon loss (i.e., fault) conditions and comparatively assessed with more conventional reinforced concrete flat plate construction. It was shown that the connections provide redundancy to accommodate fault scenarios and are also highly efficient in terms of their load carrying capabilities. In comparison to conventional flat plates, the modular system was estimated to provide greater gravity load resistance, while utilizing significantly less concrete.

**Keywords:** Prefabrication; Modular construction; Buildings; FEA; Modelling

## 1 INTRODUCTION

### 1.1 Background

PACE™, or Pre-engineered Accelerated Construction Envelope (PACE) building systems employ precast concrete elements that are assembled on-site and connected by way of external post-tensioning, with most of the structural components comprising PACE systems being fabricated off-site. Originally developed in the 1950s at the Institute for Testing Materials, in former Yugoslavia (Petrovic 1978), post-tensioned modular two-way slab systems have been used in numerous buildings constructed throughout the world (Pessiki et al. 1995a). Reported benefits obtained from the application of these modular construction systems include 1) reduced building costs and construction periods, 2) improved space-planning capabilities and expanded possibilities for building interior design as compared to traditional concrete building system, 3) optimized use of steel and concrete construction materials, and 4) increased building durability.

The specific system considered herein consists of precast slab, column, and beam modules that are adjoined by way of grouting and post-tensioning. Further, and of particular interest, the slab-column connections comprising this two-way modular slab system rely heavily on friction to sustain and carry gravity loads. This aspect of the system design differs significantly from conventional North American construction and its design and application is not specifically addressed in current North American design provisions (e.g., ACI 318-19; CSA A23.3). While the performance of this system, and closely related systems, have been analytically and experimentally examined over the course of their development (Petrovic 1978; Forgarasi 1986), openly available experimental data and related numerical research aimed at quantifying the performance of these modular building system are limited. More specifically, the bulk of the relevant literature involving precast concrete elements that are adjoined by way of post-tensioning have been focused on evaluating the performance of precast post-tensioned concrete beam-column assemblies (e.g., Stone et al. 1995, Cheok et al. 1993, Wu et al. 2017).

The above stated, there have been some investigations focused on the experimental performance of precast, post-tensioned, modular two-way slab systems (Pessiki et al. 1995b) and related numerical studies (Chen et al. 2020). These studies are perhaps the most closely related to the structural detailing of the post-tensioned connections employed in the PACE building system. Experimental work was done to study influences associated with material strength, post-tensioning forces, and grout properties on the performance of slab-column joints. The experiment results illustrated that 1) increasing the post-tensioning force in tendons led to increases in the capacity of the friction-based joints, 2) the grout forming slab-column connections are key influencers of the friction performance of the connections, and 3) the friction coefficients of the grouted connections were estimated to be significantly larger than that typically recommended for design calculations and analyses (*fib* Model Code (MC) 2010). Numerical analyses focused on examining the influence of friction on seismic performance of modular two-way slab system connections was presented by Chen et al. (2020). The study showed that estimated stiffness degradation of the joints generally occurred at lower rates, and was less severe, than in their cast-in-place counterparts.

## 1.2 Study Objectives

The PACE building system considered in this paper is comprised of prefabricated precast concrete modular elements that, when adjoined via post-tensioning, resemble something comparable to a RC flat plate or waffle slab building structure. Precast columns, which may extend several storeys, support precast slab modules which may also be paired with precast modular beams (i.e., girders) that are provided as edge beams and/or as interior beams that can be used to adjoin adjacent slab modules between column lines. The precast components (e.g., slab panels, columns, and beams) are manufactured off-site and sized to ensure cost-effective transportation and erection. Figure 1a shows the modular precast slab-column-beam concept and Figure 1b illustrates the forces induced at the modular slab-column connections due to the (typically harped) post-tensioned tendons provided along column lines. Not shown in Figure 1 is the grout that is provided between adjacent slab modules and between the modular slab and column components.

This paper reports results obtained from nonlinear finite element analysis (NLFEA) aimed at characterizing the structural performance of the post-tensioned connections comprising the PACE building system under gravity and lateral loading conditions, and at investigating alternative connection details. More specifically, because the post-tensioned connections comprising the PACE modular systems, which rely on friction to transfer shear forces, deviate substantially from typical RC slab construction in North America, numerical modelling was done to:

i) evaluate the influence of post-tensioning force on slab-column connection performance,

ii) evaluate connection performance sensitivity to friction levels (i.e., coefficients) provided at the slab-column interfaces, and

iii) estimate and contrast the relative structural performance of the PACE modular connection assembly with that of more conventional RC flat plate slab-column connections.

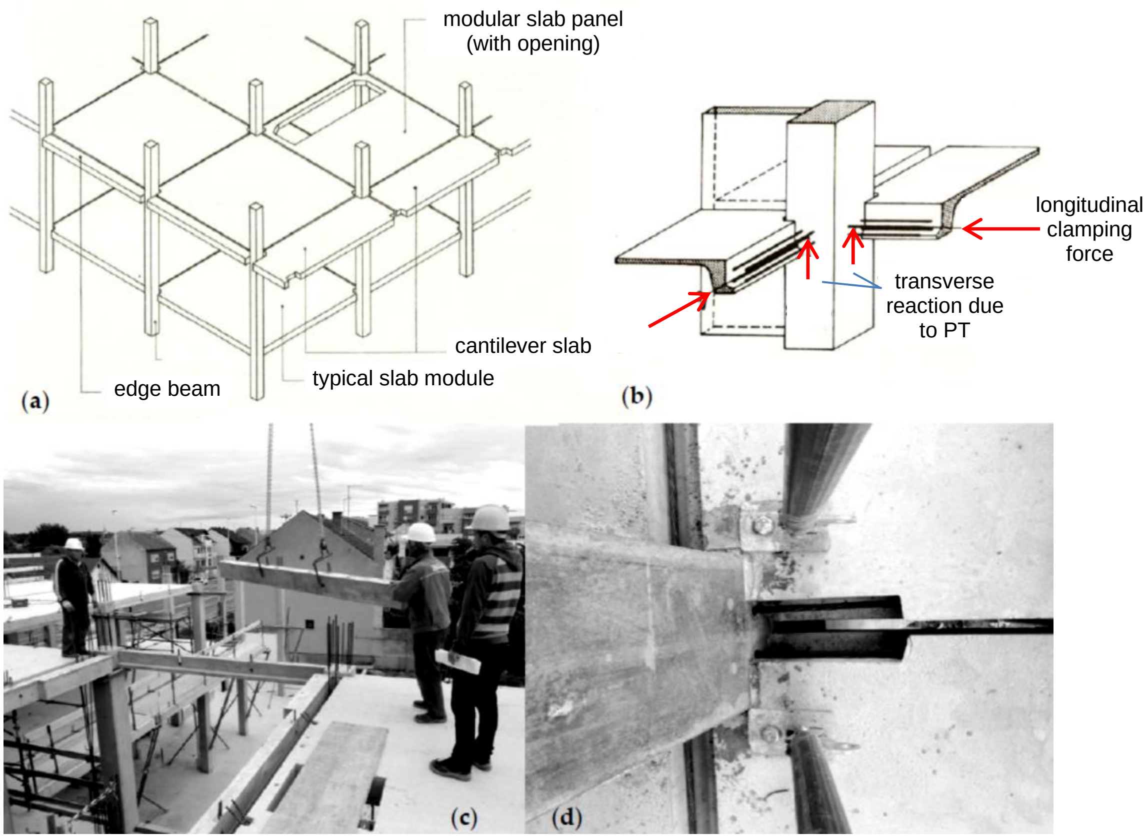


Figure 1: Modular precast building structure; (a) modular concept depicting roles of precast concrete slabs, beams, and columns; (b) clamping forces and transverse shear reaction forces generated at slab-column connections due to harped post-tensioned (PT) tendons employed in the system; (c) modular component installation; (d) grout pockets at PT slab-column connection regions (adapted from Nikolic 2018)

## 2 MODELLING APPROACH

### 2.1 Material Modelling

Numerical analyses were conducted using ABAQUS explicit, a general-purpose finite element analysis (FEA) software program that has been used by many to investigate the structural performance of RC components and subassemblies under a broad range of loading scenarios. Concrete material modelling was done using the concrete damaged plasticity (CDP) model (Lee and Fenves 1998), a continuum, plasticity-based, damage model for concrete, to simulate the nonlinear response of concrete under general loading conditions. The CDP considers two primary failure mechanisms for concrete: i) tensile cracking and ii) compressive crushing. Relevant to the compression modelling, the CDP model accounts for stiffness degradation and recovery caused by crack opening/closing of the concrete. The compressive stress-strain relation for concrete in compression were based on Thorenfeldt's relations (Thorenfeldt 1987) and the tensile strain approach reported by Genikomsou et al. (2015) was used to simulate concrete and grout fracture. The compressive strength of the concrete was assumed to be 40 MPa and the strength of the grout was taken to be 55 MPa. An overview of key CDP modelling parameters that were selected on the basis validation analyses done involving post-tensioned beam-column connections are shown in Table 1.

The constitutive relations of high-strength prestressing strand and mild reinforcing bars were modelled as bilinear with an elastic-plastic relationship. The interaction between mild reinforcement and concrete was assumed to be perfectly bonded. Slip deformations between steel reinforcement and concrete, as well as the Bauschinger effect are generally not captured well using already-available materials models within ABAQUS. Therefore, a user-defined material subroutine developed by Fang (2013), and largely based on the hysteretic model presented by Clough (1996), was used to simulate the hysteretic response of mild reinforcement. In the case of PACE system analyses, the yield stress of mild reinforcement was taken to be 400 MPa, and the 1,860 MPa post-tensioning strands were assumed to yield at 1,600 MPa.

Table 1: CDP modelling parameters used for concrete and grout

| Dilatation Angle | Eccentricity | $\sigma_{b0}/\sigma_{c0}$ | $K_c$ | Viscosity Parameter | Poisson's Ration, $v$ |
|---|---|---|---|---|---|
| 40° | 0.10 | 1.16 | 0.667 | 0.002 | 0.20 |

## 2.2 Finite Element Modelling

Isolated slab-column connection models were used to represent PACE system connections representative of those to be used in mid-rise residential building applications. The dimensions of the specific slab modules considered for the numerical modelling measured 4,750 x 3,500 mm in plan, with a rib beam height of 250 mm and slab/flange thickness of 60 mm. Two post-tensioned tendons, each with an area of 150 mm$^2$, were assumed to be provided along orthogonal column lines and, typically, all tendons were assumed to be constructed with equal jacking forces. The interior friction-based slab-column connection assembly entailed a 300 x 300 mm precast column and four precast slabs modules. Grout was assumed to be provided at the interface regions of the slab-column joints and slab-slab joints, prior to post-tensioning. Post-tensioning tendons consisted of seven-wire strands running along the column lines in both directions of the slab and were deviated such that they contributed to the negative bending resistance at the column locations and positive bending resistance at the midspan slab regions.

An illustration summarizing the typical meshing strategy used is presented in Figure 2. Most analyses were performed using a connection assembly consisting of a 2.7-m long column, two half-slab precast slab modules, and four unbonded post-tensioned tendons (see Figures 2a and 2b). Lateral restraints were provided along a plane of symmetry, permitting a one-half connection model. For several of the gravity load analyses (refer to Section 3.1), models simulating a 2x2 bay slab assembly were used (see Figure 2c).

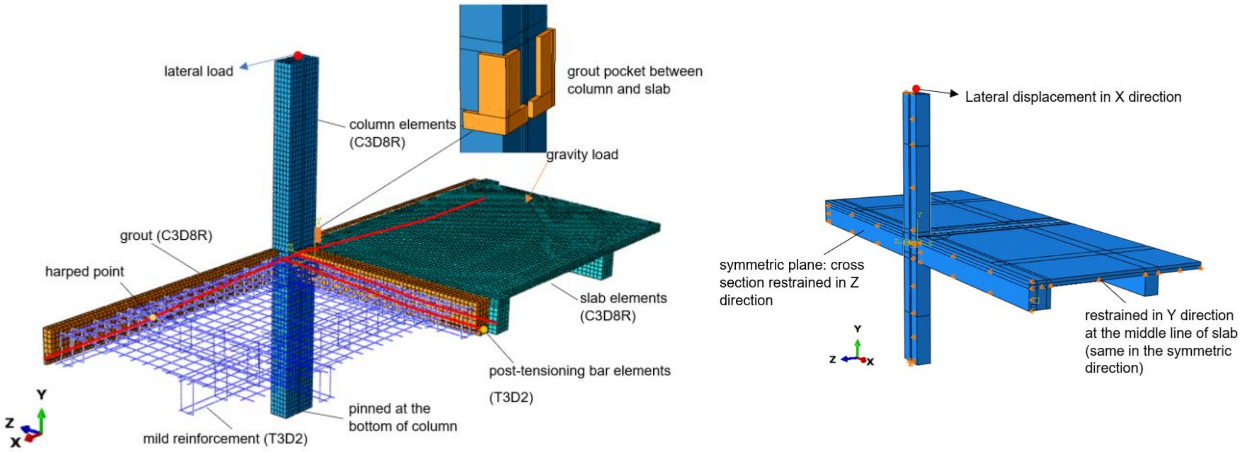
All precast concrete and grouted regions were simulated using reduced-order three-dimensional (3D) solid finite elements (C3D8R). Linear truss bar finite elements (T3D2) were employed to represent the mild steel reinforcing bars and post-tensioning tendons. Perfect bond was assumed between the concrete and mild steel bars. The post-tensioning tendons were connected to the surrounding concrete and grout via nodal coupling. Findings obtained from preliminary mesh sensitivity analyses indicated that a typical solid finite element size on the order of 30 mm provided adequate result resolution and solution stability. As the slab-column connections considered in this investigation largely rely on friction to transfer shear across slab-column interfaces, it is critical that the contact conditions between the precast modular elements be explicitly considered in the numerical model. Shear forces, as well as longitudinal normal forces, were transmitted across the interface using contact surface modelling. A friction coefficient of 0.60 was typically used based on *fib* Model Code 2010 recommendations.

Different boundary conditions were used for gravity and cyclic load analyses. The column was pinned at its bottom surface in both load scenarios. A vertical compressive force was applied on the top of the column to represent the presence of column gravity loading, using an axial load ratio of $0.10 \cdot f'_c \cdot Ag$. For cyclic lateral load analyses, a fully reversed-cyclic loading protocol with two cycles at each amplitude was considered. Displacement-controlled loading was employed in the lateral load analysis, and the lateral displacement was applied to the top of the column in the global X-direction.

# 3 NUMERICAL RESULTS

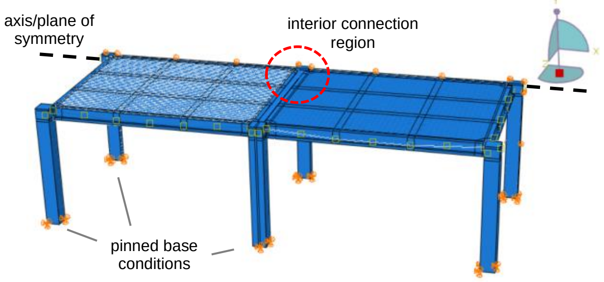
## 3.1 Response under Gravity Loading

Under simulated gravity-only loading conditions, the failure of the PACE system connection was estimated to be governed by flexural failure of the slab modules. Column-slab connection slip or joint opening were estimated to occur, but only after the development of mild steel yielding and concrete crushing within the slab modules. Load-controlled analyses involving monotonically increasing surface pressures were used to estimate the gravity load resisting performance of the modular system under different tendon stress scenarios. Figure 3 shows the computed load-deflection results obtained from the gravity load analyses, considering three different initial tendon stresses: i) an initial tendon force ($f_{pi}$) of 1,340 MPa, which does not account for any form of long term tendon losses, ii) an assumed force-in-tendon value of 1,073 MPa which was intended to conservatively account for long term tendon losses, and iii) an average tendon stress of 1,215 MPa which was obtained as a by-product of applying volumetric concrete strain offsets to simulate the presence of concrete creep and shrinkage strains that are known to lead to long term tendon losses. This third approach models long term loss contributors explicitly as opposed to assuming their influence on tendon stresses.



(a) meshing and regions for interior connection

(b) interior connection boundary conditions



(c) one-half slab model for 2x2 bay slab system considered in gravity load analyses

Figure 2: Typical finite element models to investigate PACE slab-column connections

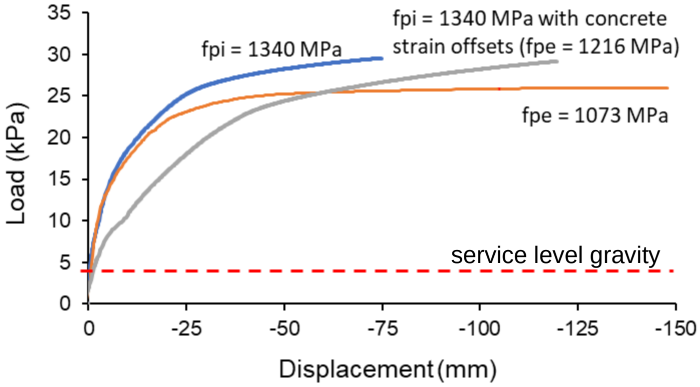


Figure 3: Estimated gravity load-displacement responses with different tendon stress levels

In all three cases, the initial tendon force is estimated to have no impact on the pre-cracking stiffness of the system; however, in the simulation employing simulated creep and shrinkage, the post-cracking stiffness of the system was significantly impacted as a result of the concrete strain offsets. This was primarily the result of the concrete strain offsets leading to more distributed cracking throughout the system. The maximum gravity load that the system was estimated to resist was estimated to be approximately 29 kPa when long term losses were neglected, was approximately 26 kPa when the effective force-in-tendon was assumed, and remained largely unaffected when long-term losses were simulated by way of concrete strain offsets. Finally, in all three tendon force scenarios, the models estimated that slab module yielding would occur prior to system failure. As noted above, slab system failure was determined to be caused by the failure of slabs as opposed to connection interface failures.

## 3.2 Response under Lateral Loading

Reversed cyclic analyses were used to estimate the suitability of the friction-based connections under lateral loading conditions. The hysteretic lateral load versus lateral displacement (and drift) curves for different gout-concrete connection friction conditions are shown in Figure 4. Analysis M3 employed a friction coefficient of 0.60, which was selected based on established recommendations (*fib* MC2010) and was aimed at capturing the likely slip-friction response of the joint, and M4 employed a friction coefficient of 1.0 in an effort to mitigate connection slip from the simulation, while still permitting crack opening and closing within the grout pockets. From the results presented, it is seen that the load-deformation responses of the connection are near-symmetric for both cases of connection friction considered and show little impact of damage propagation or deformation offset stemming from initial loading direction. Arguably the most noteworthy aspect of the response is the approximate doubling of the connection ductility because of the presence of slip-friction, which was estimated to reduce the stress levels developed in the critical grout and concrete regions comprising the connection region. In both analysis cases, failure was ultimately controlled by flexural failure mechanisms in the form of concrete and grout crushing at the connection region, near the top and bottom surfaces of the slab module.

For assessing the estimated drift levels obtained from analysis M3, which achieved a maximum drift ratio of approximately 1.9 % under the prescribed cyclic lateral loading protocol, CSA A23.3:19 drift-based shear strength reduction factors for RC flat plates subjected to seismic deformations can be used as a reference. According to the Canadian design provisions, RC flat plate connections that are required to undergo such levels of drift, are subject to appreciable strength reduction factors, effectively limiting the shear strength of the connection to approximately 30 % of their concentric shear resisting capacity. Since these analyses were performed with the inclusion of full service level gravity loads, the estimated response obtained for the PACE system meets or exceeds drift requirements associated with conventional flat plates.

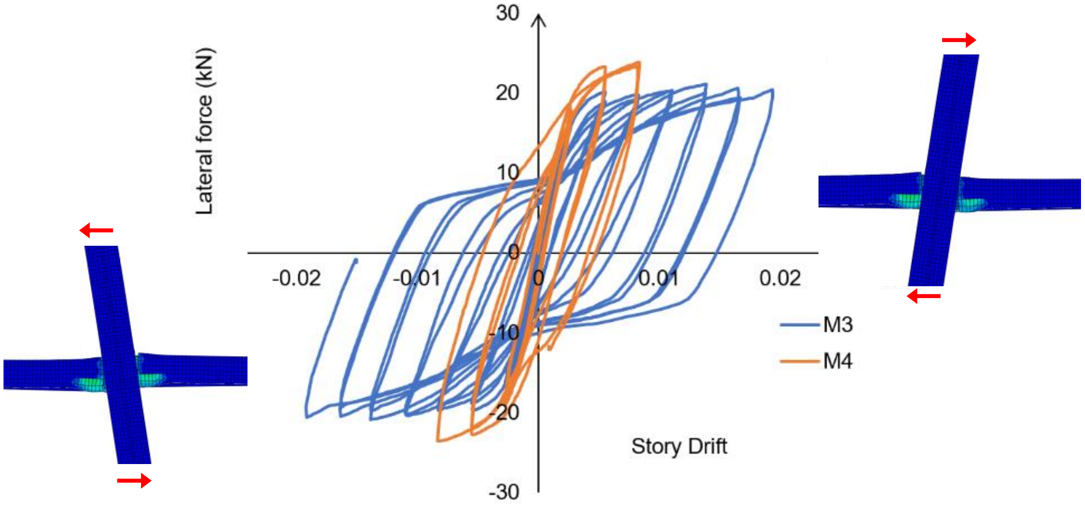


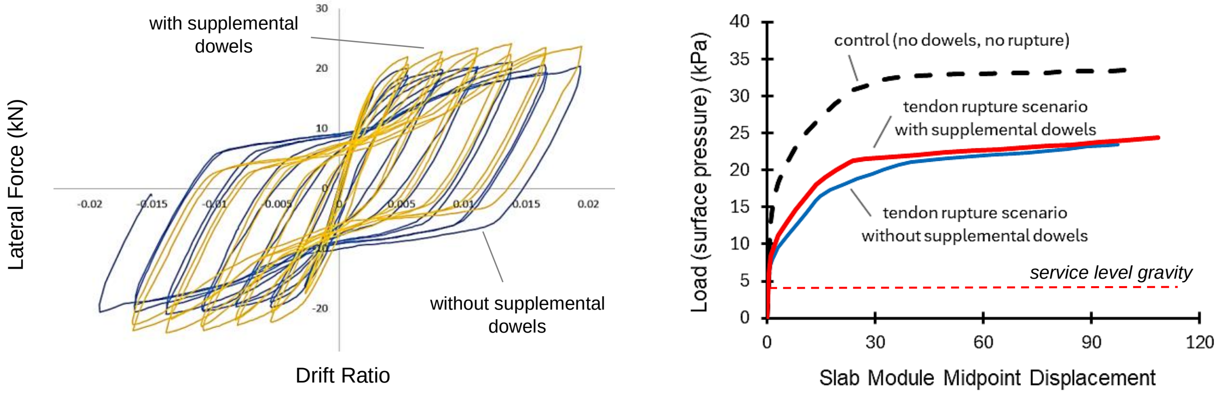
Figure 4: Computed cyclic load-displacement responses

### 3.3 Influence of Supplemental Connection Reinforcement

One point of contention with the application of friction-based connections that rely on post-tensioning forces to maintain connection integrity is the absence of bonded mild reinforcement crossing the interface between the precast slab panels and the precast columns. To investigate the potential influence of incorporating bonded mild steel reinforcement across these interfaces, the addition of 2-10M bars in each direction was considered, and the lateral and gravity load resisting response was investigated. The bars were modelled using beam finite elements and were placed along the column lines in the grout pockets between adjacent slab modules and were assumed to be 1,100 mm long, which was estimated based on development length requirements provided in CSA A23.3. It is also worth noting that, from a cross-sectional sizing standpoint, this area of reinforcement would satisfy integrity reinforcement requirements for RC flat plates (CSA A23.3).

Figure 5a presents the lateral load versus drift results for the slab-column connection presented in Figure 2, with and without supplemental dowel reinforcement. From the results presented, it is shown that the addition of the bonded mild reinforcement along the column lines had a minimal on lateral load resistance and wasn’t estimated to have any significant impact on lateral deformability or drift capacity.

Figure 5b presents the gravity load carrying performance of the system, with and without dowels, under a single strand loss scenario. In this case, it was assumed that in one direction, one of the two post-tensioning strands forming the connection, was entirely ineffective (e.g., a strand fault scenario). From the results presented, it is evident that even under an extreme strand loss scenario, the gravity load carrying capacity of the system is estimated to greatly exceed service level and factored gravity loads, regardless of whether supplemental dowel reinforcing bars are considered. It is also interesting to note that when the supplement bonded mild reinforcement is included, the impacts with respect to post-cracking stiffness tend to be less severe; however, as was the case with the lateral loading case, the additional of the mild dowel bars had limited impact on system capacity.



(a) lateral load response

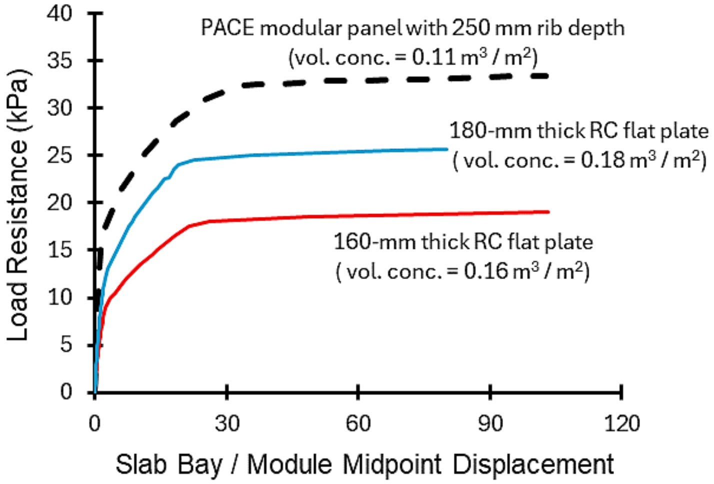
(b) gravity load response considering tendon load scenarios

Figure 5: Influence of supplemental (dowel) reinforcement (0.60 friction coefficient)

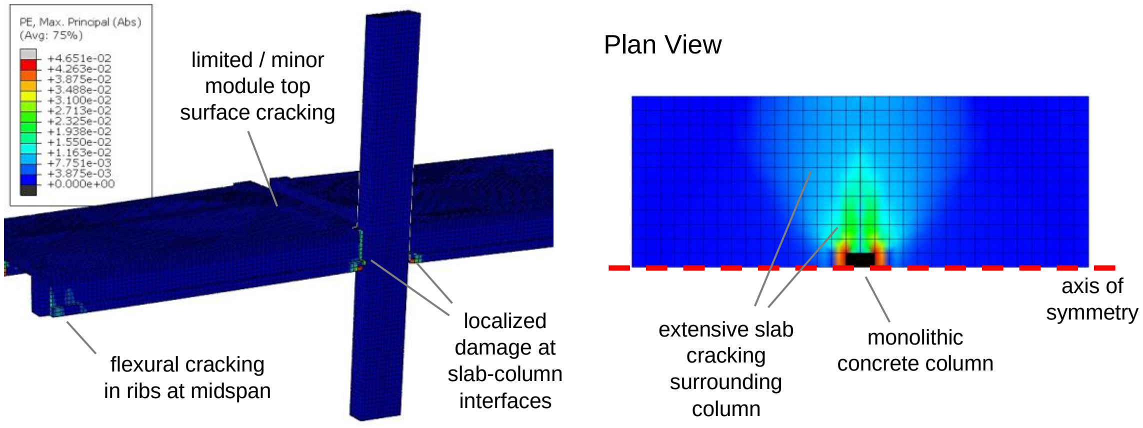
## 4 COMPARISON WITH CONVENTIONAL RC FLAT PLATES

Analyses were done to contrast the load resisting performance of the PACE system with that of more conventional RC flat plate construction. While it is difficult to establish a directly comparable RC flat plate counterpart to the design of the PACE modular system considered, a 160-mm thick, lightly reinforced concrete slab arguably represents the type of flat plate that one would expect to be designed for the factored gravity loads and spans considered in the design of PACE slab modules. Additionally, a slightly thicker ($h_s$ = 180 mm) flat plate was also considered for comparison purposes. Both flat plates were assumed to be reinforced with orthogonally placed mild steel reinforcement (400 MPa yield strength) provided in two mats and amounting to a steel reinforcement ratio of 0.50 % in the negative bending regions of the column strips, and a ratio of 0.25 % in all positive bending regions. To avoid the need to re-calibrate / re-validate the ABAQUS modelling strategy employed, the RC flat plate analyses were done using an alternative procedure that has been previously validated for a broad range of applications involving flat plate slab-column connection modelling: a RC-dedicated nonlinear finite element analysis program developed specifically for slabs and shells (Hrynyk and Vecchio 2019) that has been shown to effectively estimate the load resisting capacities, deformation capacities, and governing modes of failure for flexure- and punching-shear governed conventional RC flat plates (Goh and Hrynyk 2020), without the need for case specific calibration.

Figure 6a presents the superimposed gravity load versus centre-point slab deflection response of the PACE system alongside the estimated responses for the 160-mm and 180-mm thick RC flat plates. The figure also lists the concrete volume requirements, in terms of slab volume concrete per planar square metre of floor area, for each of the three cases considered. It should be noted that the 160-mm thick conventional RC flat plate, which requires approximately 45 % more concrete than that of the prefabricated ribbed slab module comprising the PACE system, and the 180-mm thick flat plate requires approximately 60 % more concrete than the modular system.



(a) superimposed surface pressure versus slab centrepoint displacement



(b) damage (plastic strain) development in PACE connection at ultimate

(c) top surface principal tensile strain indicative of cracking in 180-mm thick RC flat plate

Figure 6: Gravity load resisting performance comparison between PACE modular system and conventional RC flat plates

Based on the results presented, despite the PACE system requiring much less concrete than typically reinforced RC flat plates considered, it can be seen that both the load carrying capacity and the stiffness of the modular system is estimated to greatly exceed that of the lightly reinforced RC flat plates. While conventional RC flat plates with increased steel reinforcement ratios can certainly be used to provide comparable load capacities, from a concrete usage standpoint, the ribbed nature of the slab modules comprising the PACE system offers efficiencies that contribute to reducing material requirements for construction and to reducing structural load demands by way of reduced slab system weight. These material and self-weight efficiencies are difficult to replicate in conventional flat plate construction.

The computed concrete damage development, inferred by way of concrete strains, is presented in Figures 6b and 6c for the PACE and the 180-mm thick flat plate slab-column connections, respectively. Note that in the case of the modular PACE system, computed damage within the slab-column connection region was estimated to be almost entirely limited to the grout comprising the slab-column interfaces and slab-slab interfaces (not shown), but no significant cracking was estimated to occur on the top surface of the slab module. In contrast, extensive distributed cracking was estimated to occur on the top surface of the RC flat plate surrounding the column connection region, and extensive yielding of the top mat (i.e., negative) reinforcement within the slab connection region was estimated to occur. In both the PACE system and the RC flat plate, the load capacities were governed by flexural failures that occurred under positive bending at the slabs' midspan regions; however, in the case of the RC flat plates, flexural yielding was followed by flexure-induced punching shear failures at the locations of the slab-column connections.

## 5 SUMMARY AND CONCLUSIONS

Based on the numerical investigation performed and the results obtained, several key findings regarding the numerically estimated structural response of the PACE system building connections can be provided:

- The governing failure mode of the modular system was estimated to be controlled by flexural failure mechanisms within the slab modules. Flexural reinforcement yielding within the slab ribs followed by slab module concrete crushing was estimated to occur. Under gravity load levels exceeding service loads, the post-tensioning forces provided at the friction-based connection prevented both connection slip, and joint opening, from occurring.
- Under cyclic lateral loading conditions, the influence of connection slip was estimated to marginally reduce system lateral load resistance and connection stiffness; however, was also estimated to enhance the ductility of the friction-based connection system. The estimated drift capacity of the post-tensioned modular system employing friction-based shear connections was estimated to exceed the Canadian requirements specified for conventional RC flat plate connections.
- The gravity load carrying performance (stiffness and strength) provided by the PACE system was estimated to exceed that provided by comparable RC flat plates, while requiring significantly less concrete for construction its construction. The reduced concrete requirements for the PACE system are advantageous in terms of reducing both material usage and structure self-weight.

## 6 ACKNOWLEDGEMENTS

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