MODELING THE RESPONSE OF PRECAST PRESTRESSED CONCRETE HOLLOWCORE SLABS EXPOSED TO FIRE

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ABSTRACT

This paper presents the development of a three dimensional finite element model for evaluating fire performance of precast concrete hollowcore slabs. A transient thermo-structural nonlinear finite element analysis of hollowcore slab is carried out using ANSYS. In the analysis, the effect of material and geometric nonlinearities as well as high temperature properties of concrete, rebars and prestressed strands are taken into account. Response parameters that include, cross sectional temperature and deflections, are utilized to evaluate failure of the slab. The model is validated by comparing response predictions from the model with those measured in fire tests. Good agreement of model predictions with test data indicate that the proposed model is capable of predicting fire performance of the hollowcore slabs under combined effect of fire and structural loading.

Keywords: Precast concrete slabs, Fire resistance, Hollowcore slabs, Numerical model

INTRODUCTION

Precast prestressed concrete (PC) hollowcore slabs have gained wide popularity in recent years due to numerous advantages they offer over other forms of construction. These advantages include aesthetics, speedy construction, space utilization and flexibility. Structural fire safety is one of the primary considerations in buildings and hence, building codes specify fire resistance rating requirements for these hollow-core slabs. The current method of evaluating fire resistance of PC hollowcore slabs is mainly through standard fire tests. Based on limited test data, prescriptive provisions are developed for PC hollowcore slabs in terms of concrete cover thickness and slab thickness. These prescriptive provisions are inherently inadequate in scope and application, as these provisions cover only a narrow range of parameters, and do not reflect realistic fire resistance of hollowcore slabs.

Generally, concrete exhibits higher fire resistance properties as compared to steel [15]. Therefore, under fire conditions, the temperature rise in prestressing strands often governs the fire resistance of hollowcore slabs. In hollowcore slabs, presence of void cores affects thermal inertia of slabs and thus influences the temperature transmission through the slab thickness. Further, the fire response of hollowcore slabs is also affected by number of factors including type of fire exposure, load level, restraint conditions, concrete cover thickness and aggregate types. These parameters need to be properly accounted for accurate evaluation of fire resistance of hollowcore slabs.

In the last four decades, several studies, both experimental and numerical, have been carried out to evaluate fire performance of precast prestressed hollowcore slabs. Most of the fire tests were performed under standard fire conditions, solely to develop fire resistance ratings. These fire tests were carried out on some of the common configurations of hollowcore slabs and test data was utilized to extrapolate fire resistance ratings for similar hollowcore slab configurations. These fire tests, on hollowcore slabs, did not consider the effect of critical parameters, such as fire exposure, loading and restraint conditions. Further, some of the fire experiments, carried out as part of research studies, identified spalling, bond and shear failure as critical failure modes in hollowcore slabs [1,3,6,21]. The numerical studies carried out on fire performance of hollowcore slabs made an effort to study the effect of some of the critical factors, such as slab configuration, cover thickness, boundary condition and load level, affecting fire resistance of hollowcore slabs [8,9,12,18]. However, these studies did not consider the effect of different fire scenarios, concrete strength, restraint, level of prestressing on fire resistance of hollowcore slabs. In addition, the model used in numerical studies did not include the effects of spalling, bond and shear failures.

The conventional approach of evaluating fire resistance through fire tests has numerous drawbacks and is also time consuming. An alternative to fire testing is the use of numerical modeling for evaluating fire resistance of hollowcore slabs. To develop such a numerical approach for evaluating fire resistance of hollowcore, a three-dimensional finite element model was developed. Detailed description of the finite element model, together with material constitutive laws, and failure criteria are presented in this paper.

NUMERICAL MODEL

A numerical model for tracing the fire response of PC hollowcore slabs is developed using ANSYS finite element program [4]. The model accounts for geometric and material nonlinearities, and temperature dependent thermal and mechanical properties of concrete, reinforcing and prestressing steel. Fire resistance analysis of hollowcore slab is carried out at incrementing time steps from start of fire exposure (ignition) to failure of the slab. The various features of the model including discretization details, high temperature properties, boundary conditions and failure limit states are discussed below.

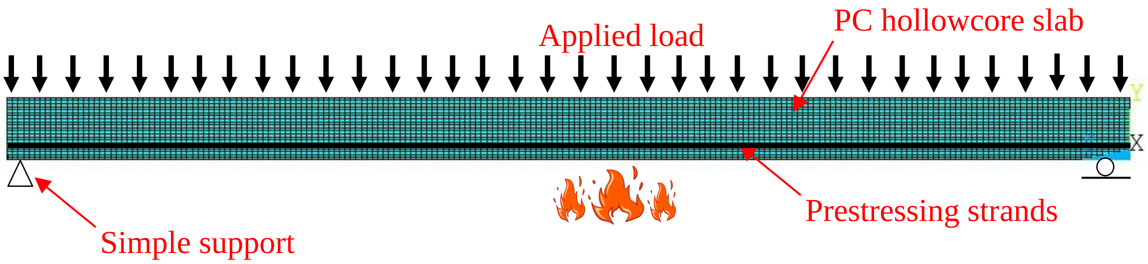
DISCRETIZATION DETAILS

For fire resistance analysis, the given PC hollowcore slab is discretized in to elements. Two sets of elements are needed for undertaking thermal and structural analysis in ANSYS. For thermal analysis, SOLID70, LINK33 and SURF152 can be used, and for the structural analysis SOLID65, LINK180 and SURF154 can be utilized.

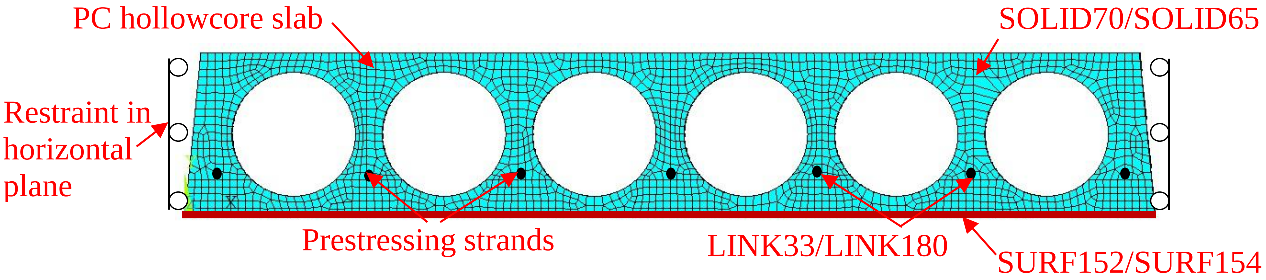
SURF152 is a surface effect element and this element was overlaid onto the exposure surface to simulate radiation of heat from fire source onto the bottom surface of the slab. SOLID70 element, which is capable of simulating 3-D thermal conduction, is used to simulate transmission of heat into the concrete slab from the surface of slab. This element has eight nodes with a single degree of freedom, temperature, at each node and is applicable to a 3-D, steady-state or transient thermal analysis. LINK33 is a uniaxial element with capability to conduct heat between nodes. Like SOLID70, LINK33 element has a single degree of freedom, temperature, at each nodal point. This conducting line element is capable of simulating steady-state or transient thermal analysis. The thermal elements were transformed (switched) in structural elements after completion of thermal analysis. The conversion was performed as follows.

- SOLID70 3-D solid elements were converted to SOLID65 3-D concrete solid elements.
- LINK33 thermal line elements were converted to LINK180 prestressing strands line elements.
- SURF152 thermal surface effect elements were converted to SURF154 elements.

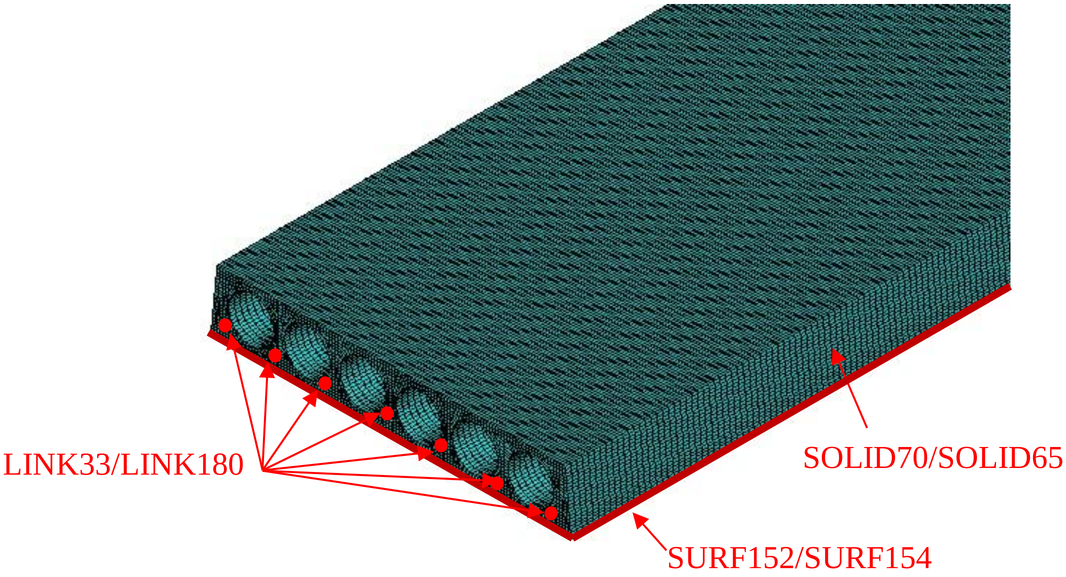
In structural analysis, SOLID65 3-D element is utilized to model concrete. This SOLID65 element is capable of simulating cracking in tension (in three orthogonal directions), crushing in compression, plastic deformations and creep. This element is defined by eight nodes having three degrees of freedom at each node: translations in nodal x, y, and z directions. LINK180 3-D spar element is used to model prestressing strands. This element can capture uniaxial tension or compression and has three degrees of freedom at each node: translations in the nodal x, y, and z directions. Plasticity, creep, rotation, large deflection, and large strain deformations in prestressing steel can also be simulated using this element. SURF154 element does not have any role (contribution) in the structural analysis. A typical PC hollowcore slab, discretized into various elements, is shown in Figure 1.



a. Typical hollowcore slab exposed to fire



b. Discretization of cross-sectional of hollowcore slab



c. Discretized hollowcore slab in longitudinal direction

Figure 1. Layout of a typical PC hollowcore slab and its discretization for finite element analysis

HIGH-TEMPERATURE MATERIAL PROPERTIES

When a hollowcore slab is subjected to fire, the properties of concrete, reinforcing steel and prestressing steel degrade with increasing temperature. For evaluating realistic fire response the variation of properties with temperature is to be taken into account. Thus, for finite element analysis, temperature dependent thermal and mechanical properties are to be provided as input data. The thermal properties include thermal conductivity, specific heat and emissivity factors, while mechanical properties include density, elastic modulus, poison's ratio, stress-strain relations and thermal expansion. All these properties are defined as varying with temperature using the relations specified in Eurocode 2 [10].

In ANSYS, plastic behavior of concrete is defined using William and Warnke's constitutive model [20], which is capable of defining concrete behavior in both tension and compression. Under loading, top fibers are subjected to compression, while bottom fibers are subject to tension. Hence, it is necessary to define concrete behavior in both compression and tension regimes. The compressive plastic behavior is defined as isotropic multi-linear stress-strain curve varying with temperature while, tensile behavior is defined as damage parameter. In ANSYS, the damage in concrete is defined in terms of crack opening and crack closing parameters. These parameters are defined as open and close crack shear transfer coefficients, (β_t and β_c respectively) and are taken to be 0.2 and 0.7 respectively [20].

Both thermal and mechanical properties of rebars and prestressing strands are defined as varying with temperature as specified in Eurocode 2 [10]. The variation of mechanical properties of rebars and prestressing strands are defined in terms of temperature dependent elasto-plastic stress-strain relations and modulus degradation parameter.

LOADING AND BOUNDARY CONDITIONS

A PC hollowcore slab, under fire conditions, is subjected to both thermal and mechanical loading. To simulate realistic scenario, analysis starts with the application of mechanical loading calculated as a percentage of ambient temperature capacity of the slab. After both loading and initial deflection levels stabilize, thermal loading due to fire exposure, is applied. Both mechanical and thermal loading are continued until failure occurs in the slab. The slab can be subjected to any specified fire exposure condition, which is to be input as time-temperature curve (points). This curve can be a standard fire (ASTM E119 [5], ISO834 [14]) or a typical design fire comprising of heating and cooling phase.

PC hollowcore slabs form part of floor assemblies, so to take the effect of adjacent slabs the longitudinal edges of the slab are assumed to be restrained on horizontal plane and free to deflect in vertical plane. In the case of localized fire exposure conditions, additional restraint gets developed from the cooler side of the slab. Figure 1 shows a layout of a typical hollowcore slab with applied loading and boundary conditions.

FAILURE CRITERIA

The conventional approach of evaluating fire resistance is based on reaching thermal or strength failure limit states as specified in ASTM E119 [5]. Accordingly, the thermal failure of a prestressed hollowcore slab is said to occur when:

- The average temperature on the unexposed surface of the slab exceeds 140°C (at 9 points) or a maximum of 180°C at any single point of the unexposed surface of the slab.
- The temperature of prestressing strands exceeds critical temperature, which is generally taken as 426°C for prestressing steel, at which strand loses 50% strength.

The strength failure is said to occur when:

- The slab is unable to resist the applied loading. This occurs when moment capacity of the slab drops below the moment caused due to applied loading.

In addition to the above limit states, deflection or rate of deflection can play a major role on the behavior of beams or slabs under fire conditions [15]. The limit states for deflection and rate of deflection criteria are adopted from British Standard (BS 476) [11] and are applied to evaluate failure of hollowcore slabs. Based on BS 476 [11], failure of prestressed slabs, according to the deflection and rate of deflection limit states, occur when:

- The maximum deflection of the slab exceeds $\frac{L}{20}$ at any fire exposure time.
- The rate of deflection exceeds the limit given by $\frac{L^2}{9000d}$(mm/min) where, L = span length of the slab (mm), and d = effective depth of the slab (mm).

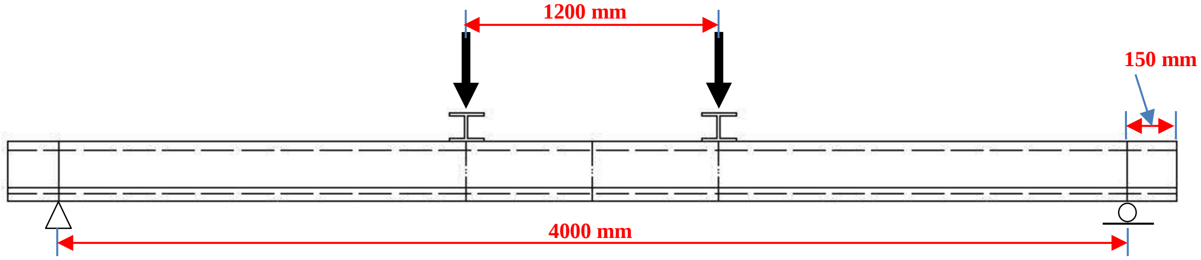
MODEL VALIDATION

The above developed model is validated by comparing predicted response parameters (temperatures, deflections and failure times) from ANSYS with measured data in fire tests. For this validation two PC hollowcore slabs tested by Breccolotti et al. [7] are selected and the validation is carried out in the entire range of loading from pre fire exposure to collapse under fire conditions. The thermal and structural response parameters predicted by ANSYS are compared against measured data from fire tests.

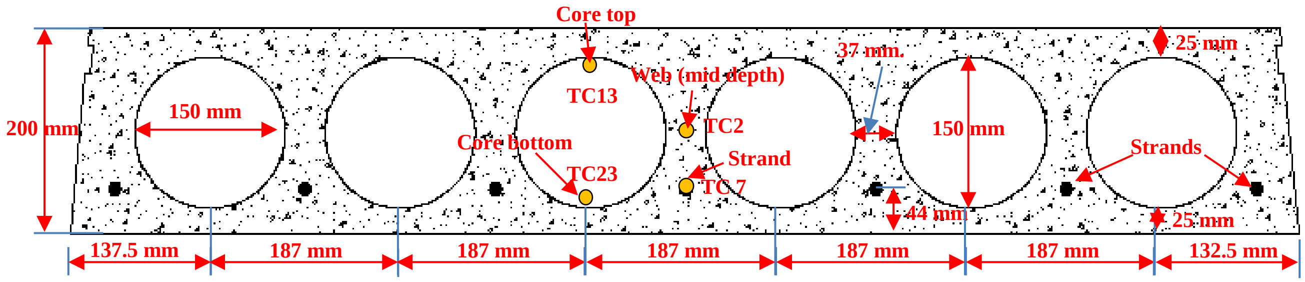
CHARACTERISTIC OF SLAB

Both PC hollowcore slabs (Slab-1 and Slab-2) selected for validation are of similar geometry, and have six cores and seven strands as illustrated in Figure 2. The slabs are 4 m long, 1.2 m wide and 200 mm thick. The cores are of 150 mm radius, with 25 mm concrete thickness at the bottom of the core. The slabs are cast with concrete having a compressive strength of 48 MPa (7 ksi.). The prestressing strands are of ⅜ in. diameter and are low relaxation strands (with yield stress of 1860 MPa (270 ksi.)). The cover thickness over the strands is 44 mm. The slabs were instrumented with a number of thermocouples at various locations in the slab. However, for validation, temperature readings from thermocouples TC7, TC2, TC23 and TC13 placed at critical locations, namely strand, web mid height, bottom of core and top of core respectively, as indicated in Figure 2, are utilized. Details of the slabs are illustrated in Table 1.

In the tests, prior to fire exposure, the slabs were loaded with four point loading scheme as illustrated in Figure 2. This loading was applied to cause a bending moment at the mid-span section equal to 60% of service loads. Specifically, a total of 40 kN (20 kN at each load point) was applied, corresponding to 33.7 kN-m mid-span bending moment. The slabs were tested by exposing to ISO834 fire scenario from bottom side. During fire tests, the progression of temperature and deflections in the slab was monitored. Full details of fire tests including detailed results from experiments can be found elsewhere [7]. The fire resistance ratings for these hollowcore slabs, calculated as per various codal provisions, are presented in Table 2.



a. Layout of hollowcore slab with loading



b. Cross sectional details and thermocouple details

Figure 2. Layout and cross-sectional details of a tested prestressed concrete hollowcore slabs

ANALYSIS DETAILS

The above selected PC hollowcore slab was analyzed by discretizing the slab in to various elements as discussed in previous section. The thermo-mechanical analysis was carried out at 5 minute time intervals till failure of the slab. The slab was subjected to simultaneous fire and structural loading, as in the tests. Results generated from the analysis, namely cross sectional temperatures, deflections, and failure times are utilized for validation. The analysis starts by subjecting the slab to static loads. Transient thermal load corresponding to test fire curve, as shown in Figure 3, is applied after equilibrium has been achieved from static mechanical loading. The slab is assumed to have failed when the strength (moment capacity), or deflection or rate of deflection exceeds the permissible limits. Arbitrary failure, based on temperature in prestressing strand exceeding critical temperature, is also evaluated.

Table 1. Geometric and material characteristics of tested slabs

Parameter	Slab-1	Slab-2
Dimension (length×width×thickness)	$4.3 \times 1.2 \times 0.2$ m^3 (14 ft. × 4 ft. × 8 in.)	$4.3 \times 1.2 \times 0.2$ m^3 (14 ft. × 4 ft. × 8 in.)
Cores	6-150 mm Ø	6-150 mm Ø
Concrete compressive strength (f'_c)	C48 MPa (7 ksi.)	C48 MPa (7 ksi.)
Prestressing strand	7-9.5 mm (⅜ in.) 1860 MPa (270 ksi.) low relaxation	7-9.5 mm (⅜ in.) 1860 MPa (270 ksi.) low relaxation
Fire exposure	ISO 834	ISO 834

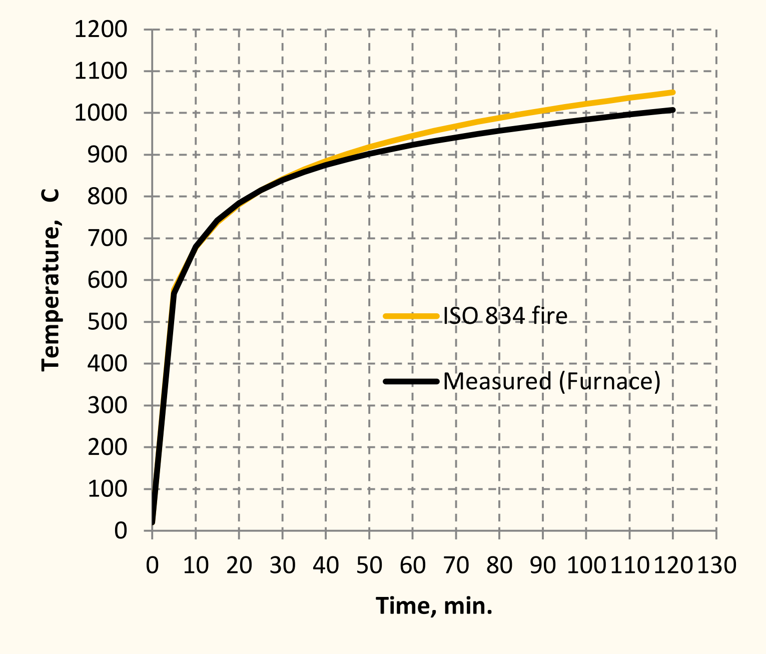


Figure 3. ISO834 time-temperature curve and measured furnace temperature

THERMAL RESPONSE

For validating thermal response predictions, predicted temperatures from the model are compared against measured data from fire tests. Figure 4 compares predicted temperature from ANSYS with test data at various locations of the slab. The temperature data for critical locations including strand, web mid height and core (bottom and top) are plotted in Figure 4. The temperature progression in the slab follows expected trend with higher temperatures at bottom layers (closer to the fire source), and gradually increasing with fire exposure time. The layers closer to the fire exposed surface have faster rate of temperature rise than layers that are farther from the fire source. The strands, which are at 44 mm depth from bottom surface, does not experience any temperature rise in the first 10 minutes of fire. The delay in temperature rise in inner layers of the slab can be attributed to low thermal conductivity of concrete and also to the presence of void cores.

After about 10 minutes, strand temperatures increase almost linearly. At 60 minutes, the strand temperatures reach 239°C, while at 120 minutes the corresponding temperature in prestressing strands is 415°C. Due to high thermal mass, top layers of concrete and unexposed surface of slab experience minimal increase in temperature, reaching only a maximum of 54°C and 45°C respectively at 120 minutes. Typical temperature field in the slab section at 60 and 120 minutes are shown in Figure 5.

A close review of Figure 4 indicate a good agreement between predicted and measured temperatures, with the exception of core temperatures (bottom and top). This discrepancy can be attributed to the fact that, there are various complexities involved in placement of thermocouples in hollowcore slabs during fabrication, especially in the core. Also, based on the reported information (measured data), the erratic temperature reading of these thermocouples in the cores could be due to the occurrence of fire induced spalling during fire tests [7]. This spalling is not accounted for in the analysis.

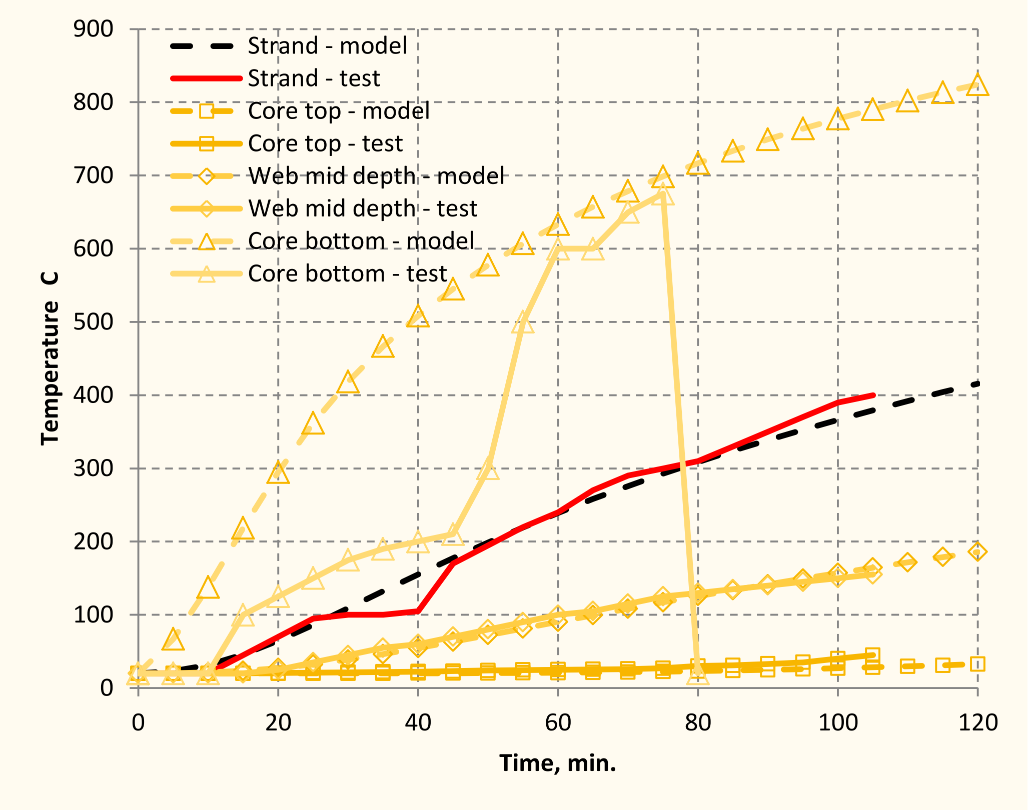
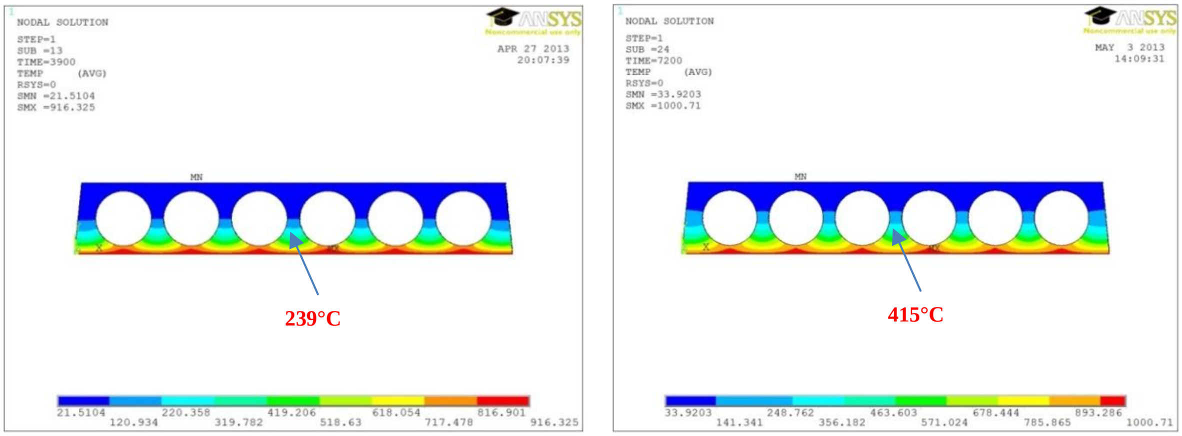


Figure 4. Comparison of predicted and measured temperatures in hollowcore slab

STRUCTURAL RESPONSE

As part of structural validation, mid-span deflection of the slab, predicted from the model, is compared against measured deflection from tests. Figure 6 compares predicted mid-span deflection with the measured data reported by Brecolotti et al. [7] for two tested identical hollowcore slabs.

At ambient conditions, PC hollowcore slabs incur initial camber due to prestressing. The initial camber in the hollowcore slab calculated from analysis compares well with camber reported by the researchers [7]. It can be seen in Figure 6 that the deflection starts to increase after fire exposure. This immediate increase in deflection can be attributed to thermal expansion of concrete. Since the hollowcore slabs are exposed to one sided fire (bottom surface), significant thermal gradients and thermal strains gets developed at the bottom of the slab. The deflection, mainly resulting from thermal strains, stabilizes after 15 minutes, as the temperature gets transmitted to inner layers of slab. The increase in deflection is minimal from 15-30 minutes since there is very little loss of stiffness, as the temperatures in prestressing strands (and upper layers of concrete) are very low (below 100°C). Beyond 30 minutes in to fire exposure, deflection further increases, and this is attributed to strength degradations in concrete and prestressing strands, due to reaching higher temperatures. The deflection increases gradually till 100 minutes of fire exposure, beyond which the slab experiences rapid increase in deflection. This abrupt increase in deflection is a clear indication of onset of structural instability. Based on test observations, it is reported that the sudden failure was due to shear failure. Figure 6 shows reasonable agreement between predicted and the measured deflections in tests.



a. Temperature field at 60 minutes b. Temperature field at 120 minutes

Figure 5. Temperature field in the PC hollowcore slab at 1 and 2 hours

FAILURE MODES AND FIRE RESISTANCE

In the fire test, Slab-1 was reported to have failed under shear crushing at 76 minutes, while Slab 2 was reported to have failed at 90 minutes, when deflection limit state was exceeded [7]. The discrepancy in two tests can be attributed to the fact that, Slab-1 exhibited early spalling of concrete cover, which induced higher deflections, causing premature failure. The shear collapse of Slab-1 could have been induced due to loss of concrete cover from spalling and formation of pass through vertical holes, as reported by researchers [7]. On the other hand, Slab-2 did not exhibit any fire induced spalling, but the fire test was aborted when deflection limit was exceeded.

Based on results output from ANSYS, the fire resistance of hollowcore slab is evaluated by applying different failure criteria. In ANSYS analysis, non-convergence occurs at 100 minutes time step and this is an indication of instability in the slab. This can be attributed to significant degradation of stiffness in both concrete and prestressing steel, due to reaching high temperatures. At 100 minutes, prestressing strands reach temperature of about 400°C and concrete (at bottom layers) reaches temperature of about 800°C. The time to reach this point, at 100 minutes, is taken as failure of the slab. However, the shear failure observed in one of the test slabs is not captured in the model, due to significant complexity in modeling the shear response under fire conditions.

Based on unexposed surface temperature criterion, the slab does not reach failure up to 120 minutes, since the maximum temperature of the unexposed surface of the slab reach only 45°C at 120 minutes. However, based on critical temperature in strand, the slab fails at 120 minutes when temperature in prestressing strands exceeds critical temperature of 426°C. The fire resistance of this slab is also calculated based on provisions in IBC 2006 [13], PCI [19], ACI 216 [2] and Eurocode 2 [10]. These provisions are based on concrete cover thickness and depth of slab. For the tested slabs, clear concrete cover thickness over the prestressing strands is 1.55 in. and equivalent slab thickness, obtained by dividing net cross-sectional area by width, is 4.57 in. Hence, the fire resistance, based on these concrete cover thickness and effective slab depth parameters, is 90 minutes as per IBC 2006 [13], PCI [19], ACI 216 [2] and Eurocode 2 [10]. Fire resistance of the slab evaluated from numerical analysis along with fire resistance measured in tests and calculated based on codal provisions are illustrated in Table 2.

The analysis results show that, typical hollowcore slabs reach structural failure prior to thermal failure under fire conditions. Nonetheless, based on concrete cover thickness, the temperatures in strands and subsequent fire resistance can significantly vary from one slab configuration to another. Thus, in hollowcore slabs, strand temperature might not yield realistic fire resistance.

Table 2. Failure times of hollowcore slab based on various failure criteria and different codal provisions

Failure criteria	Fire resistance (minutes)		
	Model	Slab-1	Slab-2
Strand temperature	120	-	-
Deflection	100	76	90
Strength	100	-	-
IBC 2006 [13]	90		
PCI [18]	90		
ACI 216 [2]	90		
Eurocode 2 [10]	90		

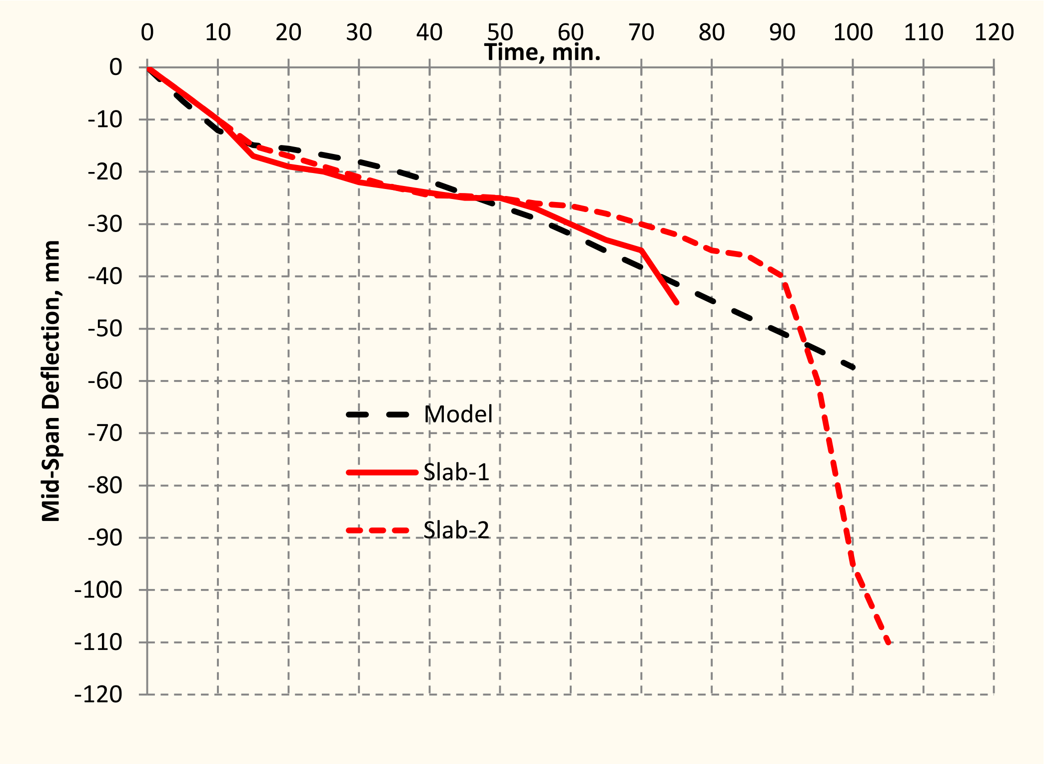


Figure 6. Comparison of predicted and test temperature at core bottom

CONCLUSIONS

Based on the results presented in this paper following conclusions can be drawn.

- A numerical approach can be applied to evaluate fire resistance of hollowcore slabs. The proposed finite element model developed using ANSYS is capable of simulating thermal and structural response of prestressed concrete hollowcore slabs exposed to fire in the entire range of loading from pre fire to failure under fire.
- Hollowcore slabs, similar to the one presented in this paper, can give 100 minute of fire resistance under standard fire exposure.
- Fire resistance of hollowcore slabs is influenced by load level, restraint, concrete cover thickness and core size. The numerical model presented in this paper can be applied to undertake parametric studies on PC hollowcore slabs in fire.
- Failure of a slab, based on critical temperature in prestressing strands, may not yield accurate fire resistance of hollowcore slabs.

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