Modeling the response of precast, prestressed concrete hollow-core slabs exposed to fire

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- This paper presents the development of a transient thermo-structural, nonlinear three-dimensional finite element model for evaluating fire performance of precast concrete hollow-core slabs.
- The effects of material and geometric nonlinearities, high-temperature properties of concrete, reinforcing bars, and prestressing strand were taken into account, with cross-sectional temperature and deflections as failure criteria.
- Good agreement between the model predictions and the test data indicates that the proposed model is capable of predicting fire performance of hollow-core slabs under the combined effects of fire and structural loading.

Precast, prestressed concrete hollow-core slabs have gained wide popularity in recent years due to their numerous advantages over other forms of construction. These advantages include aesthetics, speed of construction, efficient use of space, and flexibility. Structural fire safety is a primary consideration in buildings; thus building codes specify fire-resistance rating requirements for hollow-core slabs. The current method of evaluating fire resistance of precast, prestressed concrete hollow-core slabs is mainly through standard fire tests. The current prescriptive provisions are developed based on standard fire tests on precast, prestressed concrete hollow-core slabs, and fire resistance is derived in terms of concrete cover thickness and slab thickness. Because these prescriptive provisions do not consider fire scenarios as encountered in buildings, they may not reflect realistic fire resistance of hollow-core slabs. Further, these prescriptive methods account for a narrow range of parameters.

Generally, concrete exhibits higher fire-resistance properties than steel does.[1,2] Therefore, under fire conditions the temperature rise in prestressing strands often governs the fire resistance of hollow-core slabs. In hollow-core slabs, the presence of void cores affects the thermal inertia of slabs, influencing temperature transmission through the slab thickness. The transmission of heat from the fire source to the slab is through radiation and convection, whereas transmission of heat within the slab is through conduction in solid concrete and convection and radiation in the hollow cores. Spalling, bond slip, and shear crushing have been observed in previously reported fire tests of these slabs. Further, the fire response of hollow-core slabs is also affected by a number of factors, including the type of fire exposure, loading, restraint conditions, concrete cover thickness, and aggregate type. These parameters need to be properly accounted for accurate evaluation of the fire resistance of hollow-core slabs.[3,4]

The conventional approach of evaluating fire resistance through fire tests is expensive, time consuming, and limited in study parameters. An alternative to fire testing is the use of numerical modeling for evaluating fire resistance of hollow-core slabs. Numerical methodology allows incorporation of various parameters in an efficient and cost-effective way.[5] To develop such a numerical approach for evaluating the fire resistance of hollow-core slabs, a three-dimensional finite element model was developed. A detailed description of the finite element model, together with material constitutive laws and failure criteria, are presented in this paper.

State-of-the-art review

In the past four decades, several experimental and numerical studies have been conducted to evaluate the fire resistance of precast, prestressed concrete hollow-core slabs. Most of these studies were limited to standard fire tests and simplified numerical analyses on precast, prestressed concrete hollow-core slabs under standard fire conditions.

Experimental studies

The notable fire resistance tests on precast, prestressed concrete hollow-core slab were performed by Abrams,[6] Borgogno et al.,[7] Breccolotti et al.,[8] Bailey and Lennon,[9] Schepper and Anderson,[10] Acker,[11] Fellinger,[12] and Jensen.[13] These fire tests were performed under standard fire conditions and subjected to service loads. In most cases the critical temperature in the strand was applied as the limiting criterion to evaluate failure of the slabs. The test parameters included slab thickness, cover thickness to reinforcement, concrete strength, and load. Besides evaluating fire resistance, some of these researchers also studied failure mechanisms in slabs under fire conditions.[10–13] Few researchers used test data to study the extent of fire-induced spalling in precast, prestressed concrete hollow-core slabs.[14–16]

Most of the aforementioned fire tests were performed under standard fire exposure solely to develop fire-resistance ratings for tested precast, prestressed concrete hollow-core slabs, or test data were used to extrapolate fire-resistance ratings for similar hollow-core slab configurations. Based on these fire tests, spalling, bond slip, and shear crushing were identified as possible factors contributing to failure in precast, prestressed concrete hollow-core slabs.[10–16] However, the effect of these factors on fire resistance is not fully quantified and the reasons for failure of hollow-core slabs due to development of such failure mechanisms are not well established. Moreover, these fire tests did not consider the effect of critical parameters, such as fire scenario, range of loading, and restraint. Thus the fire behavior of precast, prestressed concrete hollow-core slabs under realistic fire, loading, and restraint is not well studied.

Numerical studies

Breccolotti et al.,[8] Fellinger et al.,[12] Dotreppe and Franssen,[17] Chang et al.,[18] and Min et al.[19] conducted numerical studies on precast, prestressed concrete hollow-core slabs in fire. Basically, the finite element approach was used for numerical studies, with the slab being discretized using linear, plane, and solid elements.[8,12,17–19] These approaches for evaluating the fire resistance of precast, prestressed concrete hollow-core slabs typically comprised the following analytical steps, conducted at various time steps until failure occurred:

- calculation of fire temperature
- calculation of cross-sectional temperature
- calculation of deflection and strength during fire exposure
- evaluation of fire resistance based on limiting failure criteria

These numerical studies investigated some of the parameters affecting the fire resistance of hollow-core slabs, such as slab configuration, cover thickness, support condition, and load. However, the effects of several realistic parameters, namely the fire scenario, concrete strength, fire-induced restraint, and prestress, have not been studied. These models are also not capable of predicting spalling and bond and shear failure, as observed in fire tests on precast, prestressed concrete hollow-core slabs. In addition, the proposed numerical models lack full validation, which further limits their application.

Code provisions

The specifications for fire-resistant design are provided in building codes and national standards. Most of these provisions are prescriptive in nature and are based on results of standard fire tests. These tabulated fire-resistance values mostly depend on strand concrete cover thickness and minimum dimensions (depth) of the slab.

In the United States, concrete structures are to be designed in accordance with the *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)*[20] and prestressed concrete structures are to be designed in accordance with the *PCI Design Handbook: Precast and Prestressed Concrete*[21] and *Design for Fire Resistance of Precast/Prestressed Concrete*.[22] In the *PCI Design Handbook*, the fire resistance ratings for prestressed concrete floor or roof slabs are in tabular form based on the concrete cover thickness to reinforcement. Further, both *PCI Design Handbook* and *Design for Fire Resistance of Precast/Prestressed Concrete* provide a rational design methodology for evaluating the fire resistance of precast, prestressed concrete slabs based on strength degradation of strand with temperature.

Although ACI 318-11 does not contain fire provisions, it references ACI 216.1-07,[23] *Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies*, which gives prescriptive specifications for evaluating fire-resistance ratings of concrete and masonry structures based on ASTM E119[24] standard fire tests. ACI 216.1-07 provisions for determining the fire resistance of precast, prestressed concrete slabs are similar to provisions in the *PCI Design Handbook* and the *International Building Code*.[25] ACI 216.1-07 also specifies minimum sectional dimensions (slab thickness) and cover thickness (concrete cover over strands) for achieving a required fire-resistance rating in precast, prestressed concrete slabs. For hollow-core slabs, the effective slab thickness is obtained by dividing the net cross-sectional area by its width. Further, the fire ratings in the *PCI Design Handbook* and ACI 216.1-07 are given for different end conditions and aggregate types.

Eurocode 2[26] provides three options for determining the fire resistance of precast, prestressed concrete slabs as tabular, simplified, or advanced methods. The tabular method is prescriptive, based on standard fire tests. It is the simplest and most direct method for calculating fire resistance. The table provides fire resistance based on the minimum thickness of the slab (excluding floor finishes), axis distance of the reinforcement (equivalent to concrete cover thickness), and different configurations of slabs (simply supported, continuous, flat, and ribbed).

The simplified method in Eurocode 2 uses temperature-induced strength reduction factors to evaluate the reduction in flexural capacity of a slab at any given fire exposure time and, thus, its fire resistance. This method is applicable where the slab is subjected to uniform fire exposure temperature and loading. Eurocode 2 also provides steps associated with advanced calculation methods to evaluate the thermal and structural responses of concrete structures (hollow-core slabs) by applying heat transfer and structural mechanics principles. This method requires validation of numerical calculations with test data. Though this method might lead to an accurate estimation of fire resistance, validated models for evaluating the fire response of prestressed concrete structures are lacking. In 2011 new equations for calculating the shear and anchorage capacity of hollow-core slabs in fire were introduced in Eurocode 2 Annex G.[27]

Other design codes, such as Australian code AS 3600,[28] New Zealand concrete standard NZS 3101,[29] and the *National Building Code of Canada*,[30] include provisions similar to those of *PCI Design Handbook* and ACI 216.1-07.

Numerical model

A numerical model for tracing the fire response of precast, prestressed concrete hollow-core slabs is developed using finite element analysis software. The model accounts for geometric and material nonlinearities and temperature-dependent thermal and mechanical properties of concrete and reinforcing and prestressing steel. Fire-resistance analysis of hollow-core slabs was conducted at incremental time steps from 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 in this paper.

Discretization details

For fire-resistance analysis, the given precast, prestressed concrete hollow-core slab is discretized into elements. Two sets of elements are needed for undertaking thermal and structural analysis in the software. Three elements were used for both thermal analysis and structural analysis.

A surface effect element was overlaid onto the fire-exposed surface of the slab to simulate the radiation of heat from the fire source onto the bottom surface of the slab. A three-dimensional (3-D) thermal conduction element is used to simulate transmission of heat into the concrete slab from the surface of the slab. This element has eight nodes with a single degree of freedom, namely temperature, at each node and is applicable to a 3-D, steady-state, or transient thermal analysis. A uniaxial element with the capability to conduct heat between nodes is used and 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.

Because the analysis is undertaken in two steps, the thermal elements were transformed (switched) into structural elements after completion of the thermal analysis. In the finite element analysis software, element switching can be used to directly adopt results from thermal analysis into structural analysis.

The conversion was performed as follows:

- 3-D solid thermal elements were converted to 3-D solid concrete elements.

- Thermal line elements were converted to prestressing strand line elements.

- Thermal surface effect elements were converted to structural surface effect elements.

In structural analysis, the 3-D solid element is used to model concrete. This 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 that have three degrees of freedom at each node: translation in nodal x, y, and z directions. The 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: translation in the nodal x, y, and z directions. Plasticity, creep, rotation, and large strain deformations in prestressing steel can also be simulated using this element. The structural element that was converted from the thermal surface effect element does not have any role (contribution) in structural analysis. **Figure 1** shows a typical precast, prestressed concrete hollow-core slab, discretized into various elements.

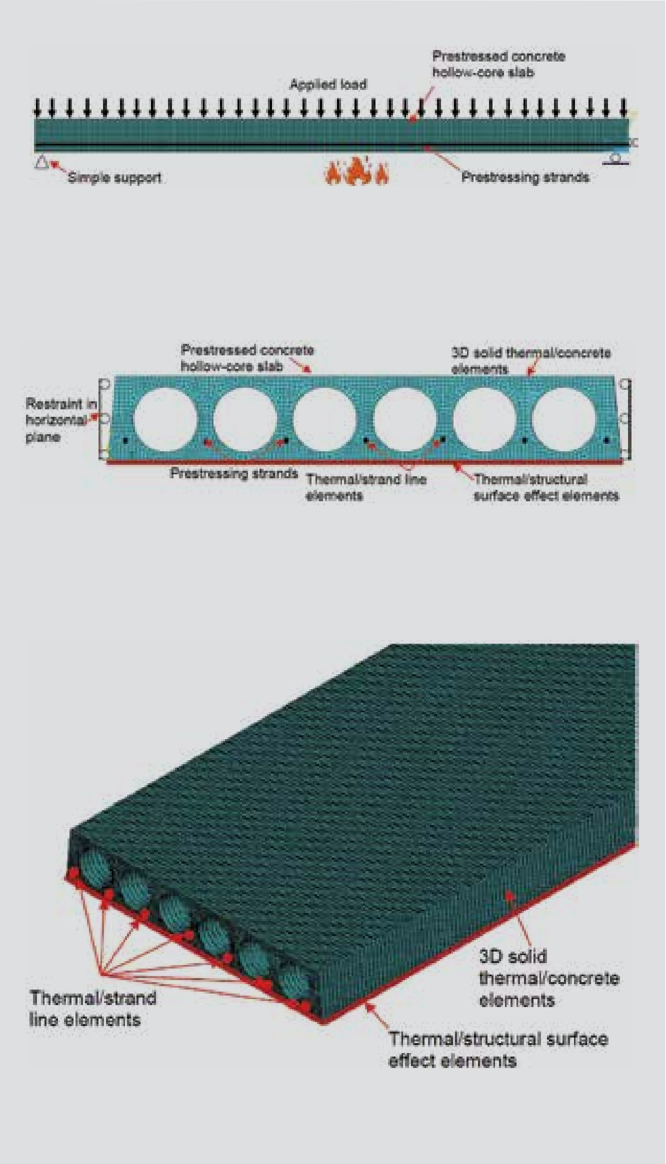


Figure 1. Layout of typical precast, prestressed concrete hollow-core slab and its discretization for finite element analysis.

High-temperature material properties

When a hollow-core 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 must 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 and specific heat and emissivity factors, while mechanical properties include density, elastic modulus, Poisson's ratio, stress-strain relations, and thermal expansion. All of these properties are defined as varying with temperature using the relations specified in Eurocode 2 (**Fig. 2** to **11**).

In the finite element software, plastic behavior of concrete is defined using Willam and Warnke's constitutive model,[31] which is capable of defining concrete behavior in both tension and compression. Under loading, top fibers of the slab 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 an isotropic, multilinear stress-strain curve varying with temperature, while tensile behavior is defined by providing concrete damage parameters. In the finite element software, the damage in concrete is defined in terms of crack opening and crack closing parameters. These parameters are defined as opened β_t and closed β_c crack shear transfer coefficients, and are taken to be 0.2 and 0.7, respectively. Shear transfer coefficients are taken as zero when there is a total loss of shear transfer (representing a smooth crack) and 1.0 when there is no loss of shear transfer (representing a rough crack).

The temperature-dependent thermal properties of reinforcing bars and prestressing strands are adopted from Eurocode 2 (Fig. 7 to 9). The variation of the stress-strain relationship with temperature is based on Eurocode 2 (Fig. 10 and 11).

Loading and boundary conditions

A precast, prestressed concrete hollow-core slab exposed to fire is subjected to both thermal and mechanical loading. To simulate a realistic scenario, analysis starts with the application of load on the slab, which is generally expressed as a percentage of the total capacity of the slab. After initial deflections stabilize, the slab is exposed to fire (thermal loading). Both mechanical and thermal loading are continued until failure of the slab. The slab can be subjected to any specified fire exposure, which is to be input as a time-temperature

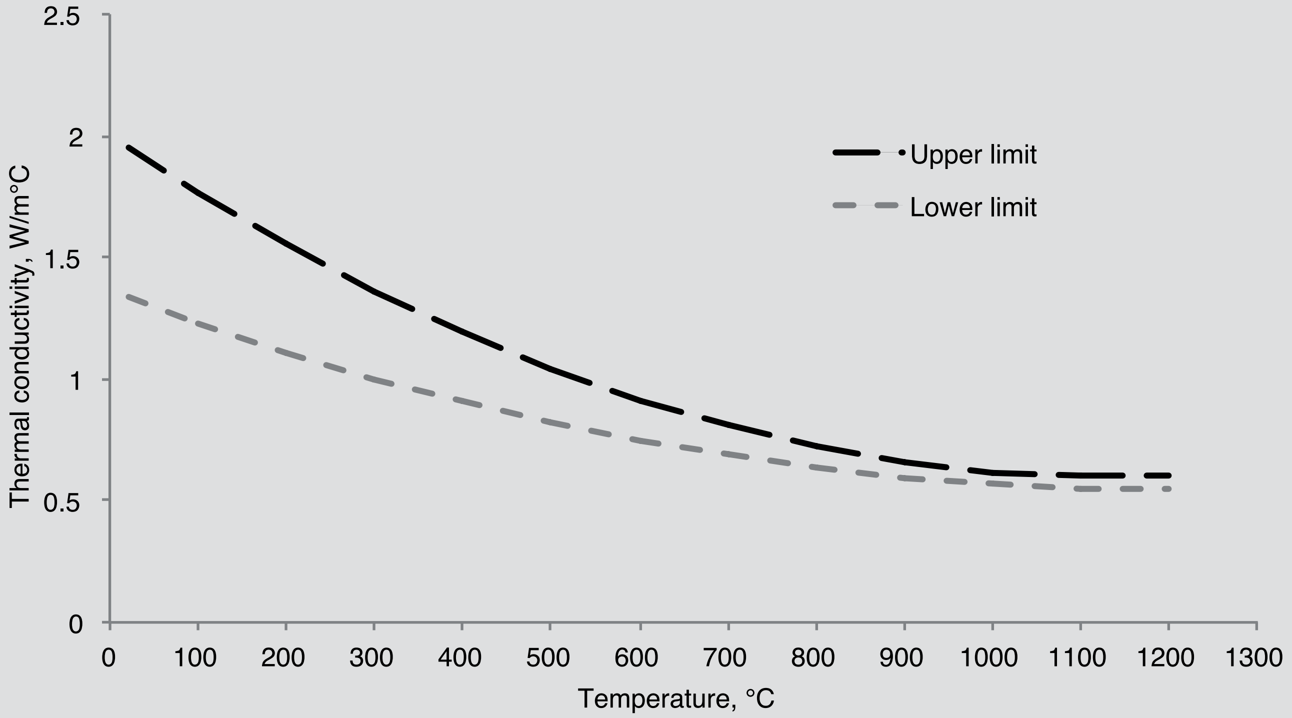


Figure 2. Variation of thermal conductivity k_c of concrete with temperature. Note: 1 m = 3.28 ft; °C = (°F – 32)/1.8; 1 W = 0.74 lbf-ft/sec.

curve. This can be a standard fire (ASTM E119 or ISO 834[32]) or a typical design fire comprising a heating and cooling phase.

Precast, prestressed concrete hollow-core slabs form part of floor assemblies, so to model the effect of adjacent slabs, the longitudinal edges of the slab are assumed to be restrained

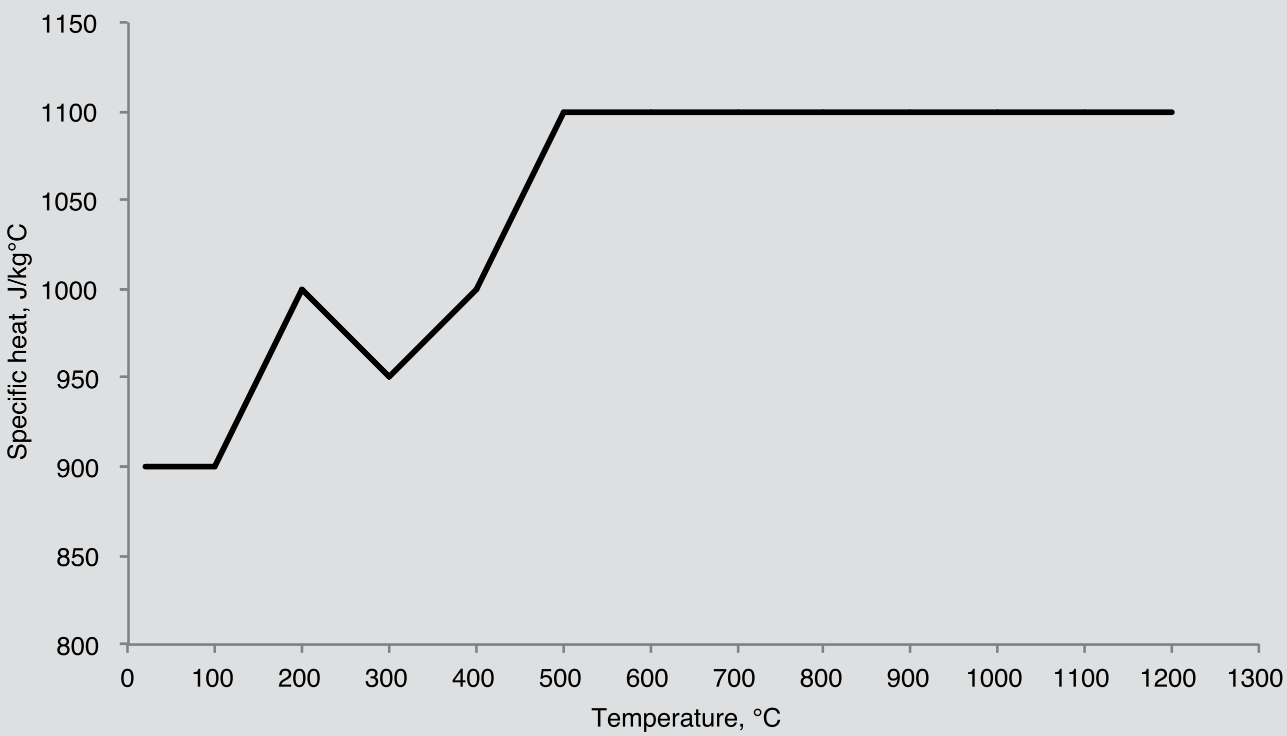


Figure 3. Variation of specific heat c_p with temperature. Note: 1 kg = 2.20 lb; °C = (°F – 32)/1.8; 1 J = 0.74 lbf-ft.

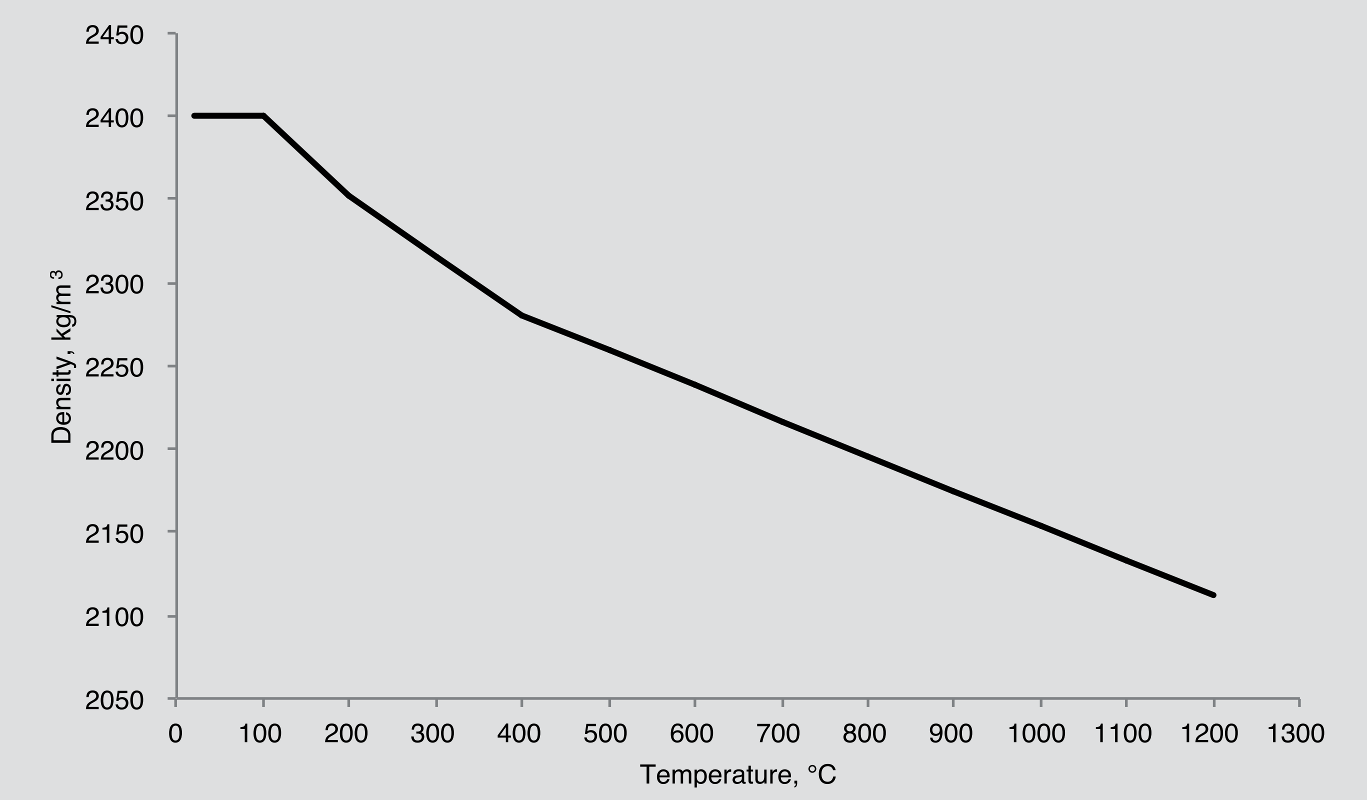


Figure 4. Variation of density ρ of concrete with temperature. Note: 1 m = 3.28 ft; 1 kg = 2.20 lb; °C = (°F – 32)/1.8.

horizontally and free to deflect vertically. This condition simulates the edge conditions in a slab, facilitated by the presence of other slabs in the transverse direction, which is considered more critical than edge slabs. The model is capable of simulating this effect. Figure 1 shows a layout of a typical hollow-core slab with applied load and boundary conditions.

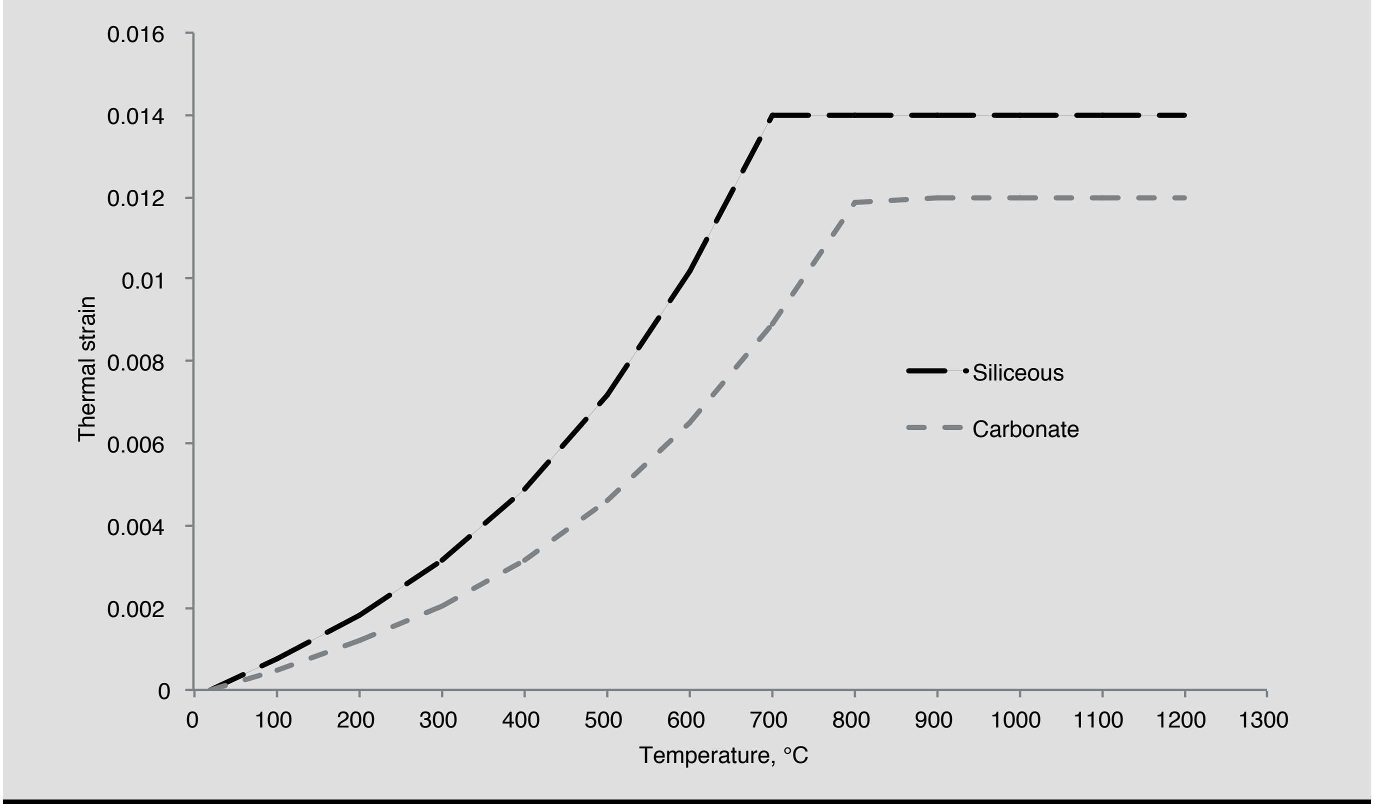


Figure 5. Variation of thermal strain ε_{th} of concrete with temperature for siliceous and carbonate aggregate. Note: °C = (°F – 32)/1.8.

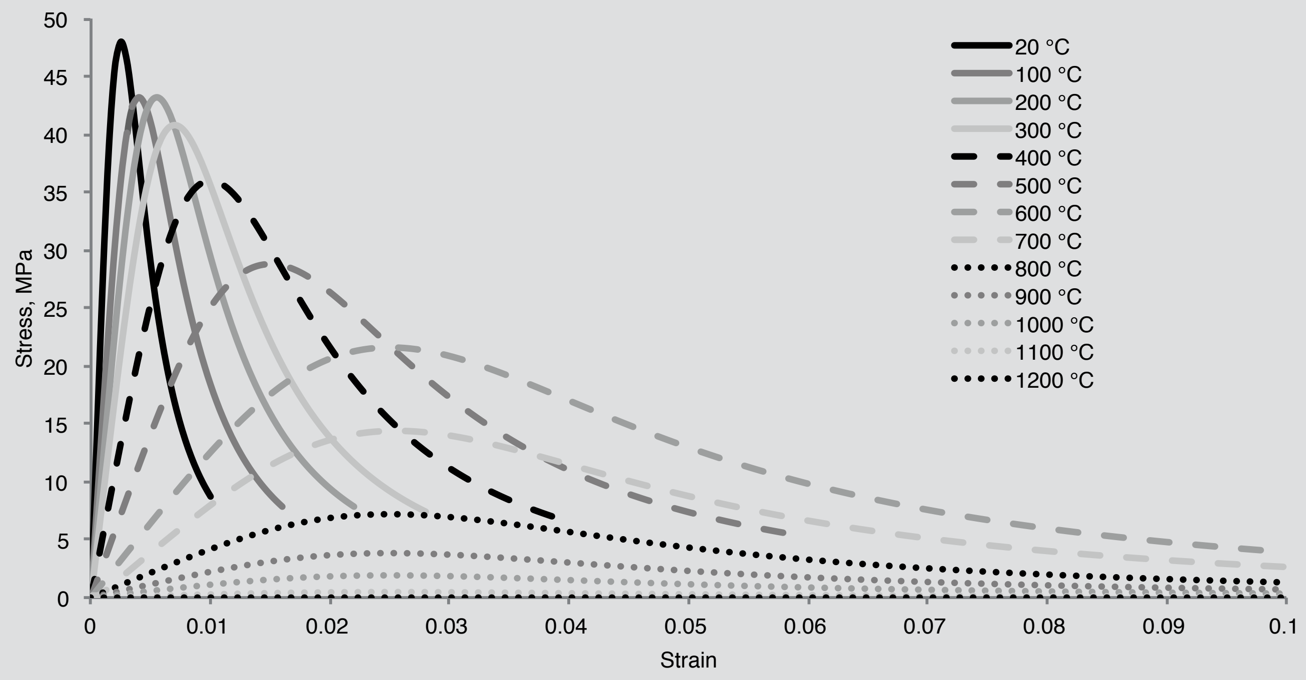


Figure 6. Variation of stress σ–strain ε relationship of concrete with temperature. Note: 1 MPa = 0.145 ksi; °C = (°F – 32)/1.8.

Failure criteria and numerical convergence

The conventional approach of evaluating fire resistance is based on reaching thermal or strength failure limit states as specified in ASTM E119. Accordingly, the thermal failure of a prestressed concrete hollow-core slab is said to occur when the following happens:

- The average temperature on the unexposed surface of the slab exceeds 139°C (282°F) at nine points or a maximum of 181°C (356°F) at any single point on the unexposed surface of the slab.

- The temperature of prestressing strand exceeds the critical temperature, which is generally taken as 427°C (800°F) for prestressing steel. Strand loses 50% of its strength at around 427°C.

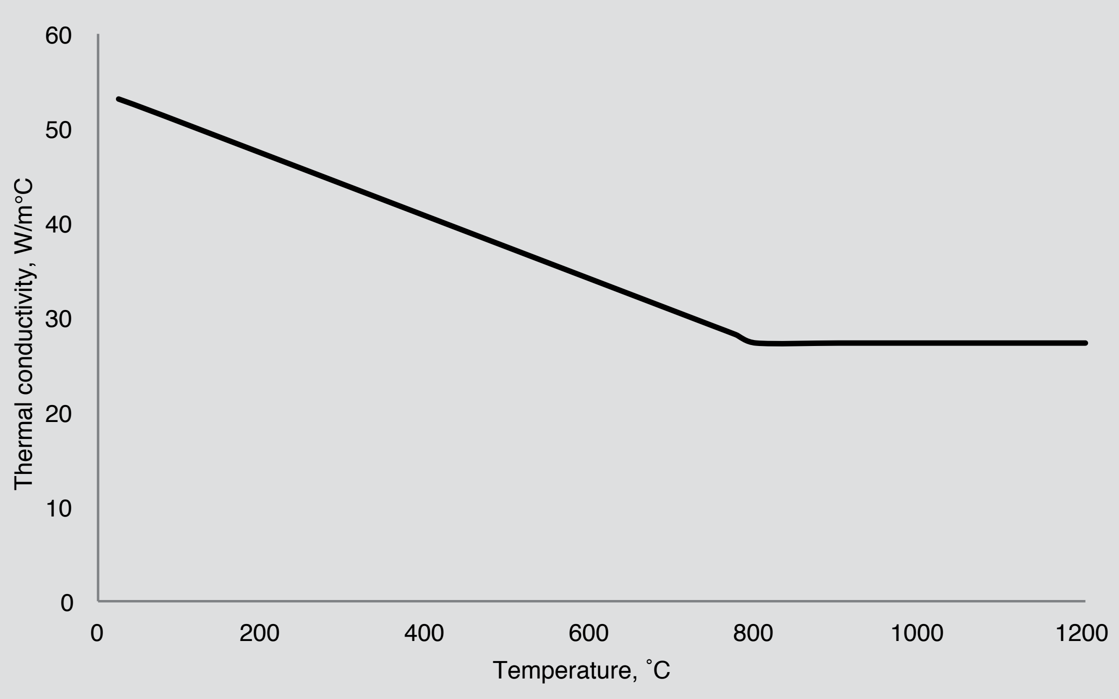


Figure 7. Variation of thermal conductivity *k* of steel (prestressing and reinforcing) with temperature. Note: 1 m = 3.28 ft; °C = (°F – 32)/1.8; 1 W = 0.74 lbf-ft/sec.

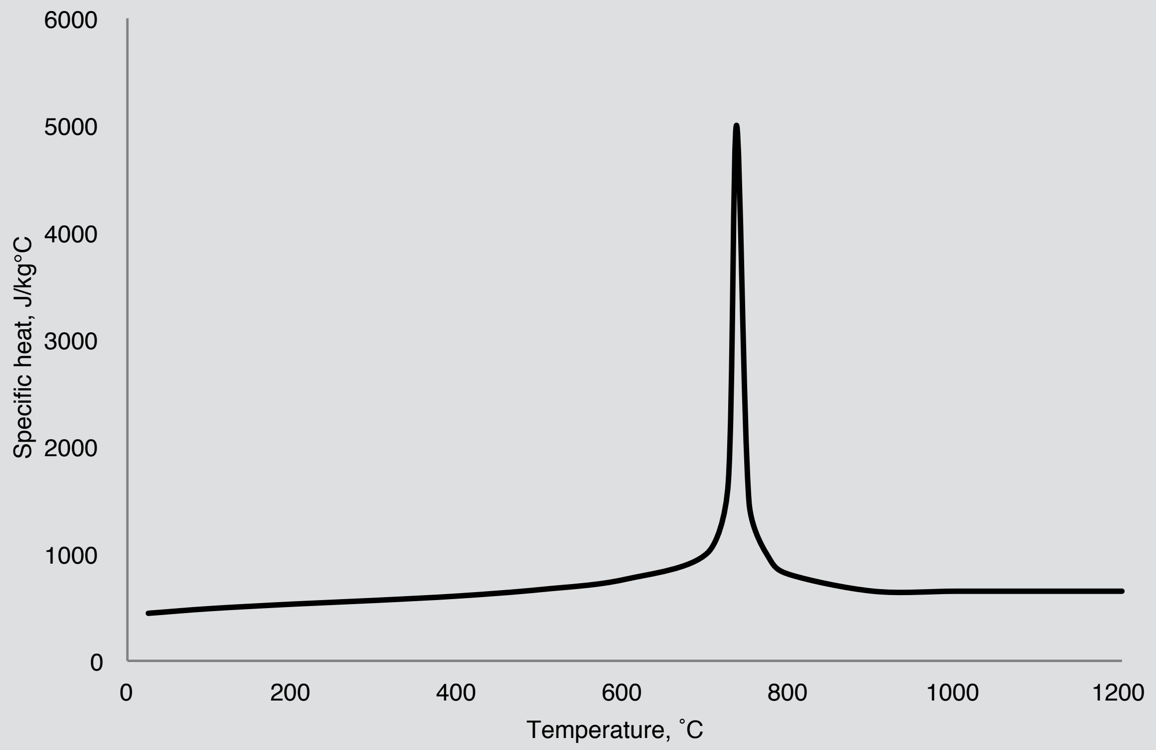


Figure 8. Variation of specific heat c_p of steel (prestressing and reinforcing) with temperature. Note: 1 kg = 2.20 lb; °C = (°F – 32)/1.8; 1 J = 0.74 lbf-ft.

The strength failure is said to occur when the slab is unable to resist the applied load. This often occurs when moment capacity at the midsection of the slab drops below the moment due to applied load.

In addition to these limit states, deflection and rate of deflection can play a major role in the behavior of beams or slabs exposed to fire.[33] A deflection criterion is applied to define failure in slabs or beams at ambient conditions, and this criterion can also be applied to define realistic failure of a prestressed slab exposed to fire. Deflections and rates of deflections are expected to be higher than

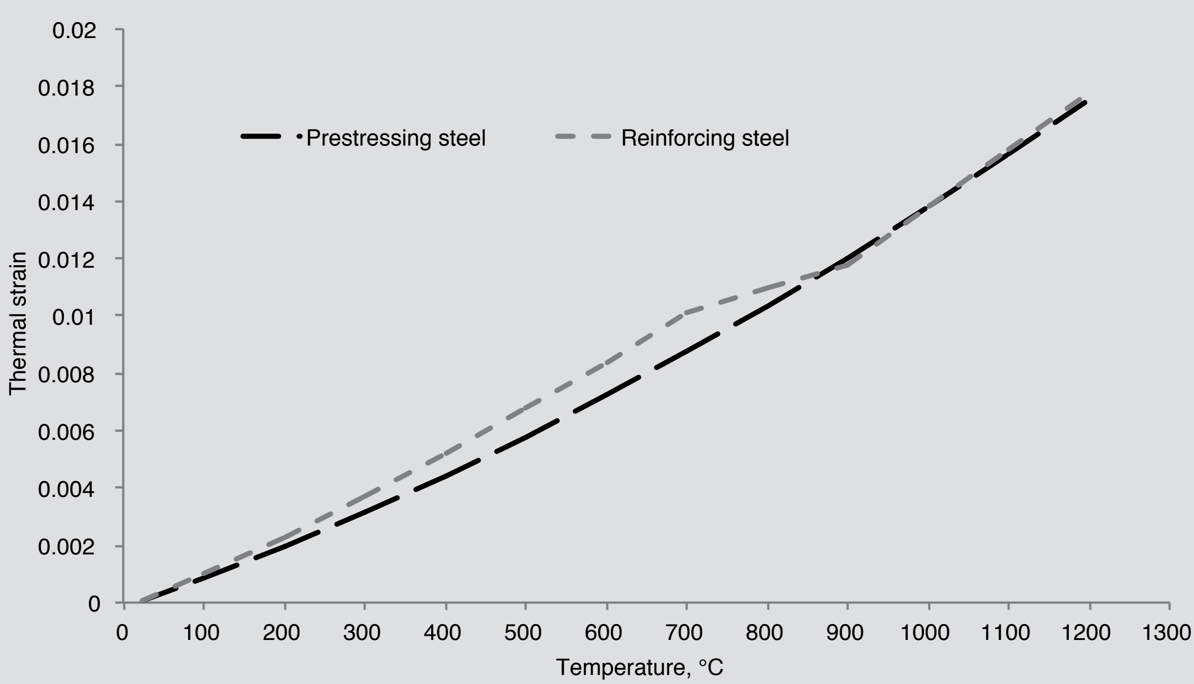


Figure 9. Variation of thermal strain ε_{th} of prestressing and reinforcing steel with temperature. Note: °C = (°F – 32)/1.8.

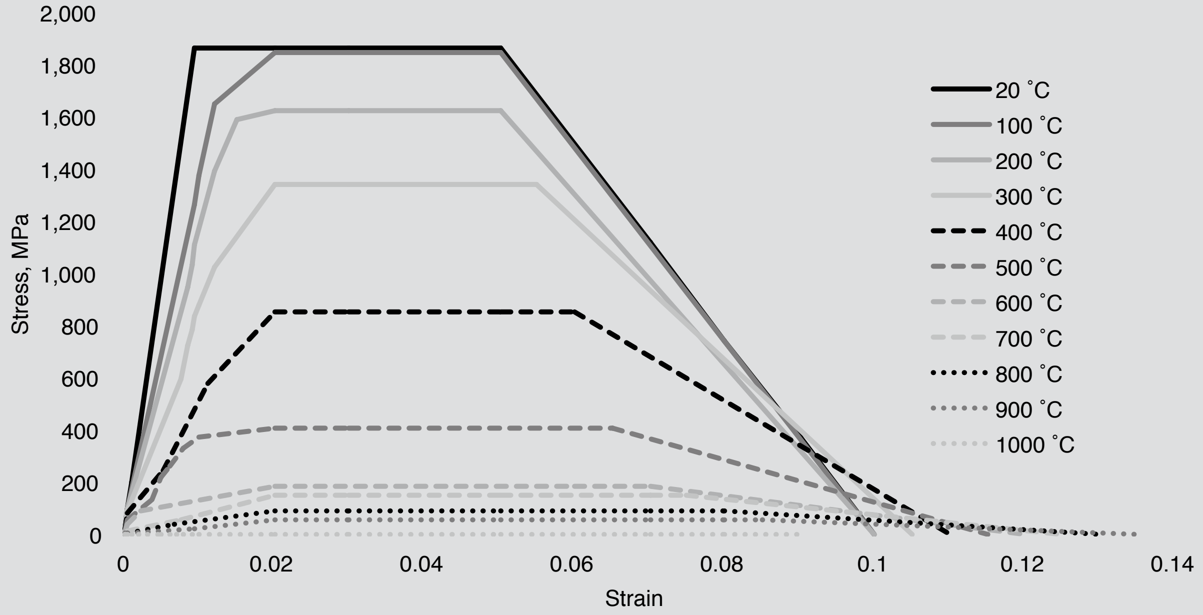


Figure 10. Variation of stress σ–strain ε relationship of prestressing strands (7-wire, low-relaxation, 1860 MPa, Class B, cold worked) with temperature. Note: 1 MPa = 0.145 ksi; °C = (°F – 32)/1.8.

those at room temperature because of deterioration of member stiffness at elevated temperatures and also because of temperature-induced creep. The limit state criteria for deflection and rate of deflection are adopted from British standard BS 476[34] and are applied to evaluate the failure of hollow-core slabs. BS 476 defines failure of prestressed slabs as occurring when either the maximum deflection of the slab exceeds $\frac{L}{20}$ at any fire exposure time, where L is the span length of the slab or the rate of deflection exceeds the limit given by $\frac{L^2}{9000d}$, where d is the effective depth of the slab.

At each time increment, the Newton-Raphson technique is used to obtain numerical convergence in the finite element model. In thermal analysis, divergence of the solution can occur when temperature variation at each node exceeds

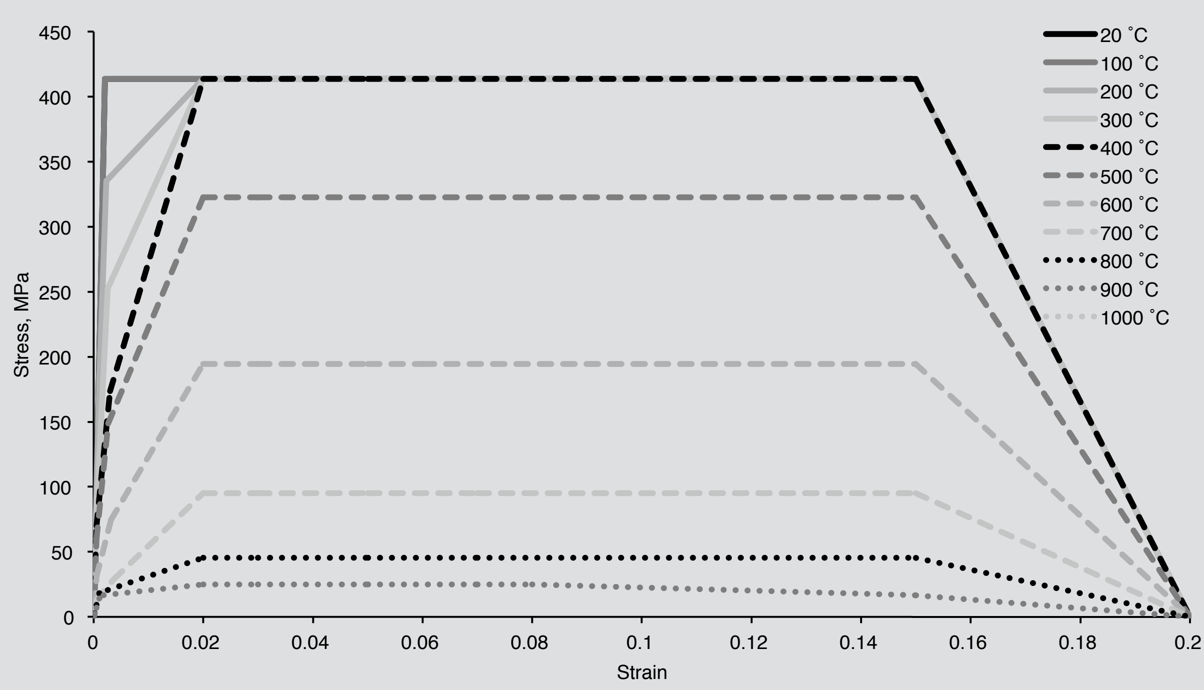


Figure 11. Variation of stress σ–strain ε relationship of reinforcing steel (414 MPa, hot rolled) with temperature. Note: 1 MPa = 0.145 ksi; °C = (°F – 32)/1.8.

0.5°C (0.9°F). In structural analysis, divergence can occur when force convergence exceeds a tolerance limit of 10%.

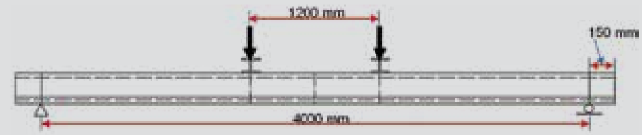
Model validation

This model is validated by comparing predicted response parameters (temperatures, deflections, and failure times) from the finite element software with fire test data. For this validation, two precast, prestressed concrete hollow-core slabs tested by Breccolotti et al.[8] were selected, and the validation was conducted in the entire range of fire loading, (before exposure to collapse). The thermal and structural response parameters predicted by the finite element software were compared with fire test data.

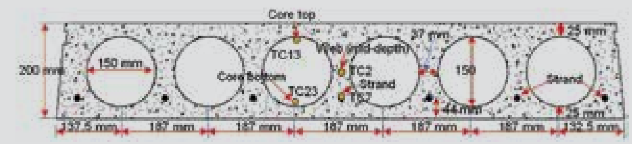
Characteristics of slab

Both hollow-core slabs (slab 1 and slab 2) selected for validation are of similar geometry having six cores and seven strands (**Fig. 12**). The slabs are 4 m (13 ft) long, 1.2 m (4 ft) wide, and 200 mm (8 in.) thick. The cores are 150 mm (6 in.) diameter with 25 mm (1 in.) concrete thickness at the bottom of the core. The slabs were cast with concrete that has a compressive strength of 48 MPa (7000 psi) and density of 1900 kg/m^3 (119 lb/ft^3). The prestressing strands are 9.5 mm ($^3/_8$in.) diameter and are low-relaxation strands (with a yield stress of 1860 MPa [270 ksi]). The cover thickness over the strands is 44 mm ($1^3/_4$ in.). 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 midheight, bottom of core, and top of core, respectively) as indicated in Fig. 12, are used. **Table 1** lists details of the slabs.

Before fire exposure, the slabs were loaded in four-point loading, with simple supports (Fig. 12). This loading was applied to cause a bending moment at the midspan section equal to 60% of service loads. Specifically, a total of 40 kN (9.0 kip) (20 kN [4.5 kip] at each load point) was applied, corresponding to 33.7 kN-m (24.9 kip-ft) midspan bending moment. The slabs were tested by exposing them to an ISO 834 fire scenario from the bottom side. This ISO 834 fire is equivalent to that of ASTM E119 fire exposure (**Fig. 13**). During fire tests, the progression of temperature and deflections in the slab were monitored. Full details of the fire tests, including detailed results from experiments, can be found elsewhere.[4] **Table 2** presents the fire-resistance ratings for these hollow-core slabs, which were calculated in accordance with various code provisions. The fire resistance is evaluated based on concrete cover thickness and slab depth and also using rational design methodology. It is calculated as 90 minutes as per PCI,[21,22] ACI 216.1-07, and Eurocode 2.



Layout of hollow-core slab with loading



Cross-sectional details and thermocouple details

Figure 12. Layout and cross-sectional details of a tested prestressed concrete hollow-core slab. Note: TC = thermocouple. 1 mm = 0.0394 in.

Analysis details

The selected precast, prestressed concrete hollow-core slab was analyzed by discretizing the slab into various elements as discussed in the discretization section. The thermo-mechanical analysis was conducted at five-minute time intervals until 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, were used for validation. The analysis started by subjecting the slab to static loads. A transient thermal load correspond-

Table 1. Geometric and material characteristics of tested slabs

Parameter	Slab-1[8]	Slab-2[8]
Dimension (length × width × thickness)	4.3 × 1.2 × 0.2 m	4.3 × 1.2 × 0.2 m
Core diameters	6 to 150 mm	6 to 150 mm
Concrete compressive strength f'_c	C48 MPa	C48 MPa
Prestressing strand	7 to 9.5 mm, 1860 MPa low relaxation	7 to 9.5 mm, 1860 MPa low relaxation
Fire exposure	ISO 834	ISO 834

Note: 1 mm = 0.0394 in.; 1 m = 3.28 ft; 1 MPa = 0.145 ksi.

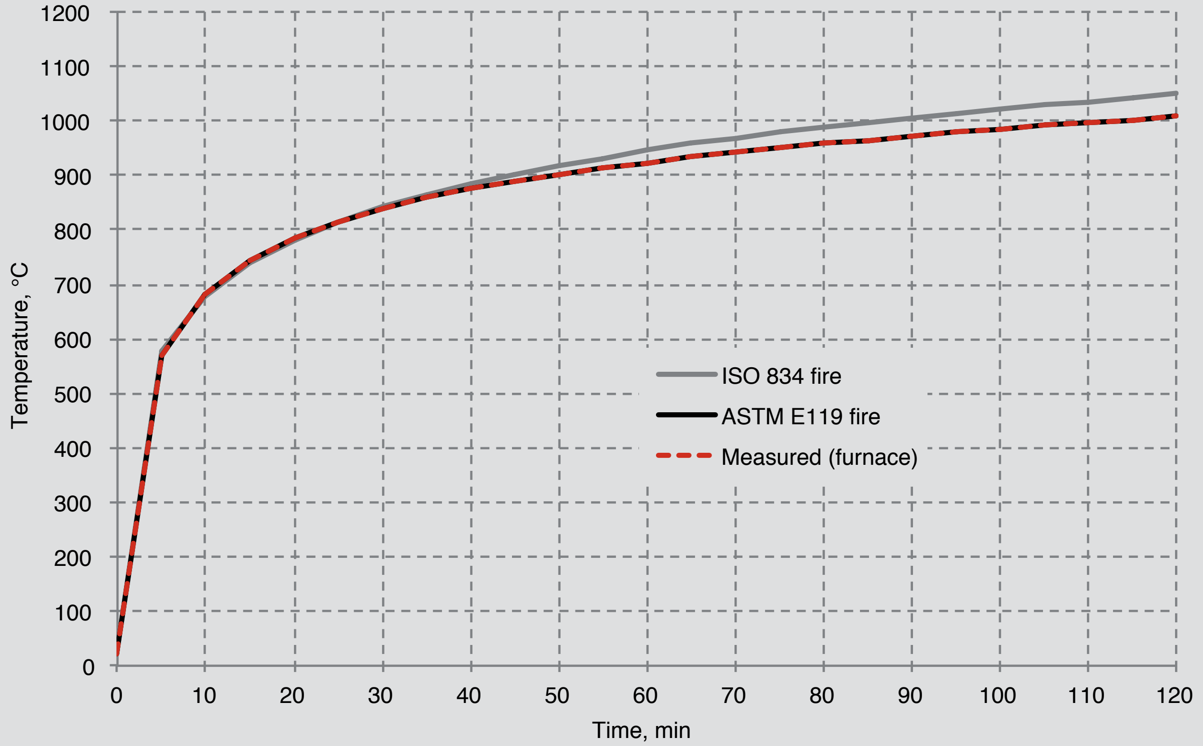


Figure 13. Standard fire time–temperature curves and measured furnace temperature. Note: °C = (°F – 32)/1.8.

ing to ISO 834 fire curve (test fire) (Fig. 13) was applied after steady state had been achieved from static mechanical loading. The slab was assumed to have failed when the strength (moment capacity), deflection, or rate of deflection exceeds its permissible limit. Arbitrary failure, based on temperature in prestressing strand exceeding critical temperature, was also evaluated.

Thermal response

For validating, predicted temperatures from the finite element software were compared with fire test data (**Fig. 14**) at various locations on the slab, namely the strand, web midheight, and core (bottom and top). The temperature progression in the slab followed the expected trend, with higher temperatures at the bottom layers (closer to the fire source) and gradually increasing with fire exposure time. The layers closer to the fire-exposed surface had a higher rate of temperature rise than layers that are farther from the fire source. The strands, which are at 44 mm ($1^3/_4$ in.) depth from the bottom surface, did not experience any temperature rise in the first 10 minutes after ignition. The delay in temperature rise in the inner layers of the slab can be attributed to the high thermal mass of concrete.

In the model, after about 10 minutes strand temperatures increased almost linearly. At 60 minutes the strand temperatures reached 239°C (462°F), while at 120 minutes the corresponding temperature in prestressing strands was 415°C (779°F).

Table 2. Failure times of hollow-core slab based on various failure criteria and different code provisions

Analysis	Failure criteria	Fire resistance, minutes		
		ANSYS model	Slab-1[8]	Slab-2[8]
ANSYS	Unexposed surface temperature	>120	n/a	n/a
	Deflection	100	76	90
	Strength	95	n/a	n/a
PCI	Strand temperature (cover thickness)	90	n/a	n/a
ACI 216.1		90	n/a	n/a
Eurocode 2		90	n/a	n/a

Note: n/a = not applicable.

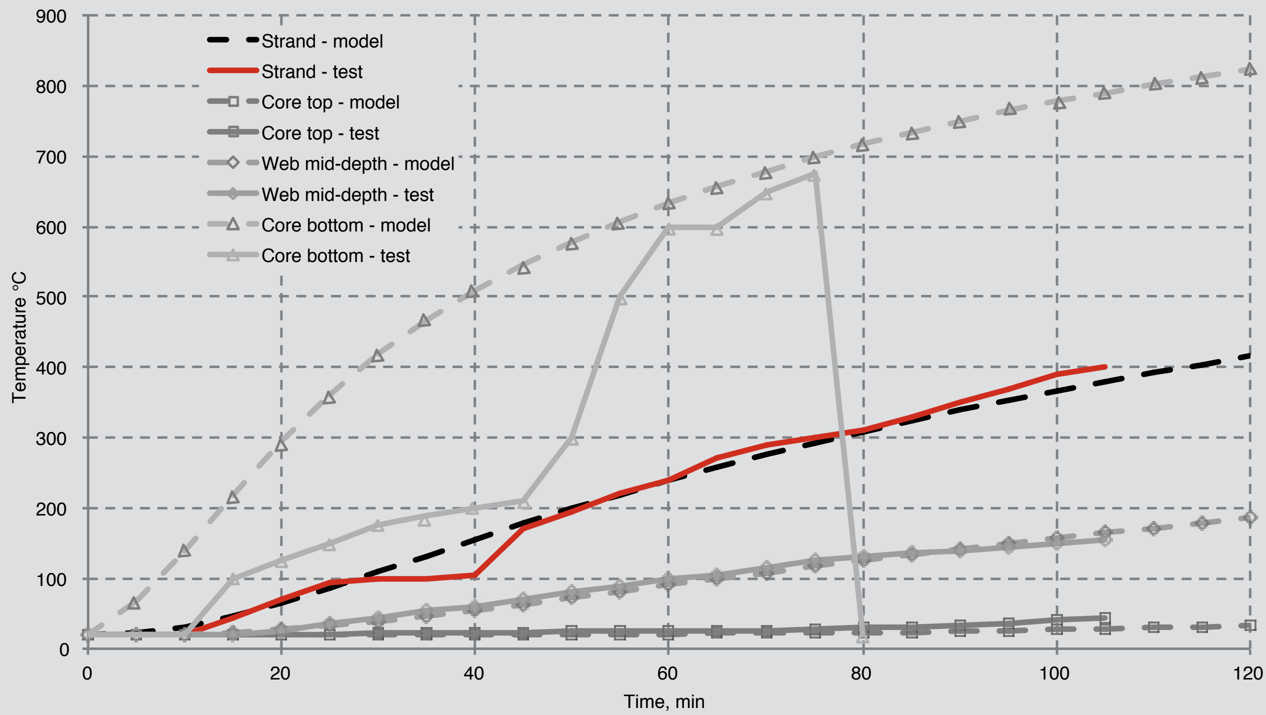


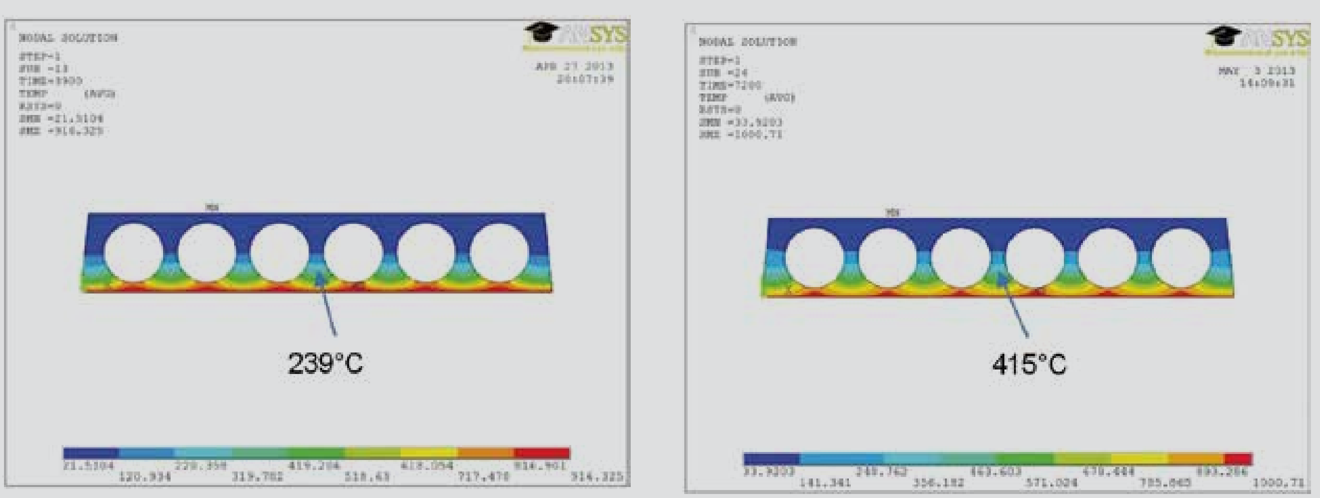
Figure 14. Comparison of predicted and measured temperatures in hollow-core slab. Note: °C = (°F – 32)/1.8.

Due to a high thermal mass, the top layers of concrete and the unexposed surface of the slab (midsection) experienced a minimal increase in temperature, reaching only a maximum of 54°C (129°F) and 45°C (113°F) respectively at 120 minutes. **Figure 15** shows a typical temperature field in the slab section at 60 and 120 minutes, as predicted by the model.

A close review of Fig. 14 indicates good agreement between predicted and measured temperatures, with the exception of core temperatures (bottom and top). This discrepancy can be attributed to various complexities involved in the placement of the thermocouples in the hollow-core slabs during fabrication, especially in the core. Also, based on the reported information (measured data), the erratic temperature readings of these thermocouples in the cores could be due to the occurrence of even minor fire-induced spalling during fire tests.[8] This spalling was not accounted for in the analysis.

Structural response

As part of structural validation, predicted midspan deflection was compared with measured deflection in two slabs (**Fig. 16**).[8]



Temperature field at 60 minutes

Temperature field at 120 minutes

Figure 15. Temperature field in precast, prestressed concrete hollow-core slab at 1 and 2 hours. Note: °C = (°F – 32)/1.8.

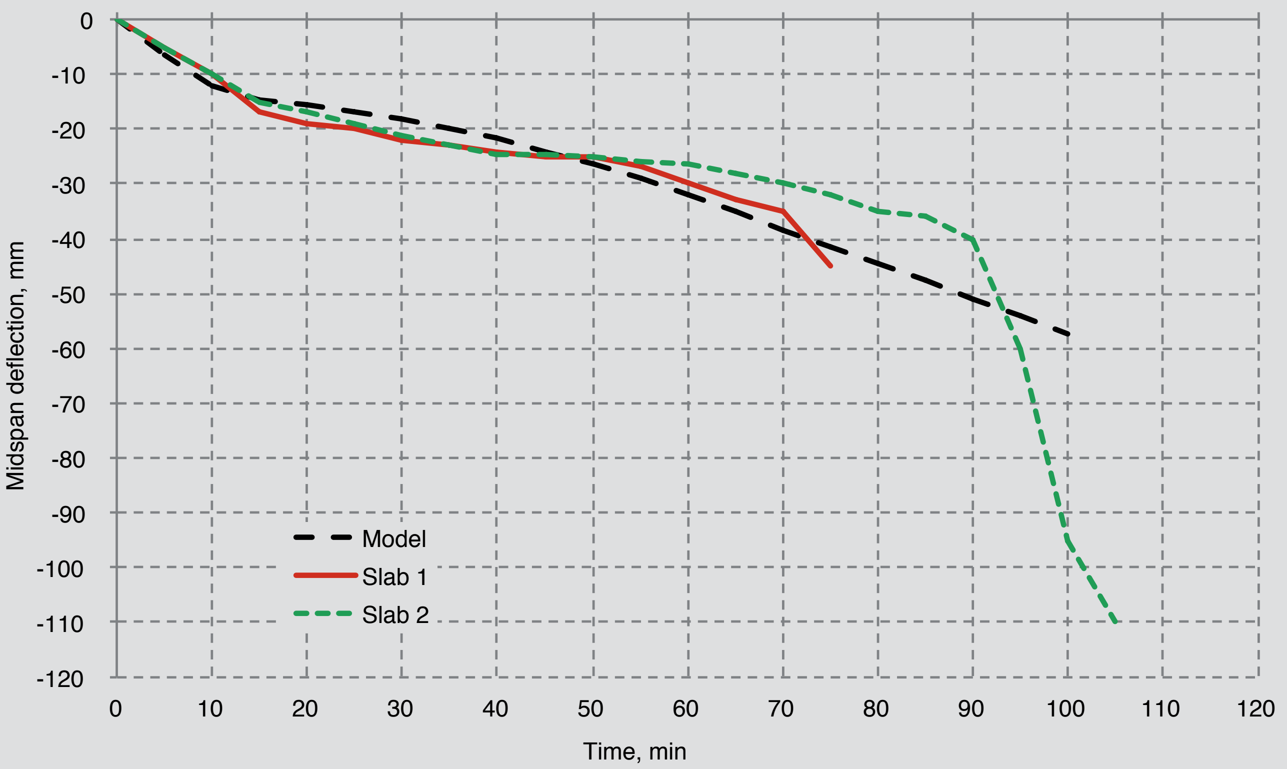


Figure 16. Comparison of predicted and measured deflection at midspan. Note: 1 mm = 0.0394 in.

At ambient conditions, precast, prestressed concrete hollow-core slabs incur initial camber due to prestressing. The initial camber in the hollow-core slab, calculated to be 9 mm (0.35 in.), from analysis compares well with the camber reported by the researchers.[4] The deflection started to increase after fire exposure (Fig. 16). This immediate increase in deflection can be attributed to the thermal expansion of the concrete. Because the hollow-core slabs were exposed to fire only on the bottom surface, significant thermal gradients and related thermal strains developed at the bottom of the slab. The deflection, mainly resulting from thermal strains, stabilized after 15 minutes as the temperatures of the inner layers of the slab increased. The increase in deflection was minimal from 15 to 30 minutes because there was little loss of stiffness, as the temperatures in prestressing strands (and upper layers of concrete) remained below 100°C (212°F). After 30 minutes of exposure deflection further increased due to strength and stiffness degradation in concrete and prestressing strands at higher temperatures. The deflection increased gradually until 100 minutes of fire exposure, beyond which the slab experienced a rapid increase in deflection, indicating the onset of structural instability. Figure 16 shows reasonable agreement between the predicted and measured deflections. **Figure 17** illustrates deflected profiles of the hollow-core slabs before fire exposure and at 100 minutes into fire.

Failure modes and fire resistance

In the fire tests, slab 1 was reported to have failed under shear crushing at 76 minutes, while slab 2 was reported to have failed at 90 minutes because of excessive deflection.[8] The discrepancy between the 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 the formation of pass-through vertical holes, as reported by researchers. On the other hand, slab 2 did not exhibit fire-induced spalling, but the test was aborted when the deflection limit was exceeded. The absence of spalling in slab 2 can be attributed to lower moisture content (relative humidity) at the time of testing because of a longer curing time.

Based on results output from the finite element software, the fire resistance of a hollow-core slab was evaluated by applying different failure criteria. In the finite element software analysis, nonconvergence occurred at 100 minutes (time step), indicating the onset of instability in the slab. This can be attributed to a significant degradation of stiffness in both concrete and prestressing steel at high temperatures. At 100 minutes, prestressing strands reached a temperature of about 400°C (752°F) and concrete (at bottom layers) reached a temperature of about 800°C (1472°F), which resulted in a rapid rise in deflection in the slab, that is, failure. **Figure 18** illustrates

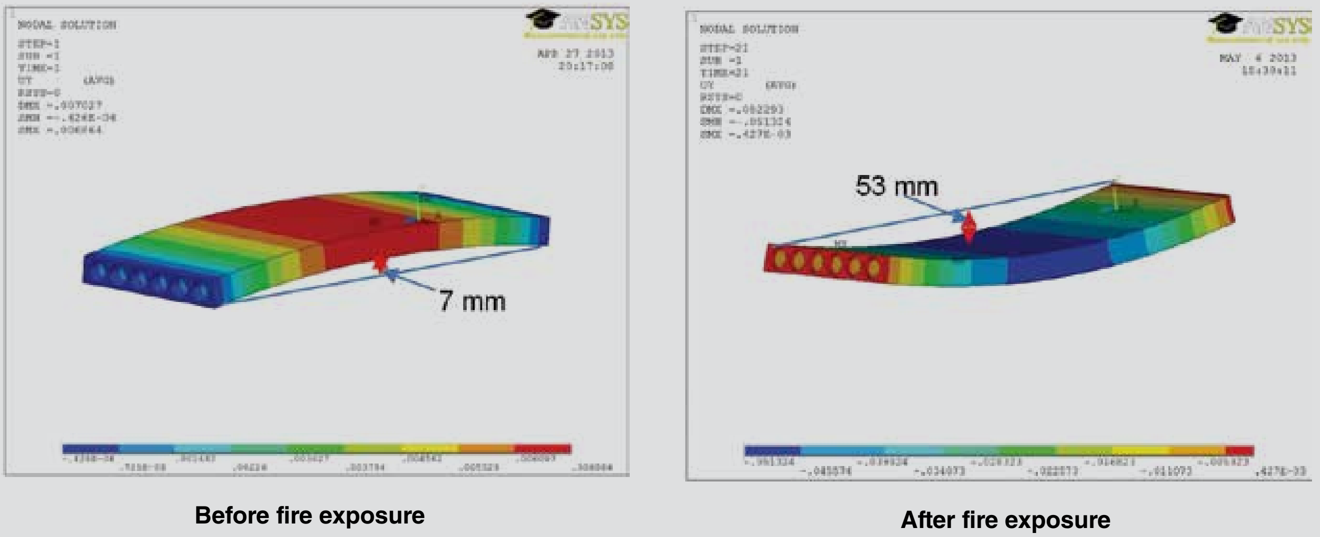


Figure 17. Deflected profile of hollow-core slab before and after fire exposure. Note: 1 mm = 0.0394 in.

the variation of the moment capacity of hollow-core slab with time of fire exposure. There was no degradation of capacity in the first 25 minutes. This can be attributed to temperatures in the range of 400°C in concrete (bottom layers) and 100°C (212°F) in the strands in the first 25 minutes (Fig. 14). Beyond 100°C (212°F), the strands started to lose strength, and this is reflected in moment capacity degradation (Fig. 18).

Based on the unexposed surface temperature criterion, the slab did not reach failure up to 120 minutes because the maximum temperature on the unexposed surface of the slab reached only 45°C (113°F) at 120 minutes. However, based on moment capacity of the slab, failure occurred at 95 minutes, when the moment capacity of the hollow-core slab dropped below the applied moment. This failure is dependent on temperature rise in the slab and the associated loss of strength and modulus of the prestressing strand, which in turn is a function of temperature in the strand. The fire resistance of this slab was evaluated based on code provisions in PCI,[21,22] ACI 216.1-07, and Eurocode 2. These provisions are based on concrete cover thickness

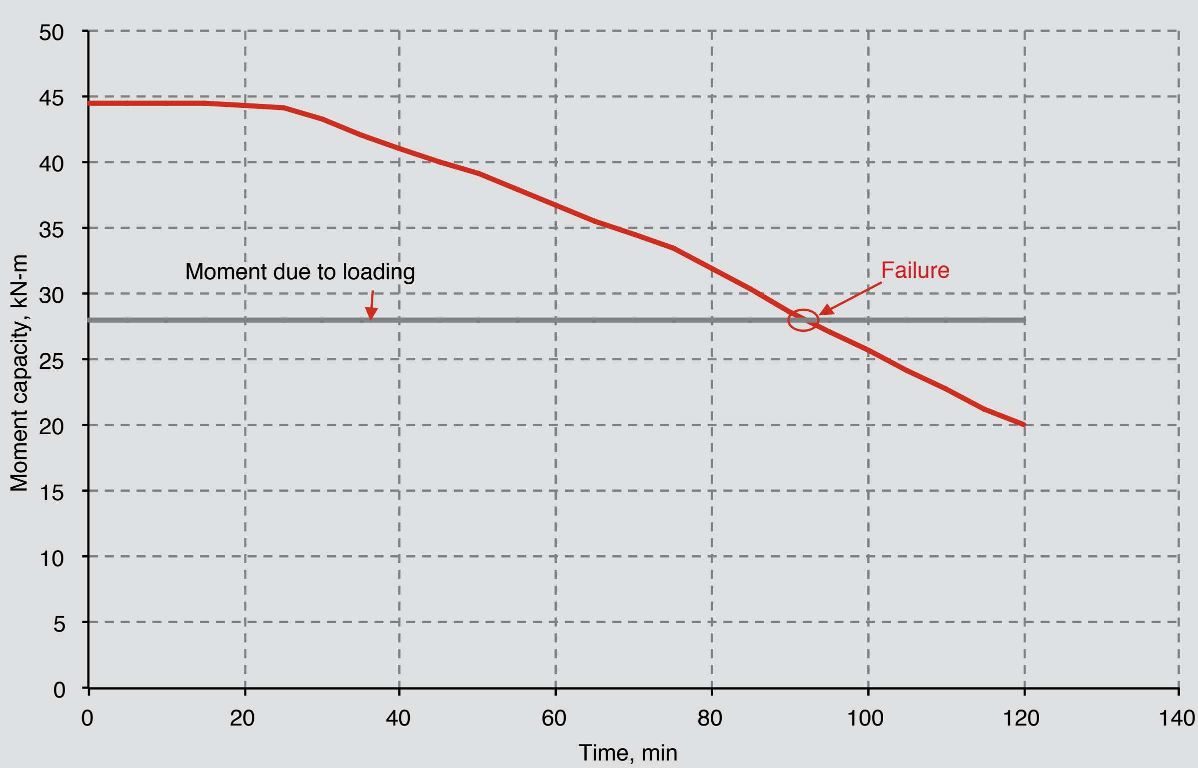


Figure 18. Variation of moment capacity of hollow-core slab with fire exposure time (model). Note: 1 m = 3.28 ft; 1 kN = 0.225 kip.

and slab depth. Accordingly, the fire resistance of this slab is 90 minutes per PCI, ACI 216.1-07, and Eurocode 2. Table 2 compares the fire resistance of the slab evaluated from numerical analysis and tests with fire resistance calculated based on code provisions.

The analysis results show that typical hollow-core slabs reach structural failure before thermal failure (limiting temperature). Nonetheless, based on concrete cover thickness, the temperature rise in strands can vary from one slab configuration to another. Thus, in hollow-core slabs, strand temperature might not depict realistic fire resistance.

Conclusion

Based on the results presented in this paper, the following conclusions were drawn:

- The proposed finite element model developed using computer software is capable of simulating the thermal and structural response of prestressed concrete hollow-core slabs exposed to fire in the entire range of loading, from pre-fire to failure.

- Hollow-core slabs similar to the one presented in this paper can give 95 minutes of fire resistance under standard fire exposure.

- The fire resistance of hollow-core slabs is influenced by load, concrete cover thickness, and core size. The numerical model presented in this paper can be applied to undertake parametric studies on precast, prestressed concrete hollow-core slabs in fire.

- Failure of a precast, prestressed concrete hollow-core slab in fire is governed by the degradation of moment capacity or increase in deflection in addition to limiting temperatures on the unexposed surface. These parameters are dependent on temperature rise in the slab and the associated loss of strength and modulus of prestressing strand, which in turn is a function of temperature in the strand. Therefore, a realistic fire scenario (time-temperature curve) has a major influence on the fire resistance of precast, prestressed concrete hollow-core slabs.

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Notation

d = effective depth of slab

L = span length of slab

β_t = opened crack shear transfer coefficients = 0.2

β_c = closed crack shear transfer coefficients = 0.7

About the authors

Venkatesh Kodur is a professor and director of the Centre on Structural Fire Engineering and Diagnostics at Michigan State University in East Lansing. His research interests include evaluation of fire resistance of structural systems through large-scale fire experiments, numerical modeling, and characterization of materials under high temperature. His research contributions have led to the development of a fundamental understanding of the fire behavior of materials and structural systems and have also resulted in numerous design approaches and innovative and cost-effective solutions for enhancing the fire resistance of structural systems. He has published more than 300 peer-reviewed papers in journals and conferences in structural and fire engineering areas.

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Abstract

This paper presents the development of a three-dimensional finite element model for evaluating fire performance of precast concrete hollow-core slabs. A transient thermo-structural, nonlinear finite element analysis of hollow-core slab was conducted using finite element analysis software. In the analysis, the effects of material and geometric nonlinearities, high-temperature properties of concrete, reinforcing bars, and prestressing strand were taken into account. Response parameters, including cross-sectional temperature and deflections, were used to evaluate failure of the slab. The model was validated by comparing response predictions from the model with fire test data. Good agreement between model predictions and test data indicates that the proposed model is capable of predicting fire performance of hollow-core slabs under the combined effects of fire and structural loading.

Keywords

Fire resistance, hollow-core slabs, numerical model.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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