FIRE RESISTANCE TESTS ON HOLLOWCORE SLABS UNDER STANDARD AND DESIGN FIRE EXPOSURE

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ABSTRACT

This paper presents results of fire resistance tests on six prestressed concrete (PC) hollowcore slabs subjected to combined loading and fire scenarios. The varied parameters in tested slabs include aggregate type, restraint condition, fire scenario and load level. In the tests, cross-sectional temperatures, mid-span deflections and restraint forces were measured throughout the fire exposure time. Data generated from fire tests show that fire scenario, load level, support conditions and aggregate type have significant effect on the fire performance of hollowcore slabs. No major spalling occurred in the slabs, and all six slabs sustained fire exposure for more than two hours before attaining failure through reaching limiting temperature on unexposed surface of the slab. Results from tests also show that, hollowcore slabs perform better under design fires than standard fires, and support restraint enhances the fire resistance of PC hollowcore slabs.

Keywords: Precast concrete slabs, Fire resistance, Hollowcore slabs, Fire tests, Design fires

INTRODUCTION

In recent years prestressed concrete (PC) hollowcore slabs are being increasingly used in building applications due to numerous advantages these slabs offer over other floor systems. Structural fire safety is one of the primary considerations in buildings and hence, building codes generally specify fire resistance requirements for hollowcore slabs. These requirements are to enhance the safety of occupants and fire fighters, control spread of flame, and minimize property damage in the event of fire. Currently, fire resistance of hollowcore slabs is assessed based on standard fire tests, or prescriptive approaches. The fire tests are expensive, time consuming and may not yield realistic fire resistance, as they cover only limited numbers of parameters[1,2].

PC hollowcore slabs generally comprise of concrete and prestressing strands as reinforcement. Flexural capacity of such hollowcore slabs is generally governed by stress level in strands. When subjected to fire conditions, both concrete and prestressing steel experience loss of strength[3], leading to degradation in moment capacity with fire exposure time. When the capacity falls below the moment, due to applied loading, failure of the slab occurs. In addition, failure can also result when the temperature on the unexposed surface of the slab exceeds the limiting temperature criteria, or flame breaches through the slab. The rate at which moment capacity of a hollowcore slab degrade, is a function of number of parameters including cover thickness to prestressing strand, core size, fire intensity and support conditions. The effect of many of these critical parameters on fire response of hollowcore slabs is not fully taken in to consideration in current prescriptive provisions. Further, in conventional practice, the strength failure of the slab in a fire test is typically assessed based on reaching a critical temperature in the prestressing strand. Such evaluation of failure based on strand temperature might not yield realistic fire resistance.

In the last four decades, several experimental studies have been carried out to evaluate fire resistance of PC hollowcore slabs. Most of these studies were limited to standard fire exposure conditions, and were focused only on obtaining fire resistance ratings for specific configurations[4-14]. The test variables included slab thickness, cover thickness to reinforcement, concrete strength and load level. In most cases, unexposed surface temperature or the critical temperature in strand was applied as the limiting criteria to evaluate failure of slabs. Few researchers utilized test observations to study the extent of fire induced spalling and cracking phenomenon in PC hollowcore slabs[12,14]. Based on these fire tests, spalling, bond slip and shear crushing were identified as possible factors contributing to failure in PC hollowcore slabs[8-12,14]. However, the reasoning for different failure patterns in hollowcore slabs is not well established. Moreover, these fire tests did not consider the effect of critical parameters, such as fire scenario, range of loading and restraint conditions. Thus, the behaviour of PC hollowcore slabs, under realistic fire, loading and restraint condition, is not well established.

To overcome some of these limitations, fire resistance tests on six PC hollowcore slabs have been conducted under standard and non-standard (design) fire exposure. Data generated from these tests is utilized to trace the response of hollowcore slabs under fire exposure.

FIRE RESISTANCE EXPERIMENTS

Six prestressed concrete hollowcore slabs were tested to evaluate fire behavior of these slabs by exposing them to different fire scenarios, load levels and restraint conditions. Details on fabrication and instrumentation of slabs, as well as test procedure followed in fire resistance tests, are discussed below.

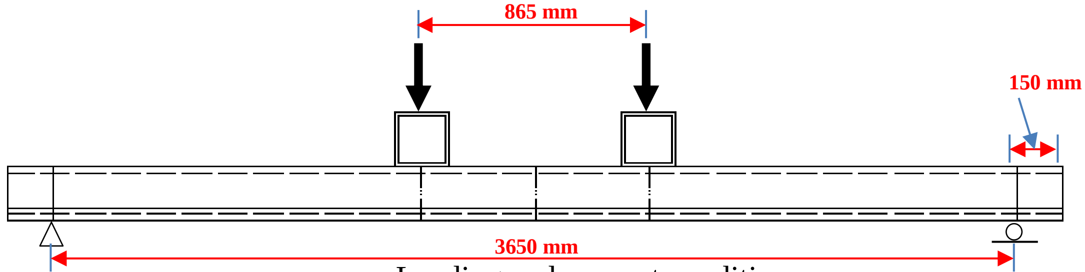
DESIGN AND FABRICATION

The hollowcore slabs were designed as per PCI design manual provisions[15] meeting commercial specifications. All six PC hollowcore slabs were of 4 m (13 ft.) in length, 1.2 m (4 ft.) in width and 200 mm (8 in.) in depth, and had six cores and seven prestressing strands as reinforcement. The cores in the slabs were of 150 mm (6 in.) diameter, with 25 mm (1 in.) concrete thickness at the bottom of the core. The prestressing strands were of 12.7 mm (½ in.) diameter and were of low relaxation strand type, with tensile strength of 1860 MPa. (270 ksi.) Concrete cover thickness over the strands was 44 mm (1¾ in.). Detailed layout and cross sectional configuration of a typical PC hollowcore slab tested in the laboratory is shown in Figure 1.

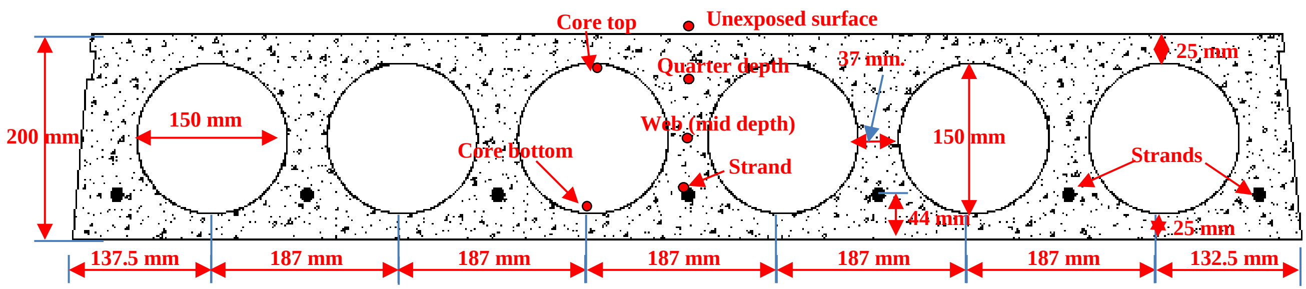
Two batch mixes of concrete were used to fabricate the slabs, namely carbonate aggregate batch mix for four slabs designated as Slab 1, Slab 3, Slab 5 and Slab 6, and siliceous aggregate batch mix for the remaining two slabs designated as Slab 2 and Slab 4. The mix proportions used in two batch mixes of concrete are tabulated in Table 1. Concrete used for fabrication of these slabs was designed to achieve minimum required transfer compressive strength of 21 MPa (3.1 MPa), within 10 hours of concrete pouring, for facilitating speedy casting and stripping process.

The slabs were cast at a local fabrication plant (Kerkstra Precast Inc.) through concrete extrusion process. This extrusion process involved specialized extrusion die of predetermined hollowcore configuration (die with 200 mm (8 in.) depth and six 150 mm (6 in.) diameter cores was used for these slabs), which run over a 150 m (500 ft.) long bed. The prestressing strands were laid on the bed, as per design (strand) configuration, and anchored using steel chucks at the ends. Prestressing was carried out by stretching the strands, using hydraulic jacks, to predetermined prestressing force (70% of tensile strength of strand). The bed surface was lubricated for easy stripping of slabs from casting bed. The concrete hopper continuously fed concrete mix to the extrusion equipment, wherein slab was extruded by forcing the concrete mix through the vibrating die. The vibration of die ensured production of continuous and well compacted slab. Slabs of required span length were later (after 10 hours) cut using wet saw before stripping from casting bed.

The measured compressive strength of two batches of concrete, at the time of transfer and stripping, was in the range of 35 to 37 MPa (5.1 to 5.4 ksi.). All six slabs were stored for 2 months in plant yard, and then shipped to Michigan State University (MSU) Civil Infrastructural Laboratory, where they were stored at 25°C and 40% relative humidity till fire tests were undertaken. The compressive strength of concrete and relative humidity of slabs were measured periodically during curing stage. The average compressive strength of concrete measured at 28 days, 90 days, and on the day of testing, along with the relative humidity of test slabs measured on test day, are tabulated in Table 1 and Table 2.



a. Loading and support conditions



b. Cross-sectional details with instrumentations

Figure 1. Layout and cross-sectional details of a typical prestressed concrete hollowcore slab

The instrumentation in PC hollowcore slabs included thermocouples, LVDTs (linear variable displacement transducer) and load cells, as shown in Figure 1. Thermocouples were placed at various locations within the slab namely, strand, mid depth, quarter depth, core bottom, core top and on unexposed (top) surface, to monitor temperature progression throughout fire exposure duration. LVDTs were installed on slabs to record progression of mid-span deflection during fire exposure and load cells were used to monitor the axial restraint load in restrained slab. Due to the nature of fabrication process, instrumentation had to be installed in the slabs after the extrusion process, wherein thermocouples were placed by drilling holes at specific locations, right after casting, while LVDTs and load cells were placed prior to fire tests.

TEST CONDITIONS AND PROCEDURE

Two PC hollowcore slabs were tested, in each fire test, by subjecting them to predetermined fire, loading and boundary conditions in a fire test furnace commissioned at MSU Civil Infrastructure Laboratory. This fire test furnace consists of a steel framework supported by four steel columns and a fire chamber of 3.05 m (10 ft.) in length, 2.44 m (8 ft.) in width and 1.78 m (6 ft.) in height. The furnace is equipped with six gas burners, which are capable of producing maximum heat power of 2.5 MW. Six type-K Chromel-Alumel thermocouples, as per ASTM E119 specifications[16], are also placed on four walls of the furnace to monitor furnace temperature during fire tests. The input gas and ventilation are controlled manually to maintain the average furnace temperature consistent with a specified fire curve (standard or non-standard (design) fire exposure). All thermocouple, LVDT and load cell channels are connected to a data acquisition system, which display and record temperatures, displacements and axial force in real time. There are two view ports on two opposite walls of the furnace for taking visual observations during a fire test.

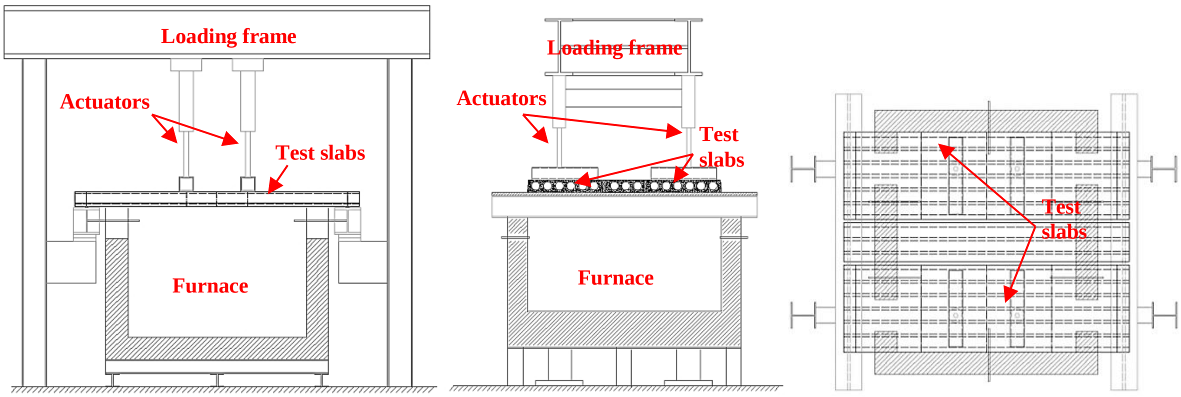
Table 1. Batch proportions of concrete mixes

Materials (per m^3)	Batch 1	Batch 2
Cement (Type I), kg	315	315
Fine aggregate (2NS), kg	911	950
Coarse aggregate, kg	1002.64	943
Coarse aggregate type	Carbonate - Natural Stone - Rounded	Siliceous - #67 LS - Angular
Water, litre	95	95
Water cement ratio (W/C)	0.334	0.334
Unit weight of concrete, kg/m^3	2410	2390
Concrete strength f_c' 28 day, MPa	56	58
Concrete strength f_c' 90 day, MPa	65	78
Slabs fabricated	Slab 1, Slab 3, Slab 5, Slab 6	Slab 2, Slab 4

Note: 1 kg = 2.2 lb, 1 m = 3.28 ft; 1 MPa = 0.145 ksi.

During fire tests, middle portion of the test slabs, comprising of 2.44 m (8 ft.) out of a total clear span of 3.65 m (12 ft.), was exposed to fire, and this simulates a compartment fire exposure, wherein sections of the slab closer to the supports are not directly exposed to the flames. In the tests, the locations of maximum shear force and flexural moment due to applied load lies in the fire exposure zone, since the loading was through two point loads closer to mid-span of the slab (see Figure 1a). Five out of six slabs (Slabs 1 to 4 and Slab 6) were tested under simply-supported conditions. The slabs were supported at the ends on steel sections (W14×96[17]). Semicircle rods were welded to these steel sections to allow free rotation of slab at the ends. The sixth slab (Slab 5) was restrained for longitudinal/axial expansion. Superimposed loading was applied using hydraulic actuators through extension columns, and were distributed along the slab width, using hollow steel sections (HSS 8×8×½[17]). Four point loading scheme was adopted to apply loading on the slabs, as shown in Figure 1(a).

In the case of Slab 5 with restrained boundary conditions, two steel hollow structural sections (HSS 8×8×½[17]) were used to provide axial restraint to the slab. Two post tensioning rods, of 25.4 mm (1 in.) diameter and with ultimate capacity of 534 kN (120 kips), were run through the cores of the slab to secure the steel hollow structural sections to slab ends. This method of restraining applies uniform restraining force across the cross-section of the slab ends, and is in line with that experienced in real scenarios wherein, axial restraint is provided by surrounding slabs or walls. Load cells were attached to the ends of these post-tensioning rods to monitor the fire induced axial force that develop during fire exposure.



a. E-W elevation b. N-S elevation c. Plan

Figure 2. Test setup for undertaking fire resistance tests on PC hollowcore slabs

The type of fire exposure was varied between tests. In Test 1, Slab 1 and Slab 2 were tested under a design fire exposure (DF1) to simulate a typical office fire without a decay phase. In Test 2, Slab 3 and Slab 4 were tested under design fire (DF2) exposure simulating similar office/library fire, comprising of 120 minutes of growth phase followed by a decay phase with a cooling rate of 10°C/minute. These fire scenarios represent typical ventilation controlled conditions encountered in buildings, and the fire intensity is calculated based on fuel load available, compartment characteristics and ventilation scenarios in buildings. In Test 3, Slab 5 and Slab 6 were tested under standard ASTM E119 fire[17] representing growth phase of fire only. The time-temperature curves corresponding to three fire scenarios are shown in Figure 3.

Table 2. Results of fire resistance tests on hollowcore slabs

Test slab	Aggregate type	Test day comp. strength (f'_c), MPa	Applied loading (% of capacity)	Support condition	Test day RH %	Fire scenario	Failure mode	Extent of spalling	Fire resist-ance, min.
Slab 1	Carbonate	74	50	SS	60	DF1	n.f.	None	n.f.
Slab 2	Siliceous	87	50	SS	60	DF1	n.f.	Minor	120
Slab 3	Carbonate	75	60	SS	55	DF2	n.f.	None	n.f.
Slab 4	Siliceous	91	60	SS	55	DF2	n.f.	Minor	120
Slab 5	Carbonate	75	60	AR	55	ASTM - E119	Flexural crushing	None	120
Slab 6	Carbonate	75	60	SS	55	ASTM - E119	Flexural cracking	None	120

Note: SS = simply supported, AR = axially restrained, RH = relative humidity, ‘n.f.‘ = no failure, 1 MPa = 0.145 ksi.

The loading on slabs was chosen to simulate typical service load levels on hollowcore slabs. Slabs 1 and 2 were tested under 50% load level (57.8 kN (13 kips), representing 50% of the capacity of the slab at room temperature) and Slabs 3 to 6 were tested under 60% load level (69.4 kN (15.6 kips), representing 60% of the capacity of the slab at room temperature).

During fire tests, care was taken to maintain a uniform load level on slabs throughout the fire exposure duration.

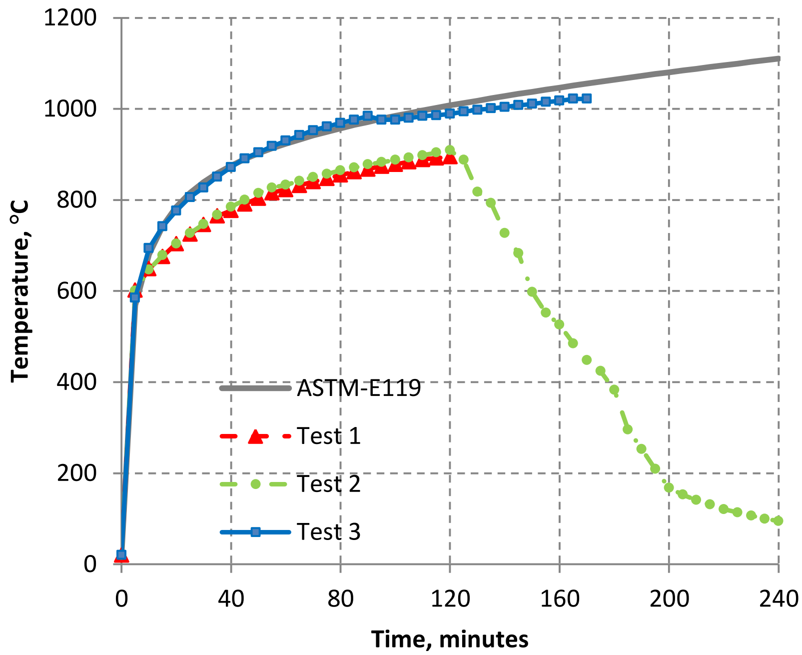


Figure 3. Time-temperature curves, simulated during fire tests

RESULTS AND DISCUSSION

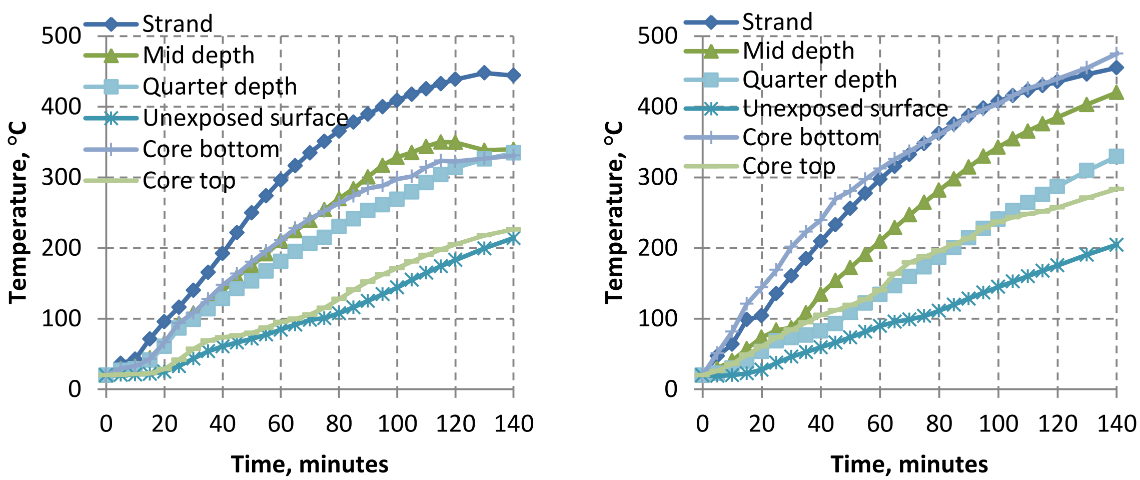
Data and observations generated in fire tests is utilized to trace the progression of cross-sectional temperatures, mid-span deflection, restraint force, cracking and fire induced spalling with fire exposure time in hollowcore slabs.

TEMPERATURES

Typical cross-sectional temperature progression in hollowcore slabs is illustrated by plotting temperature progression at the level of strand, mid-depth, quarter depth, unexposed surface, core bottom and core top in Figure 4 for Slab 4 and Slab 5.

In the first 20 minutes of fire exposure, sectional temperatures gradually increase with time, and as expected, the temperatures in concrete layers farther from the fire exposure surface are lower than those layers closer to the exposure surface. This can be attributed to low thermal conductivity and high specific heat of concrete, which delays temperature transmission into inner layers. In all slabs, temperatures in concrete gradually increase to 100°C, and typically plateau in this temperature range for 20 to 40 minutes of fire exposure. This temperature plateau can be attributed to utilization of heat for evaporation of free moisture present in concrete which occurs around 100°C.

Beyond 20 minutes of fire exposure, temperatures at all locations increase at a gradual pace with time. Close observation of Figure 4 reveal that, temperature in prestressing strands is typically higher than the temperature at the bottom surface of the core, even though the core bottom surface is closer to fire exposed surface than the strands. This is mainly due to dissipation of heat occurring from the core surfaces, which reduces temperatures in these layers. The temperature on the unexposed surface of Slab 2, 4, 5 and 6 reach the limiting temperature of 181°C at 120 minutes into fire exposure, whereas unexposed temperature in Slab 1 and Slab 3 does not exceed this temperature limit throughout the fire exposure duration. This infers that as per ASTM-E119 limiting criterion, Slabs 2, 4, 5 and 6 attain failure based on insulation (unexposed surface temperature) criterion at 120 minutes. In all tested slabs the average temperature measured at 6 points on the unexposed side of slab is less than the critical temperature of 139°C at 120 minutes. However, all slabs continue to carry load beyond 120 minutes without any signs of failure from strength degradation criterion. The strand temperature at 120 minutes is 500°C, and this clearly infers that the evaluation of fire resistance based on attaining critical strand temperature (427°C) might not yield realistic fire resistance in hollowcore slabs. The temperature trend in all other slabs is similar to Slab 4 and Slab 5.



a. Slab 4 b. Slab 5

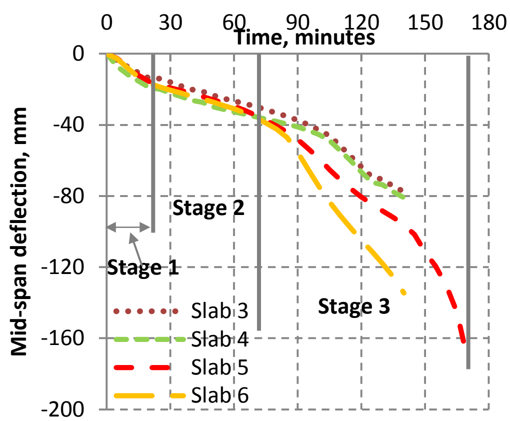
Figure 4. Typical cross-sectional temperatures in hollowcore slabs

MID-SPAN DEFLECTION AND AXIAL RESTRAINT FORCE

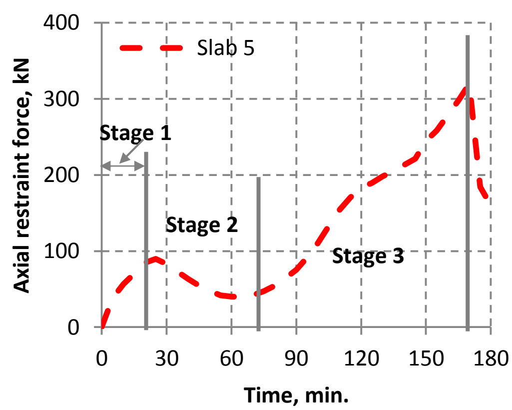
The variation of mid-span deflection in Slabs 3 to 6 and axial restraint force in Slab 5 is plotted in Figure 5. The mid-span deflection in all slabs progress with fire exposure time and follow similar trend. The deflections and axial restraint force plotted in Figure 5 can be grouped into three stages. In Stage 1, in first 20 minutes of fire exposure, the deflections in all slabs and axial restraint force in Slab 5 increase at a rapid pace. These result mainly from thermal strains generated due to high thermal gradients, generated along the slab depth, occurring in early stage of fire exposure. However, concrete and strands undergo very little strength degradation in this stage due to low temperatures in strands and inner layers of concrete.

In Stage 2, after 20 minutes into fire exposure, deflections in all slabs increase at a slightly slower pace and axial force in Slab 5 decrease rapidly up to 75 minutes into fire exposure. This increase in deflection and decrease in axial force is due degradation of strength and modulus in concrete and strand, as temperatures increase in inner layers of concrete reducing thermal gradients.

Finally, in Stage 3 (beyond 75 minutes), deflections in all slabs and axial restraint force in Slab 5 increase at a rapid pace, and this is mainly attributed to high creep strains resulting from very high temperatures in concrete and strands, which reach above 500°C. Variation in the level of deflection in different slabs is pronounced in this stage. Slabs 5 and 6 show much higher deflections as compared to Slabs 3 and 4, and this is due to the fact that ASTM-E119 fire scenario produce slightly higher fire intensity than DF2 fire scenario (see Figure 3). Slab 5 shows lower deflections than Slab 6, and this is can be attributed to the presence of support restraints which enhances the stiffness of the slab.



a. Mid-span deflections



b. Axial restraint force

Figure 5. Structural response of hollowcore slabs under fire condition

CRACK PROPAGATION AND SPALLING PATTERN

Visual observations made during and after fire tests show that all slabs developed flexural cracks in early stages of fire, originating from the bottom fire exposed surface. In addition, Slab 1, Slab 3 and Slab 6 also developed some level of shear cracking during early stages of fire exposure. However, these shear cracks did not affect the flexural capacity of the slabs, as these cracks were restricted to lower parts of the slab and did not propagate through the top portion of the slab. The flexural and shear cracks widened in all slabs with fire exposure time. Failure of Slab 6 occurred due to widening of flexural cracks. In the case of axially restrained Slab 5 failure was through flexural cracking and crushing of concrete on the top surface at the mid-span section. Slab 5 sustained fire exposure for a longer period than the other three slabs, but showed severe concrete damage on the fire exposed surface due to higher internal stresses, generated from axial restraints.

There was no fire induced spalling in Slabs 1, 3, 5 and 6, which were made of carbonate aggregate concrete. Slabs 2 and 4, fabricated with siliceous aggregate concrete, showed minor pitting (spalling) on the fire exposed surface. This minor spalling in siliceous aggregate concrete Slabs 2 and 4 is attributed to stronger interlocking and bond between cement paste and aggregate surface, which increases the risk of pore pressure induced spalling[18,19].

FAILURE TIMES

Failure in horizontal members such as floors and slabs, under fire exposure, is typically assessed based on insulation, integrity and stability criteria as specified in ASTM-E119[16] or ISO834[20]. Based on insulation criteria, failure of slab is said to occur when the average temperature on the unexposed surface of the slab exceeds 139°C (measured at 9 points) or a maximum of 181°C, above initial temperature, at any single point of the unexposed surface of the slab. As per integrity criteria, failure of slab is said to occur when flame breaches through the unexposed side (surface) of the slab through any fire induced cracks or holes. Under stability criteria, failure occurs when the moment capacity of the slab, at the critical section, drops below the moment caused due to applied loading. In most previous studies, the strength failure in hollowcore slabs is linked to critical temperature reached in prestressing strands, which is taken as 427°C. This simplistic correlation is only applicable when the slab is subjected to a load equivalent to 50 percent of its capacity and thus, might not yield realistic fire resistance for other levels of loading. In addition to above limit states, deflection or rate of deflection limit states are given in British Standard (BS 476)[21] wherein, failure of a slab is said to occur when the maximum deflection in the slab exceeds L/20 at any fire exposure time, or the rate of deflection exceeds $L^2/9000d$ (mm/min) after attaining a maximum deflection of L/30, where, L = span length of the slab (mm), and d = effective depth of the slab (mm).

a. Slab 2 b. Slab 6 c. Slab 1

Figure 6. Illustration of typical spalling and cracking in PC hollowcore slabs under fire exposure

Failure times of all six slabs were evaluated based on above discussed limiting criteria. Accordingly, no significant cracks (or holes) developed in any of the slabs. Therefore, the flame did not breach through the unexposed side of the slabs and hence, no integrity failure occurred in the slabs. Based on insulation criteria, all slabs exhibited a minimum of 120 minutes of fire resistance, as shown in Table 2. However, all slabs continued to carry load beyond 120 minutes indicating that failure evaluated based on unexposed temperature criterion does not represent structural failure of the slab. Thus, based on stability criteria, failure times in Slab 5 and Slab 6 were found to be 170 and 140 minutes respectively. The fire resistance in Slab 5 is about 30 minutes higher than that in Slab 6, and this is due to the effect of axial restraints which enhanced the stiffness of the slab. It should be noted that the calculated fire resistance based on PCI design handbook[15] for these slabs is 90 minutes, which might be overly conservative.

CURRENT STUDIES

Evaluating fire resistance of hollowcore slabs through fire tests is expensive and time consuming, and also only the effect of limited number of parameters on fire resistance is captured in fire tests. An alternative to fire tests is the use of numerical models for evaluating fire resistance of hollowcore slabs. For this purpose, a finite element based numerical model has been developed for tracing the response of fire exposed hollowcore slabs[22,23]. This model accounts for geometric and material nonlinearities, presence of voids in the slab, and temperature dependent thermal and mechanical properties of concrete, reinforcing steel and prestressing steel. Fire resistance analysis of a hollowcore slab is carried out at various time steps in a sequentially coupled thermal and structural analyses by incrementing time from the start of fire exposure (ignition) till failure of the slab. The time to reach failure is taken to be the fire resistance of the slab[22,23].

Data generated in the above fire tests is being utilized to validate the numerical model. The validation is achieved by comparing thermal and structural response predictions obtained from model with measured values in fire tests. The validated model will be applied to undertake parametric studies to study the effect of critical factors, such as support restraint, fire scenario and load level, on fire performance of hollowcore slabs. Data generated from these parametric studies will be used to develop a rational design guidance for evaluating fire resistance of hollowcore slabs. Such design guidance will facilitate fire design of hollowcore slabs in a performance based environment.

CONCLUSIONS

Based on the results presented in this paper, the following conclusions can be drawn on the fire behavior of prestressed concrete hollowcore slabs:

- Hollowcore slabs, similar to ones discussed in this paper, provide minimum of two hours of fire resistance under service level loading and typical standard and design fire exposure.

- Hollowcore slabs exhibit better fire performance under realistic fire scenarios than under standard fire scenarios.
- Axial restraint has significant influence on the fire response of hollowcore slabs, and can enhance fire resistance by about 30 minutes.
- Siliceous aggregate concrete slabs are more susceptible to fire induced spalling than carbonate aggregate concrete slabs. Also, carbonate aggregate concrete slabs are more prone to shear cracking than siliceous aggregate concrete slabs.
- Further study needs to be performed utilizing numerical models to study the effect of critical parameters, such as depth, cross-sectional configuration, support restraint, fire scenario and load level, on the fire performance of hollowcore slabs.

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