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# Application of Rational Methodology for Evaluating Fire Resistance of Concrete Structures

**Abstract.** Current methods of evaluating fire resistance of concrete structures are mainly prescriptive in nature and developed utilizing data from standard fire tests. These methods may not yield realistic fire resistance, especially for new types of concrete, and geometric configurations subjected to realistic fire loading and restraint scenarios. Many of the drawbacks in current prescriptive approaches can be overcome through rational approaches for evaluating fire resistance. For undertaking such rational approaches, a nonlinear finite element based numerical model and input parameters namely, high temperature material constitutive models, realistic fire, load and support conditions data are required. In this paper, the applicability of rational approach for evaluating fire resistance is illustrated through a case study on typical prestressed concrete hollowcore slabs. Results from the study clearly show that rational approaches for fire resistance evaluation yields higher fire resistance than that obtained through prescriptive based approaches.
**Keywords:** concrete structures, fire resistance.

Concrete finds wide applications in buildings, parking structures, and transit structuresdue to its numerous advantages, such as versatility, cost, fire resistance and low maintenance costs, over other construction materials. Fire is one of the most severe hazardsin buildingsduring their lifetime and thus, building codes specify certain fire resistance ratings for structural members. Fire resistance is the duration during which the structural member exhibit resistance, based on insulation, integrity and stability failure criteria.

The current method of evaluating fire resistance in structural members is mainly through prescriptive based approaches. These methods are derived based on standard fire tests and often do not reflect realistic fire resistance of structural members. The prescriptive based fire ratings for concrete structuresare specified in various codes and standards [1 ÷ 7]. In the prescriptive methods, minimum sectional dimensions and cover thickness (concrete cover over reinforcement) are specified for achieving a required fire resistance rating in concrete member. In addition, aggregate type, density and restraint support conditions of a structural member is given limited consideration in some codes. Limited guidance on the use of rational design approaches for evaluating fire resistance of concrete structures are also present in PCI [2] and Eurocode 2 [4]. These rational approaches are typically based on sectional analysis and utilize temperature induced strength reduction factors to evaluate reduction in load carrying capacity of a structural memberat agiven fire exposure time. When the reduced sectional capacity drops below applied moment during fire event, failure is said to occur. None of the current fire resistance guidelinesfully account for realistic fire, loading, and restraint conditions, as well asspalling and various failure modes encountered in concrete structural members under fire conditions. Many of these drawbacks can be overcome, through the application of performance based approachfor evaluating fire resistance of concrete structures.

In addition to limitations in fire resistance evaluation, there are other factors, such as material properties, sectional shapes, that affect the fire performance of concrete structures. Over the last three decades, there have been significant research and development activity in improving the properties of concrete, which has led to new types of concrete namely, high strength concrete (HSC), fiber reinforced concrete (FRC), high performance concrete (HPC), self-consolidating concrete (SCC) and ultra HPC. Also in recent years, to enhance architectural, structural and sustainability considerations, innovative cross-sectional configurations such as, hollowcore slabs, double-T beams, and steel decked slabs have been introduced in building applications. Current prescriptive methods cannot be directly applied for these newer concrete types and sectional configurations due to problems such as fire induced spalling and different failure modes. For this reason, fire performance of concrete structural members in modern buildings can be significantly different from that of conventional concrete structural members. Rational approaches can be effectively applied for evaluating fire performance of structural members in these cases. In these rational approaches, all critical factors influencing fire resistance namely, concrete type, sectional configuration, support conditions, loading pattern, and fire scenario can be accounted for. In this paper the application of such a performance based rational design approach for evaluating fire resistance is illustrated through a case study onprestressed concrete (PC) hollowcore slabs.

## Factors governing fire resistance

For evaluating fire resistance through rational approaches, the critical factors that influence fire resistance of structural member are to be known. Data from previous experimental and analytical studies can be utilized to gauge the factors that influence fire resistance of concrete structural members [8 ÷ 14]. The key factors that influence the fire performance of concrete structures are briefly discussed here.

**Concrete strength.** Concrete strength can have significant influence on fire resistance of concrete structures. Studies have shown that concrete with strengths higher than 70 MPa

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(10 Ksi) exhibit faster degradation of strength, and are vulnerable to spalling due to significant reduction in interstitial voids. These drawbacks cause lower fire resistance in HSC members thanmembers fabricated with NSC [15 ÷ 18].

**Concrete moisture content.** The moisture content in concrete, expressed in terms of relative humidity (RH), influences the extent of spalling in concrete structures with higher RH levels leading to greater spalling [10]. Concrete structures built with HSC can retain high moisture content for long periods due to low permeability of HSC mixes. Fire-resistance tests on full-scale HSC columns haveshown that significant spalling occurs when the relative himidity is higher than 80%. Thus, HSC aremore susceptible to spalling which may result in lower fire resistance.

**Concrete density.** The effect of concrete density has been studied through fire tests on the normal and lightweight columns, slabs and blocks [11]. The extent of spalling in concrete members was much greater when the lightweight aggregate was used. This could be partly attributed tohigher free moisture present in the lightweight aggregate, which creates higher vapor pressure under severe fire exposures.

**Fire intensity.** Fire intensity affects extent of spalling and thus, can indirectly influence fire resistance of concrete members. As spalling is not a major phenomenon in NSC columns, heating rate has small effect on fire performance of NSC members, as compared to HSC members. The spalling of HSC is muchmore severe in fires characterized by fast heating rates or high fire intensities, typical of hydrocarbon fires [12, 13]. Thus, higher heating rates or higher fire intensities significantly reduce fire resistance of concrete structures.

**Specimen dimensions.** Generally, the fire resistance of a concrete member increases with member dimensions due to increased capacity and thermal mass. However, the risk of explosive thermal spalling increases with the size of member size [14]. This is due to the fact that the specimen size is directly related toheat and moisture transport through the structure, as well as the capacity of larger structures to store moreenergy. When spalling mitigation measures are incorporated, the risk of explosive spalling decreases and the fire resistance increases with the size of the members. As spalling is not a major phenomenon in NSC columns, fire resistance increases with the size of the members.

**Fiber reinforcement.** The presence of fibers in concrete mix influences extent of fire induced spalling and thus, fire resistance of any concrete member. Results from experimental studies show that the addition of polypropylene fibers (about 0,1 – 0,15% by volume) toconcrete mix minimizes spalling in the HSC columns under fire conditions and thus enhances its fire resistance. The polypropylene fibers melt at 160 to 170 °C (320 to 340 °F) and create pores in concrete which help in reducing thepore pressure in the concrete [12, 18 ÷ 21]. The addition of steel fibers (about 1,75% by weight) enhances the tensile strength of concrete and thus reduces spalling [19].

**Load intensity and type.** The type of load and its intensity have a significant influence on spalling and the resulting fire resistance. Higherload intensity leads to lower fire resistance [10, 17, 18]. The effect is more pronounced in HSC members since the loss ofstrength with a rise in temperature is greater for HSC than for NSC. A loaded HSC structural member is susceptibleto higher spalling than an unloaded member. This occurs due to the fact that a loaded structural member is subjected to stressesdue to load in addition to the pore pressure generated by steam. Further, the extent of spalling is higher if the load isof an eccentric (or bending) type since this will induce additional tensile stresses.

**Type of aggregate.** Of the two commonly used aggregates, the carbonate aggregate (predominantly limestone) provides higher fireresistance in concrete than does the siliceous aggregate (predominantly quartz). This is due to lower thermal conductivity and higher specific heat of carbonate aggregate which lowers the rate of increase of heat in concrete members fabricated with carbonate aggregate. Ingeneral, the fire resistance of the concrete member made with carbonate aggregate concrete is about 10% higher than concrete member made with siliceous aggregate concrete [9, 10, 16]. This trend is applicable for both NSC and HSC members.

**Sectional shape/configuration.** Sectional configuration has significant influence on the fire response of a concrete member. As an illustration, a hollowcore slab of equivalent cross-section exhibits lower fire resistance as compared to a traditional solid slab. A typical cross-section of PC hollowcore slab and solid slab is illustrated in Figure 1. In a solid slab, the temperature transmission from fire source to unexposed surface is mainly governed by conduction of heat whereas, such temperature transmission through a hollowcore slab occurs via conduction in the solid concrete portion, and convection

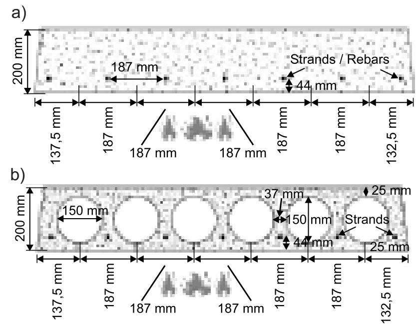


**Fig. 1. Comparison of cross-sectional profiles of typical fire-exposed prestressed concrete: a) solid slab; b) hollowcore slab**

and radiation in the hollow cores. This causes significant variations in the cross sectional temperature profilein these two slabs. Also, hollowcore slabs experiences faster transmission of heat to the unexposed side of the slab, as compared to solid slabs, due to lower mass of concrete. Also, the shear capacity in hollowcore slabs can be much lower than that in solid slabs due to significant loss of cross--section around mid-depth of the slab, as a result of voids [22].

**Reinforcement.** Concrete structures, depending on the type of reinforcement, are grouped under reinforced concrete (RC) and prestressed concrete (PC) structures. Studies have shown that, prestressed concrete members have lower fire resistance than reinforced concrete members [10]. This is due to the fact that the prestressing strand experiences higher rate of strength loss than that of reinforcing steel bar.

## Rational approach for evaluating fire response

Undertaking performance-based fire resistance analysis througha rational approach involves a number of steps namely, assessing multiple fire scenarios, evaluating sectional temperature, determining structural response, and then applying failure criteria for evaluating fire resistance [9]. These steps are illustrated through a flowchart, as shown in Figure 2. For implementing performance based approach to evaluate fire resistance, a validated computer modelto perform thermo-structural analysis is required.

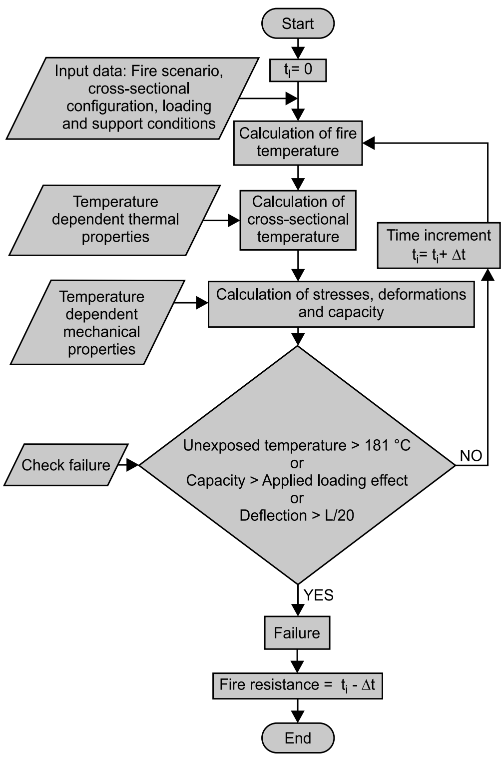


**Fig. 2. Flowchart showing steps associated with fire resistance analysis of hollowcore slabs**

In fire resistance analysis, a structural member is discretized in to various elements. This discretization can be different for thermal analysis and structural analysis depending on the capability of different elements available in a computer program. The analysis is carried out sequentially in various time increments till failure occurs.

Fire intensity in a fire scenario depends on available fuel load, ventilation, and type of lining materials in a compartment (wall and floor). Thus, a fire scenario that reflects actual fire event needs to be input in the computer model for evaluating fire response. The time-temperature curves generated during a fire can be calculated using fuel load and compartment characteristics. Alternatively, simplified time-temperature curves (standard or design) given in standards for fire in different occupancy can be selected. By utilizing this fire time-temperature curve, a thermal analysis is to be performed to evaluate the temperature profile of the structural member. The required inputs for such thermal analysis are thermal conductivity, specific heat, thermal expansion of concrete and reinforcing/prestressing steel. The sectional temperature progression is then applied as body loads at different nodes for undertaking structural analysisto evaluate deflections, stresses and axial restraint forces. For this structural analysis, high temperature material property definitions for concrete and reinforcement such as, stress-strain relationships as well as concrete damage parameters are to be provided as input.

Results from thermal and structural analysis are utilized to evaluate failure at each time step. For this, failure criteria specified in standards such as ASTM-E119 [23], BS476 [24] or ISO834 [25] are applied to evaluate failure, and the time to reach the step at which failure occurs is taken as the fire resistance of the structural member. Through these steps, it is possible to evaluate realistic fire performance of concrete structural members.

## Application of rational approach for evaluating fire resistance

For the purpose of illustration of the application of performance-based fire design approach, a case study involving analysis of fire response of PC hollowcore slabs under different fire and slab characteristics is presented here. The analysis is carried out using ANSYS finite element program. Various steps in analysis are discussed in this section.

**Numerical Model.** A finite element based numerical modelfor tracing the behavior of PC hollowcore slabs under fire conditions is developed in ANSYS finite element program [26]. This model accounts for geometric and material nonlinearities, core configurations, support conditions, fire scenarios, and temperature dependent thermal and mechanical properties of concrete and prestressing steel. Fire resistance analysis of a PC hollowcore slab is carried out at various time steps by incrementing time from the start of fire exposure (ignition) till failure of the slab under fire exposure. The time to reach failure point is taken to be fire resistance of the slab. Full details of the development of the numerical model can be found elsewhere [27].

**Slab characteristics and analysis parameters.** Four PC hollowcore slabs, designated as Slab 3, Slab 4, Slab 5 and Slab 6, were selected for fire resistance analysis. All slabs were of 4 m in length, 1,2 m in width and 200 mm in depth, and designed according to PCI design specifications. The cores in these slabs were of 150 mm radius, with 25 mm concrete thickness at the bottom of the core. These slabs were designed with seven low relaxation prestressing strands, with yield stress of 1860 MPa and diameter of 12,7 mm, and with a concrete cover thickness of 44 mm. Slabs 3, 5 and 6 are assumed to be made of carbonate aggregate concrete and Slab 4 is assumed to be made of siliceous aggregate concrete. These slabs were subjected to simultaneous loading and fire exposure.

These slabs were analyzed under two different fire scenarios and the analysis variables are listed in Table. Slabs 3 and 4 were subjected to design fire and Slabs 5 and 6 were subjected to ASTM-E119 standard fire. The two fire curves corresponding to two fire scenarios are shownin Figure 3. All

**Summary of analysis parameters and results**

| Test slab | Aggregate type | Compressive strength ($f'_c$) [MPa] | Applied loading [% of capacity] | Support condition | Fire scenario | Fire resistance [min] | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | insulation | stability (strength) | ACI 216.1/PCI/ EC2/AS 3600 |
| Slab 3 | Carbonate | 75 | 60 | SS | DF | 140 | 135 | 90 |
| Slab 4 | Siliceous | 75 | 60 | SS | DF | 120 | 120 | 90 |
| Slab 5 | Carbonate | 75 | 60 | AR | ASTM-E119 | 120 | 165 | 90 |
| Slab 6 | Carbonate | 75 | 60 | SS | ASTM-E119 | 120 | 130 | 90 |

Note: SS – simply supported; AR – axially restrained; 'DF' – design fire

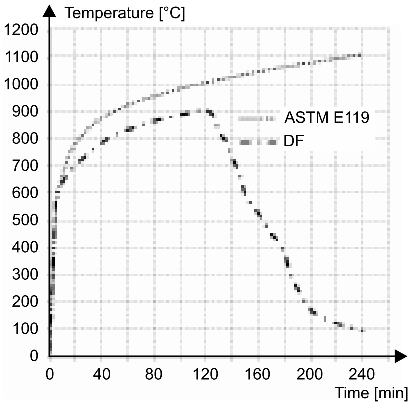


**Fig. 3. Time-temperature curves of fire exposure**

slabs were subjected to super-imposed loading which corresponds to 60% of room temperature flexural capacity. Slab 3, Slab 4 and Slab 6 were analyzed with simply supported ends while, Slab 5 was analyzed with restraint end conditions, to study the effect of restraint on fire resistance.

**Analysis details.** For fire resistance analysis, the given PC hollowcore slab is discretized into two sets of elements, one for undertaking thermal analysis and the other for undertaking structural analysis [26, 27]. For thermal analysis, SOLID70, LINK33 and SURF152 elements are used, while for structural analysis SOLID65, LINK180, SURF154 and COMBIN40 elements are utilized. The rationale for the selection of these thermal and structural elements for fire resistance analysis is discussed in detail elsewhere [27]. A typical PC hollowcore slab, discretized into various elements, is shown in Figure 4. The hollowcore slabs were subjected to two concentrated loads and fire scenarios as illustrated in Figure 3.

The output parameters from ANSYS include sectional temperatures, deflections, and degradation of moment capacity at each time step. These parameters are utilized to evaluate failure by applying varying limiting criteria specified in ASTM-E119 [23] and BS476 [24].

**Material properties.** For finite element analysis on PC hollowcore slabs, temperature dependent thermal and mechanical properties of concrete and strand 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

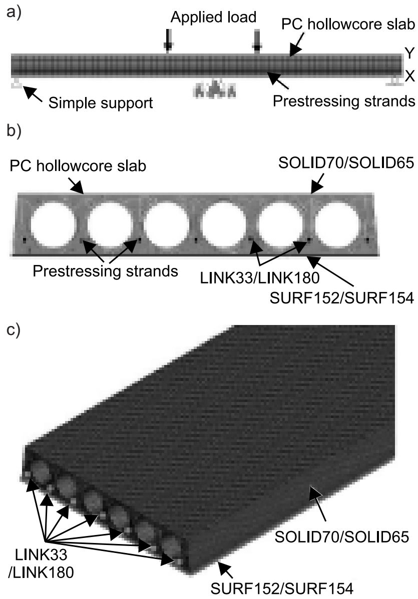


**Fig. 4. Layout of a typical PC hollowcore slab and its discretization for fire resistance analysis: a) typical hollowcore slab exposed to fire; b) discretization of cross-sectional of hollowcore slab; c) discretized hollowcore slab in longitudinal direction**

thermal expansion. All these properties are defined as varying with temperature using temperature dependent relations specified in Eurocode 2 [4]. In ANSYS, plastic behavior of concrete is defined using Willam and Warnke's constitutive model [28], which is capable of accounting for concrete behavior in both tension and compression. In flexural members, 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 isotropic multi-linear stress-strain curve varying with temperature, while tensile behavior is defined using damage parameters. 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, ($\beta_t$ and $\beta_c$ respectively) and are taken to be as 0,2 and 0,7 respectively [28]. Shear transfer coefficients are taken as zero when there is a total loss of shear transfer (representing no shear transfer in a smooth crack) and 1,0 when there is no loss of shear transfer (representing complete shear transfer in a rough crack).

**Failure limit states.** The failure of slabs under fire conditions is evaluated based on different failure limit states as specified in ASTM-E119 [23], BS476 [24] or ISO834 [25]. Accordingly, failure ofhorizontal members (floors and slabs) under fire exposureoccurs through reaching insulation, integrity and stability limit states. Based on insulation criteria, failure of slab is said to occur when the average temperature measured at 9 points on the unexposed surface of the slab exceeds 139 °C or temperature at any point exceeds 181 °C above initial temperature. Based on integrity criteria, failure occurs when flame breaches through unexposed side of the slab. As per stability (strength) criteria, failure is said to occur when the slab cannot sustain the applied loading which is generally evaluated through comparing flexural capacity against bending moment under fire conditions at a given time step. Many fire tests have shown that hollowcore slabs are susceptible to shear failure, but this is often ignored in current approaches. Such shear failure mechanism can also be accounted for while assessing fire resistance of PC hollowcore slabs through performance based fire design. In simplified approach, strength failure in hollowcore slabs is assessed by relating degradation in capacity to the critical temperature in prestressing strand, taken as 427 °C. This is again unrealistic, since critical temperatures in strands at failure can vary depending on the load level (relating to bending moment).

In addition to the above three limit states, British Standard (BS 476) [24] specifies deflection or deflection rateas a failure limit state for horizontal members (beams or slabs). Based on BS 476 [24] criteria, failureof prestressed slabs, occur when the maximum deflection of the slab exceeds $L/20$ at any fire exposure time, or the rate of deflection exceeds the limit given by $L^2/9000d$ (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).

**Results of fire resistance analysis.** Data generated from ANSYS is utilized to evaluate fire response of four PC hollowcore slabs. The fire behavior of these slabs is evaluated in terms of temperature progression, mid-span deflection, and flexural capacity, which are plotted in Figure 5 to Figure 7. Further, the fire resistance (failure times) of slabs is evaluated based on different limiting failure criteria discussed in Section 4.5. These failure times, evaluated based on ANSYS response parameters and provisions in current codes of practice are listed in Table.

Typical temperature progressions in Slab 4 and Slab 5 (with siliceous and carbonate aggregate concrete) are shown in Figure 5. In the initial stages of fire exposure, in the first 20 minutes, the temperatures at the level of prestressingstrand, mid-depth, quarter depth, unexposed surface, core bottom and core top increase gradually with time. As expected, the temperatures in concrete layers farther from the fire exposure surface are lower than those layers closer to the exposure surface. Beyond 20 minutes of fire exposure, temperatures at all locations increase at a gradual pace with time. The temperatures on the unexposed surface of slab reach the limiting temperature of 181 °C at 120 minutes into fire exposure, and this marks the failure point in these slabs according to insulation criteria as specified in ASTM-E119 [23].

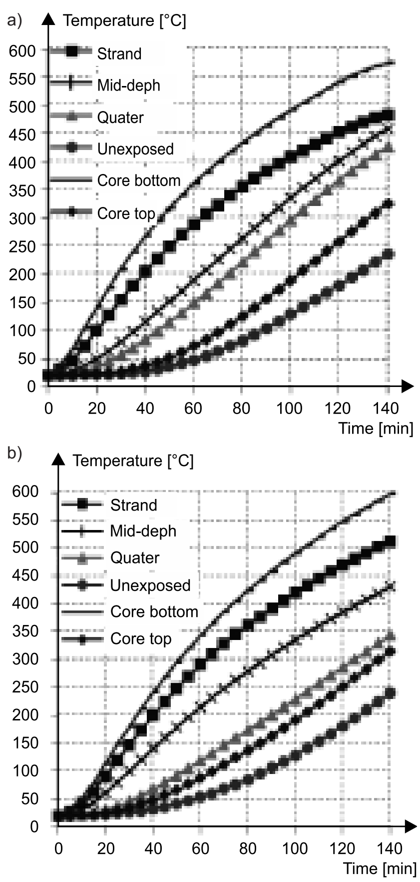


**Fig. 5. Comparison of measured and predicted sectional temperatures in siliceous and carbonate aggregate concrete slabs: a) siliceous aggregate concrete slab; b) carbonate aggregate concrete slab**

The deflection response for all four slabs ispresented in Figure 6. The deflection progression can be grouped into three stages. In Stage 1, in first 20 minutes, the deflections increase at a slower pace and these deflections mainly result from thermal strains (temperature induced thermal expansion in concrete and prestressing steel) due to high thermal gradients occurring in the early stage of fire exposure. After 20 minutes

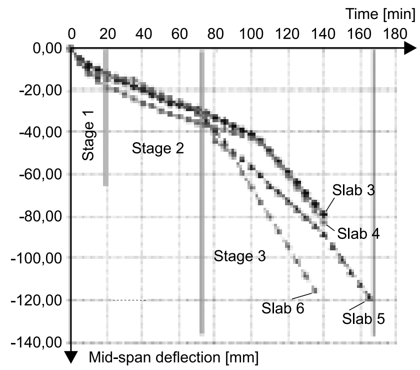


**Fig. 6. Comparison of measured and predicted mid-span deflections in different slabs**

of fire exposure, in Stage 2, deflections increase at a slightly slower pace due to reduction in thermal gradients, as temperature increases in the inner layers of concrete. The deflections in this stage are mainly resulting from the degradation in strength and modulus properties of concrete and prestressing strand due to higher temperatures. Finally, in Stage 3 beyond 75 minutes, deflections increase at a rapid pace and are mainly due to creep effects, which get pronounced at very high temperatures in concrete and prestressing strand.

Based on results output from ANSYS [26], the fire resistance of hollowcore slab is evaluated by applying different failure criteria. Accordingly, slabs did not fail under integrity criteria, as no indication of breaching of flames through the unexposed side of the slab was possible. Based on insulation criteria, the unexposed surface temperatures in Slabs 4, 5 and 6 reach 181 °C, and attain failure at 120 minutes, while in Slab 3 insulation criterion is reached in 140 minutes. Lower fire resistance in Slab 4, as compared to Slab 3, can be attributed to higher thermal conductivity and lower specific heat of siliceous aggregate concrete [10], which leads to faster transmission of temperatures in Slab 4. It should be noted that Slab 5 and Slab 6, whose fire resistance based on insulation criterion is same as Slab 4 (exposed to design fire), are exposed to ASTM-E119 fire, which is of slightly higher intensity.

All four slabs continue to sustain load beyond 120 minutes, which infer that reaching unexposed surface limiting temperature does not represent strength failure in these slabs. Based on stability (strength) criteria, as specified in ASTM E119 [23], failure is said to occur when flexural capacity of the slab drops below the bending moment (caused by a load equivalent to 1,2 times dead and 1,5 times live load) under fire conditions at a given time step. Application of strength criterion results in failure times of 135, 120, 165 and 130 minutes in Slab 3, Slab 4, Slab 5 and Slab 6 respectively, as illustrated in Figure 7. This is significantly higher than that obtained based on prescriptive based tables in different codes [1 ÷ 7], which yields 90 minutes for these slabs. The significantly higher fire resistance in Slab 5, as compared to Slab 6, is due to the presence of axial restraints that increases the stiffness of the slab. Full details on the effect of axial restraint on fire resistance is discussed elsewhere [29 ÷ 31]. These slabs were tested in the lab and a fire resistance of 170 and 140 minutes were observed in Slab 5 and Slab 6, whereas, Slab 3 and Slab 4 did not undergo strength failure.

The analysis results show that typical hollowcore slabs reach insulation failure before reaching structural failure. Nevertheless, based on concrete cover thickness, the temperature rise in strands can vary from one slab configuration to another. Thus, in hollowcore slabs, reaching certain (critical) strand temperature might

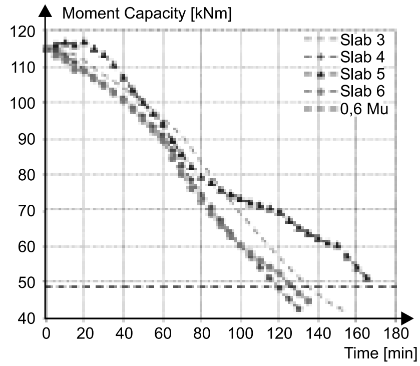


**Fig. 7. Comparison of variation of moment capacity with fire exposure time in different slabs**

not infer realistic fire resistance. In addition, restraint and other conditions can influence fire resistance and all these factors can be accounted for through a performance based approach to fire design.

## Conclusions

Based on the study presented in this paper, the following conclusions can be drawn on the fire design of concrete structures:

- current approaches for evaluating fire resistance of concrete structures are prescriptive in nature and are based on standard fire tests and empirical methods. Thus, these methods might not yield realistic fire resistance for newer types of concrete, innovative structural shapes and realistic fire, loading and support conditions;
- a performance based numerical approach can be applied for evaluating realistic fire resistance of concrete structures. In such an approach, the various factors such as, realistic fire scenarios, loading patterns, support restraints, high temperature properties of materials, and sectional configurations can be duly accounted for;
- newer types of concrete exhibit lower fire resistance due to faster strength degradation and susceptibility to fire induced spalling. Also, newer sectional shapes, such as hollowcore slabs, are prone to shear failures under fire condition due to significant reduction in cross-section. These factors are to be given due considerations in evaluating fire resistance of structural members;
- performance based approach applied for evaluating fire response of hollowcore slabs show that slabs made with carbonate aggregate concrete, generally possess better fire resistance, than that made with siliceous aggregate concrete. Also fire scenario and support conditionsinfluence the fire response wherein, slabs perform better under design fire and under the presence of axial restraints;
- application of rational methodology on hollowcore slabs yields a fire resistance of 120 minutes of fire resistance, which is higher than that obtained from prescriptive methods.

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