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Performance-based Fire Safety Design of Reinforced Concrete Beams

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ABSTRACT: A numerical model, in the form of a computer program, is presented for tracing the fire behavior of reinforced concrete (RC) beams over the entire range of loading from pre-fire conditions to collapse under fire. The three stages associated with the analysis of fire resistance; namely, establishing the fire temperature–time development, calculating the heat transfer through the structure from the fire, and the structural analysis are explained. The model, which accounts for nonlinear material properties at elevated temperatures, is capable of predicting the fire resistance of RC beams under realistic fire scenarios, load levels, and failure criteria. The validity of the numerical model is established by comparing the predictions from the computer program with results from full-scale fire resistance tests. Through the results of numerical study, it is shown that the type of failure criterion, load level, and fire scenario have significant influence on fire resistance of RC beams. The computer program can be used to undertake performance-based fire safety design of RC beams for any value of the significant parameters, such as fire exposure, concrete cover thickness, section dimensions, concrete strength, concrete type, and load intensity.

KEY WORDS: fire resistance, performance-based design, structural fire safety, high temperature, reinforced concrete beams, high strength concrete, numerical model.

INTRODUCTION

REINFORCED CONCRETE (RC) structural systems are quite frequently used in high-rise buildings and other built infrastructure due to a number of advantages they provide over other materials. When used in buildings, the provision of appropriate fire safety measures for structural members is an important aspect of design since fire represents one of the

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most severe environmental conditions to which structures may be subjected in their life time. The fire resistance of RC members is generally established using prescriptive approaches which are based on either standard fire resistance tests or empirical calculation methods.

There have been only limited studies on evaluating the fire performance of RC beams [mostly fabricated with normal strength concrete (NSC)]. Furthermore, much of the current knowledge on the fire behavior of RC beams is based on standard fire resistance tests under a standard fire exposure. Also, failure is often based on a thermal criterion (critical temperature in reinforcing bars) alone, without any due consideration to strength or deflection criteria. There have been limited research studies on evaluating the fire performance of RC beams under realistic (design) fire scenarios. Thus, there is very limited experimental data, numerical models, or design specifications for predicting the fire resistance of RC beams under design fire scenarios. Additionally, the current approach of determining fire resistance of RC beams by testing under standard fire conditions may not be realistic, since a number of factors such as realistic load levels and actual failure criteria are not accounted for. Furthermore, compartmentation characteristics including opening size, compartment size, opening location, and lining material, as well as realistic fire scenarios, which influence the behavior and eventual failure of an RC beam, are not taken into consideration.

This article presents the development of a validated computer model for undertaking performance-based design of RC beams exposed to fire. The model is based on a macroscopic finite element approach and uses a series of moment–curvature (M–K) relationships for tracing the response of the beam in the entire range of behavior, from a linear elastic stage to the collapse stage under any given fire and loading scenarios. The model is verified against experimental data by comparing the predicted temperatures, deflections, and fire resistance times with the measured values from fire tests. Results from the parametric study are presented to illustrate the influence of various components of a performance-based approach, including realistic failure criteria, loading conditions, and fire scenarios, on fire resistance of RC beams.

FIRE SAFETY DESIGN OF RC BEAMS

Current Prescriptive-based Approaches

The structural behavior of RC beams under fire conditions is evaluated through standard fire resistance tests on RC members. Standard fire resistance tests, though useful in evaluating comparative fire performance, have a number of drawbacks and do not provide realistic fire performance assessment. Data from such limited standard fire tests on RC beams have been used to develop current code provisions for fire resistance evaluation of RC beams [1,2]. Thus, the current code provisions are simplistic, prescriptive, and not realistic because they do not account for factors such as spalling. As an illustration, the failure of an RC beam in a fire test is based on the temperature attained in the steel reinforcement (just prior to failure), under a standard fire exposure, without any consideration to the behavior of the beam during the entire fire. In empirical design methods, the fire resistance of an RC beam is only dependent on the concrete cover thickness over the reinforcement and the overall dimensions of the beam, without any consideration to important factors such as level of loading, fire scenarios, and failure criteria [1]. These cover thickness specifications are primarily determined based on corrosion control requirements and then checked for limiting temperature transmission to rebars. This limiting temperature, which is often called critical temperature, is defined as the temperature at which steel (reinforcement) loses 50% of its strength. For steel reinforcing rebars, it is 593°C, and for prestressing steel it is 426°C [3].

Although there are some methods of calculating the fire resistance of RC beams such as those provided by the SFPE Manual [4], such methods do not account for material nonlinearity and thus they cannot predict the deflection of the beam. Furthermore, those methods do not account for creep strain and transient strain which have a significant effect on the fire response of RC beams, especially at later stages of fire exposure. Therefore, the current design approaches cannot be used under the recently introduced performance-based codes, such as NBC [5] and Eurocode 2 [6], which provide rational, cost-effective, and innovative fire safety solutions.

A review of the literature indicates that only a limited number of fire resistance tests have been conducted on RC beams, which is in contrast to large amount of data available from fire tests on RC columns. Furthermore, the review also shows that there have only been very limited numerical studies on fire behavior of RC beams. Again, this is in contrast with the fire behavior of RC columns which was the focus of a number of analytical studies [7,8]. The limited analytical studies on RC beams reported by Dotreppe and Franssen [9] and Ellingwood and Lin [10], have a number of limitations and drawbacks. Specifically, they are not validated in the whole range of behavior and do not account for important factors such as fire exposure scenario, failure criterion, concrete strength, and load level. Also, the above analytical studies focused only on the behavior of RC beams fabricated with NSC and cannot be used for high strength concrete (HSC) beams. This is because, for the case of HSC, spalling under fire situations, as well as greater deterioration of strength properties at elevated temperatures, has to be accounted for.

Spalling is theorized to be caused by the build-up of pore pressure during heating [11,12]. HSC is believed to be more susceptible to this pressure build-up because of its low permeability compared to NSC. The extremely high water vapor pressure, generated during exposure to fire, cannot escape due to the high density of HSC and this pressure often reaches the saturation vapor pressure. At 300°C, the pressure reaches about 8 MPa. Such internal pressures are often too high to be resisted by the HSC mix having a tensile strength of about 5 MPa [11]. Data from various studies show that predicting fire performance of HSC, in general, and spalling, in particular, is very complex since it is affected by a number of factors [11–13].

Performance-based Approach

In recent years, there has been an increased focus on moving toward performance-based fire safety design from the current prescriptive-based approaches [14–16]. This is mainly due to the cost-effective and rational fire safety solutions performance-based design approaches provide. One of the key aspects in any performance-based design is the fire resistant design of structural members. For evaluating fire performance of structural members, two levels of analysis can be used. The first approach is the use of mathematical models that simulate the conditions to which structural members are subjected during exposure to fire. The other approach is the use of design formulas, which are derived using mathematical models and simplified to a form that they can be incorporated into building codes.

At present, there are very few methods or tools that can be applied for performance-based fire safety design of RC beams. This is because the current methods are unable to account for factors such as spalling, all strain components and to predict deflection of RC beams exposed to fire. A comprehensive research program is needed for developing a rational methodology to facilitate performance-based fire safety design of RC beams for any given concrete strength, beam size, load, and fire scenarios.

In the performance-based approach, the fire resistance of RC beams is determined based on selection of one or more realistic fire scenarios, loading conditions, and failure criteria. These main components to be considered in any performance-based fire safety design approach are discussed in the following sections:

Fire Scenarios

The current practice of evaluating fire resistance of RC beams is based on standard fire tests, in which the beam is exposed to a standard fire as specified in Standards such as ASTM E119 [17] and ISO 834 [18]. While standard fire resistance tests are useful benchmarks to establish the relative performance of different RC beams under the standard fire condition, they should not be relied upon to determine the survival time of RC beams under realistic fire scenarios. Nor does the standard heating condition bear any relation to the often less severe heating environments encountered in real fires.

Figure 1 illustrates various time–temperature curves for standard and some realistic fire scenarios. In the standard fires (ASTM E119 fire, hydrocarbon fire, and external fire), the fire size is the same (irrespective of compartment characteristics), temperature increases with time throughout the fire duration, and there is no decay phase. However, in real fires, the fire size is a function of compartment characteristics, such as ventilation, fuel load, and lining materials, and there is a decay phase as clearly shown in Figure 1 (design fires Fire I and Fire II). In the decay phase of the realistic fire scenarios, the cross section of the beam enters the cooling phase, in which the reinforcing steel recovers parts of its strength and stiffness, and thus the fire resistance of the beam might increase.

Loading Conditions

The current codes of practice for evaluating fire resistance through standard fire tests are generally based on a load ratio of about 50%.

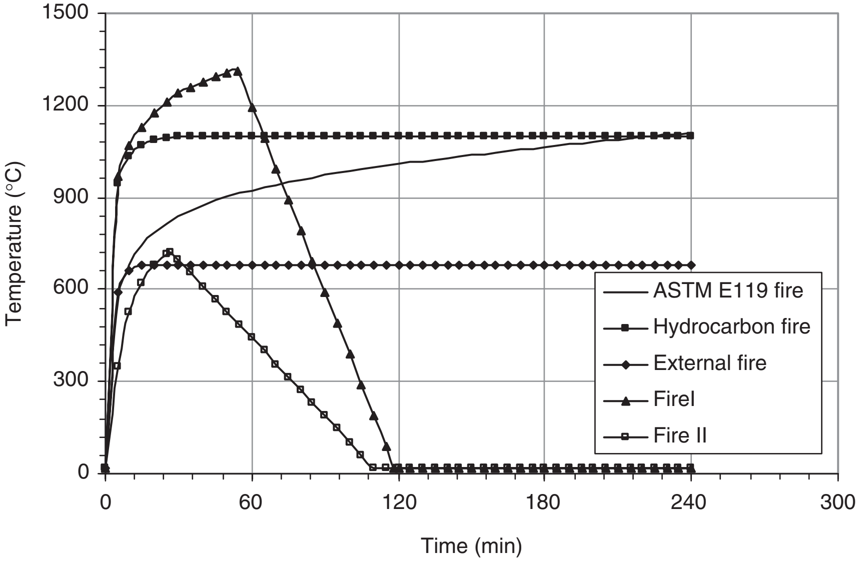

Figure 1. *Various fire scenarios used in the analysis.*

Load ratio is defined as the ratio of the applied load on the beam under fire conditions to the strength capacity of the beam at room temperature. Load ratio depends on many factors including the use of the building, the dead-load/live-load ratio, and the safety factors (load and capacity factors) used for design under both room temperature and fire conditions. The loads that are to be applied on RC beams, in the event of fire, can be estimated based on the guidance given in ASCE-07 standard [19] (1.2 dead load + 0.5 live load) or through actual calculation based on different load combinations. Based on ASCE-07 [19] and ACI 318 [20], and for typical dead to live load ratio (in the range of 2–3), the load ratio ranges between 65% and 70%.

Furthermore, the load ratio might influence the fire resistance of RC beams calculated based on realistic failure criteria. Thus, for innovative, realistic, and cost-effective performance-based fire safety design, it is important to evaluate the fire resistance of RC beams based on actual load levels.

Failure Criteria

The conventional approach of evaluating fire resistance is based on thermal and strength failure criteria as specified in ASTM E119 [17]. Accordingly, the thermal failure of an RC beam is said to occur when:

- the temperature in steel rebars (tension reinforcement) exceeds the critical temperature which is 593°C for reinforcing steel.

The strength failure is said to occur when:

- the beam is unable to resist the applied service load.

Deflection and rate of deflection can also play a major role on the behavior of RC beams exposed to fire conditions. In fact, a deflection criterion is required to define failure of RC beams at ambient conditions and this criterion should be considered to define realistic failure of an RC beam exposed to fire. Such deflections and rate of deflections are expected to be higher than those at room temperature, prior to failure under fire conditions, due to deterioration of member stiffness at elevated temperatures and also due to temperature induced creep. British Standard (BS) 476 [21] considers the deflection and rate of deflection criteria for defining failure. Although those deflection limit states might have been set to limit damage to the furnace during a fire test, limiting deflection and rate of deflection can be important under some realistic fire conditions. This is because the integrity of the structural member cannot be guaranteed with excessive deformations. Moreover, defining fire resistance based on limiting deflection will help to facilitate the safety of fire fighters and also to safely evacuate occupants prior to structural collapse. The deflection and rate of deflection limit states suggested by BS 476 are:

- the maximum deflection of the beam exceeds $L/20$ at any fire exposure time, or
- the rate of deflection exceeds the limit given by the following expression:

$$\frac{L^2}{9000d}(\mathrm{mm/\,min}), \tag{1}$$

where $L =$ span length of the beam (mm) and $d =$ effective depth of the beam (mm).

Other Factors

Other major components to be considered for evaluating failure of RC beams under fire exposure scenarios include spalling and the effect of restraints. Although spalling may not be an important factor for NSC, excessive spalling can occur in HSC due to the low permeability and presence of silica fume, which causes the pore pressure to increase to high levels enough to cause spalling [11,12]. Spalling has the effect of reducing the cross-sectional area of the beam, and increasing the heat penetration to the steel reinforcement. Thus, spalling might result in significant reduction in the strength and stiffness of beam, which in turn might cause early failure of the RC beam. However, spalling may not be required as a separate failure criterion, since lots of excessive spalling leads to loss of strength and higher deflection which in turn determines the fire resistance and thus the failure of the beam.

End restraints to RC beams can be rotational, axial, or both. Under fire conditions, rotational restraints can improve the fire response of an RC beam through moment redistribution between support (negative moment) and span (positive moment) sections within the length of the beam. Therefore, rotational restraints increase the fire resistance of RC beams. Even if the moment redistribution has been considered in the design at room temperature, rotational restraints are expected to have a positive effect on the fire resistance of RC beams. This is because the tensile steel (at the bottom of the beam) for span moment is closer to the fire exposure than that for support moment, which makes the reduction in the negative (support) moment capacity smaller than that in the positive (span) moment capacity. Furthermore, the curvature ductility of an RC beam under fire conditions is higher than that at room temperature, which allows for more redistribution of bending moment under fire exposure.

The effect of axial restraints on the fire resistance of RC beams depends on the vertical location of the restraint force. Generally, the axial restraint force in an RC beam is expected to be below the neutral axis of the RC beam section as a result of the anticipated thermal gradients. This can improve the fire resistance of the RC beam through the arch action associated with axial restraints, which increases the strength and the stiffness of the beam under fire exposure. However, axial restraints may increase spalling of concrete which in turn might reduce the fire resistance of RC beams.

NUMERICAL MODEL

A numerical model for predicting the behavior of RC beams, exposed to fire, was developed as part of the current study. The numerical procedure is performed in three steps; namely, the calculation of temperatures of the fire to which the beam is exposed, the calculation of the temperatures in the beam, and the calculation of the resulting strength, deflections, and rate of deflection of the beam. The numerical model uses (M–K) relationships to trace the response of an RC beam in the entire range of loading up to collapse under fire. The model is capable of undertaking fire resistance analysis for beams exposed to any given fire time–temperature curve.

In the numerical model, the RC beam is divided into a number of segments along its length (as shown in Figure 2) and the mid-section of the segment is assumed to represent the behavior of the whole segment. The fire duration is divided into a number of time steps and at each time step the analysis is carried out in three steps; namely, fire scenario analysis, heat transfer analysis, and strength analysis. In the fire scenario analysis, the temperatures due to fire exposure are established at each time step using the time–temperature curve of the specified fire exposure. Some standard and design fire scenarios (Figure 1) are incorporated in the numerical model. However, any given fire scenario with a defined time–temperature relationship can also be included, as input to the model.

The fire temperature is used as input data to carry out a heat transfer analysis in which the thermal properties of the constituent materials are used

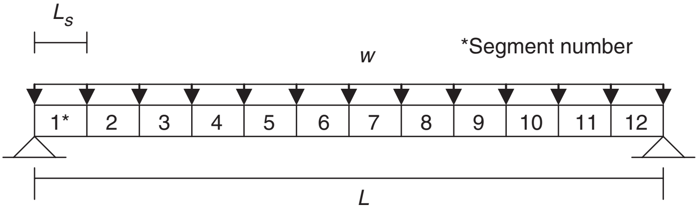

Figure 2. *Layout of a typical RC beam and its idealization for analysis.*

to determine the temperature profile within the cross section of each segment. In the heat transfer analysis, the cross-sectional area of each segment is subdivided into a number of elements and using a finite element formulation the temperature rise in a beam segment is computed. Reinforcing steel is not considered in the heat transfer analysis. This is because steel rebar area is very small compared to the concrete area (a ratio of about 1–3%), and thus the effect of steel reinforcement on the heat transfer analysis is small and can be neglected [8].

Following the heat transfer analysis, an M–K relationship is generated for each segment at various time steps. It has been well established that M–K relationships appropriately represent the behavior of an RC beam at ambient conditions. In the current model, such M–K relationships are established as a function of time for various segments in the beam and they are in turn used to trace the response of the beam under fire conditions. The M–K relationships, at various time steps, are generated using the changing properties of constituent materials; namely, concrete and reinforcement. In this way, the material nonlinearity will be implicitly accounted for in the analysis.

The M–K generation, at elevated temperatures, is carried out using the same rectangular network described above and shown in Figure 3. Values for curvature and topmost fiber total strain (in concrete) are assumed. Then, the total strain in each of the rebars and concrete elements is computed from the assumed strain and curvature. The stresses in the rebars and the concrete

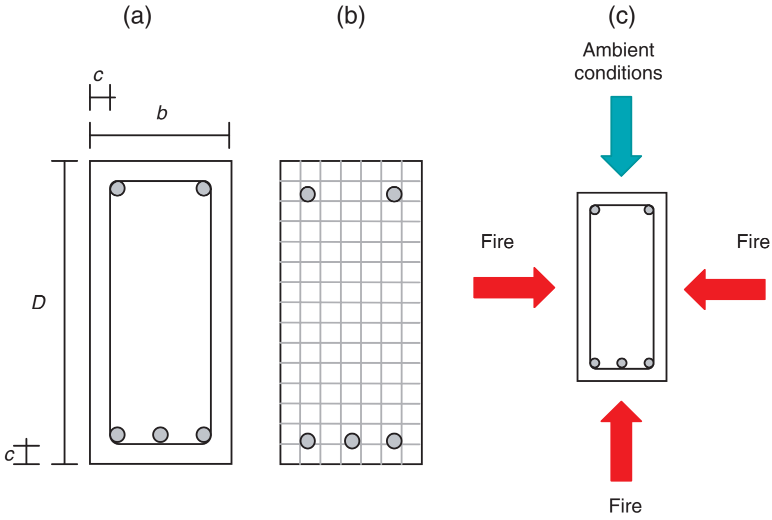

Figure 3. *Cross section of an RC beam and its discrtization for analysis. (a) cross-sectional details; (b) discretization and (c) boundary conditions for heat transfer analysis. (The color version of this figure is available online.)*

elements are determined using the constitutive laws of the materials. The temperature of a rebar is assumed to be equal to the temperature at the location of the center of the rebar. Once the stresses are known, the forces are computed in the concrete and the rebars. The curvature is iterated until equilibrium of forces is satisfied. Once the equilibrium is satisfied, the moment is calculated, and thus the curvature and the moment are stored to represent a point on the M–K curve. The value of the topmost fiber total strain is incremented to generate subsequent points on the M–K curve. This procedure is repeated for each time step of fire exposure. The generated M–K curves are used for tracing the behavior of the beam through nonlinear structural analysis.

Various strain components including mechanical strain, thermal strain, and creep strain for both concrete and reinforcing steel and transient strain for concrete are accounted for in the model. The creep and transient strains, which are often not accounted for, might play a major role in predicting the fire behavior of RC beams particularly deflection and rate of deflection.

Spalling of concrete is incorporated into the model through a simplified approach proposed by Kodur et al. [7]. This approach is based on detailed experimental studies and considers various material and structural parameters that influence spalling. The simplified approach assumes spalling to occur in concrete elements where temperatures exceed 350°C. In addition, the approach takes into account other factors that may affect spalling such as configuration and spacing of stirrups, presence of steel or polypropylene fibers, and aggregate type.

Using the M–K relationships, the load (moment) the beam can carry at a particular time step is evaluated. Also, the deflection of the beam at that time step can be calculated through a stiffness approach by evaluating the average stiffness of the beam. The average stiffness of the beam is computed using segmental stiffness, which is estimated from the already computed M–K relationships at elevated temperatures. A flowchart showing the numerical procedure for fire resistance calculations is given in Figure 4.

The temperatures and strength capacities for each segment, and computed deflections in the beam, are used to evaluate failure of the beam at each time step. At every time step, each beam segment is checked against four sets of predetermined failure criteria, which include prescriptive thermal limit state, and performance-based strength and deflection limit states. The prescriptive thermal failure criterion (critical temperature in tension rebars) is presented here to compare the predicted fire resistance, computed based on the prescriptive approach, with predicted fire resistance calculated based on the performance-based approach. Four failure criteria are incorporated into the model based on the prescriptive and the performance-based approaches. The time to reach each of those failure criteria is stored and used to compare

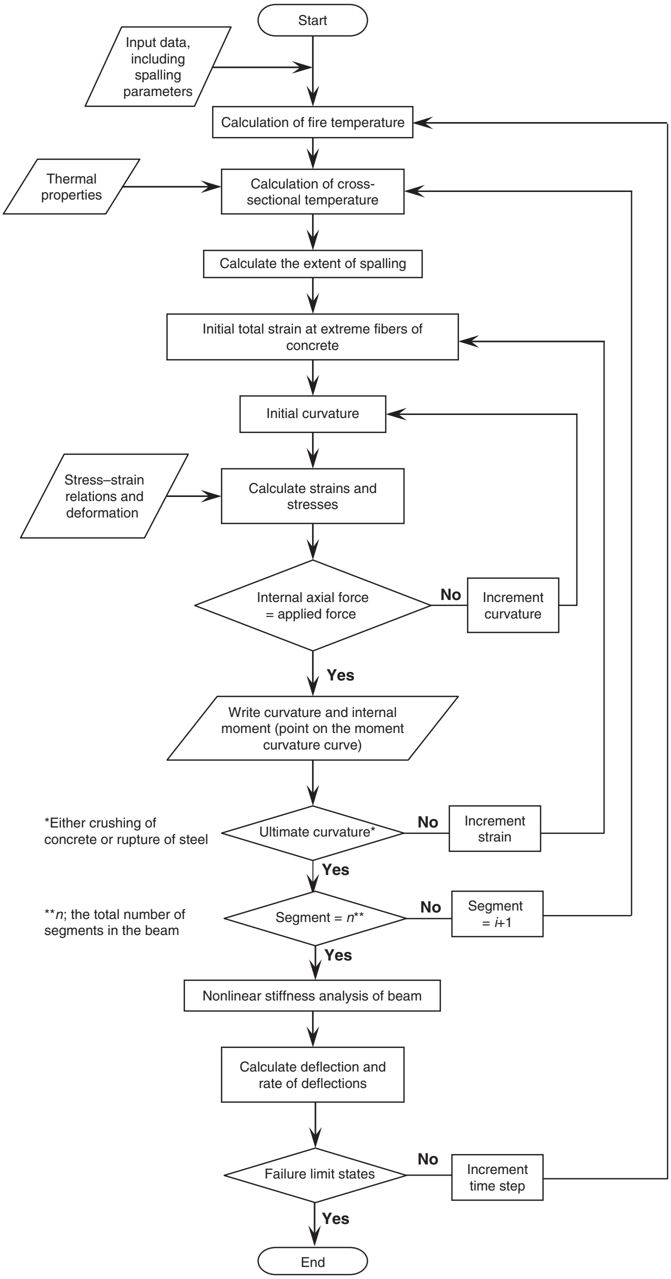

Figure 4. *Flowchart showing the steps associated with the analysis of an RC beam exposed to fire.*

the two fire safety design approaches. However, the program keeps generating results until strength failure is reached. The four failure criteria adopted in the model are:

(1) The temperature in steel rebars (tension reinforcement) exceeds the critical temperature which is 593°C for reinforcing steel.
(2) The beam is unable to resist the specified applied service load.
(3) The maximum deflection of the beam exceeds $L/20$ at any fire exposure time, where L is span length.
(4) The rate of deflection exceeds the limit given by Equation (1).

The computer program generates various critical output parameters, such as temperatures, stresses, strains, deflections, and moment capacities at various given fire exposure times. Full details of the numerical model, including the derivation of appropriate equations, are presented in [22].

Thus, the proposed numerical model is capable of accounting for nonlinear high-temperature material characteristics, complete structural (beam) behavior, various fire scenarios, load levels, concrete types (such as different aggregate types, fiber mixes, and concrete strengths), spalling mechanism, and four sets of failure criteria.

COMPUTER IMPLEMENTATION

Computer Program

The numerical procedures described in this section require a huge amount of computation since an iterative approach has to be used. Therefore, to facilitate the above set of calculations, the numerical procedure was incorporated into a computer program, written in FORTRAN. Figure 4 shows a flowchart of the numerical procedure associated with the computer program. The given RC beam is idealized to be a set of longitudinal beam segments. The analysis starts at ambient conditions (pre-fire-exposed stage), and then the time is incremented in steps till failure of the beam. At each time step, the procedure starts with calculating the fire temperature. Heat transfer analysis is then carried out to compute temperature distribution in the cross section of each segment. The third step is the strength analysis wherein the M–K curves, during fire exposure, are generated. The M–K relationships at any time step are obtained by successive iterations of concrete strain and curvature until the internal axial force balances the applied axial force (which is generally equal to zero for beams).

For any given concrete strain, the curvature is varied until the resultant internal axial force is equal to zero. Once the curvature is determined, the internal moment of the cross section can be obtained by adding the moments of all elements. The moment of each element is simply the internal force in that element multiplied by the distance between the center of the element and the geometrical centroidal axis of the cross-sectional area.

The last step in the analysis is to construct the global stiffness matrix of the beam and the associated loading vector. The obtained system of nonlinear stiffness equations is solved using an iterative procedure described by Campbell and Kodur [23] and the deflections are computed. These deflections and rate of deflections of the beam, together with temperatures and strength capacities for each segment, are checked against the limiting values discussed above to assess the failure state of the beam under fire conditions at that time step. The time increments continue until the beam attains failure due to fire. Full details of the computer model are given by Kodur and Dwaikat [22].

Idealization

For thermal and mechanical analyses of RC beams, the cross section of the beam is idealized as a mesh of elements as shown in Figure 3. The number of elements in each direction is to be specified in the input file. The program determines the element size based on the specified number of elements. The program allows any rebar configuration. However, the section must be symmetrical around the vertical centroidal axis, because lateral torsional calculations are not included in the model.

Fire Scenario

Three standard fire scenarios; namely, ASTM E119 standard fire [17], hydrocarbon standard fire [24], external standard fire [25], as well as two design fire scenarios (Figure 1) are incorporated into the program. The user has the option of selecting any of the five fire exposures. Relevant time–temperature relationships for the five fire exposures are built into the program. In the input file, the user has to specify the type of fire exposure and the program automatically uses the time–temperature relationship for the given fire scenario to calculate the fire temperature at any time step.

Boundary Conditions for Heat Transfer Analysis

The beam is assumed to be exposed to fire from three sides with the fourth side exposed to ambient conditions. Both convection and radiation heat transfer mechanisms are accounted for at all boundaries. The ambient temperature is assumed to be 20°C. Figure 3(c) shows the boundary conditions assumed in the program for the heat transfer analysis.

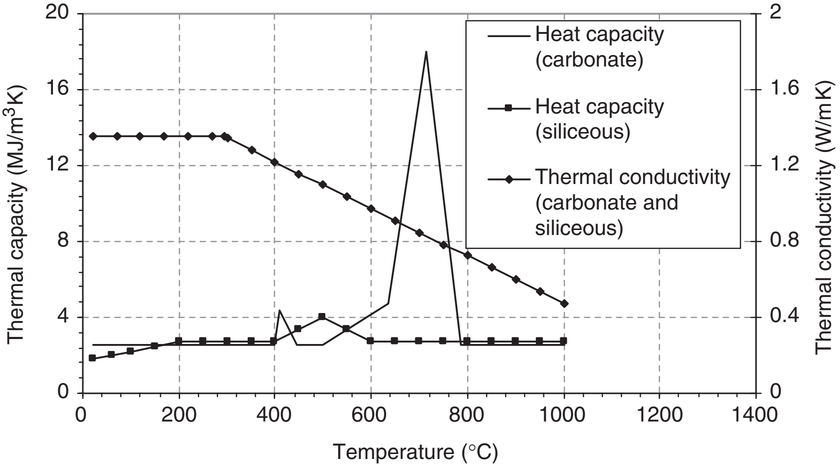

Figure 5. *Thermal properties of concrete as a function of temperature.*

Material Properties

Concrete

Three sets of concrete properties, which include thermal, mechanical, and deflection properties, suggested by Eurocode 2 [6], Kodur et al. [7], and those given in the ASCE Manual [26], were incorporated into the program. Although the concrete properties given in ASCE Manual can only be applied for NSC, the concrete properties given by Kodur et al. [7] and Eurocode 2 can be used for both NSC and HSC. The program selects any one of these three models based on the user specifications in the input file. The user also has the option of selecting aggregate type (siliceous or carbonate) of concrete. Relevant formulas for both the mechanical and thermal properties of concrete as a function of temperature are built into the program. The variation of thermal conductivity and heat capacity as a function of temperature for concrete, which are used in the analysis, are shown in Figure 5. Furthermore, Figure 6 shows stress–strain curves (given in the ASCE Manual) that has been incorporated into the program for NSC at various temperatures. In the input file the user has to specify the 28-day compressive strength of concrete, the initial moisture content, the concrete model (Eurocode 2, ASCE Manual or Kodur et al.), and the type of aggregate in the concrete.

Steel Reinforcement

The mechanical properties of reinforcing steel (stress–strain–temperature relationships) that are given in the ASCE Manual [26] are incorporated into

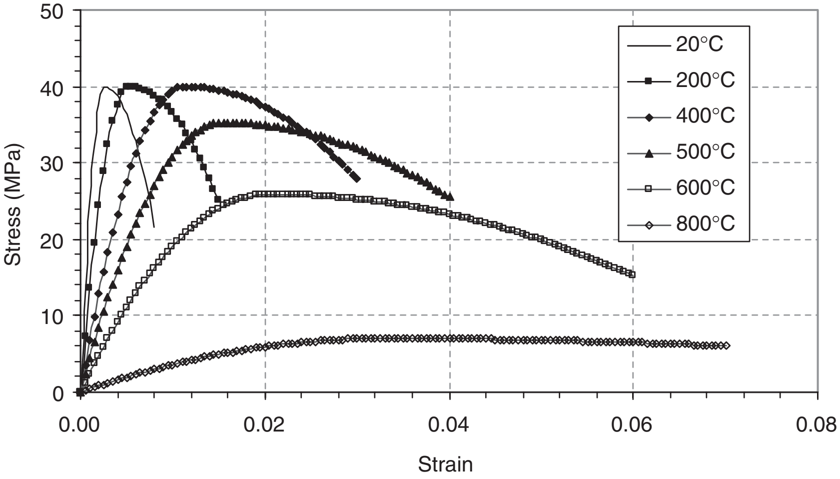

Figure 6. *Stress–strain curves of concrete (NSC) at various temperatures [26].*

the program. Figure 7 shows the stress–strain curves of reinforcing steel at various temperatures. The user has to specify the yield strength of steel in the input file, and the program automatically uses the built-in stress–strain relationships.

Input Data

The basic input for the program consists of cross-sectional properties, material properties (such as concrete strength, yield strength of rebars), fire scenario, load ratio, and general data such as the number of time increments. The sequential order of the input data must be followed, and consistent units must be used throughout.

Output Results

The output from the program includes results from the thermal and structural analyses. At each incremental time step, the temperature at each node of Figure 3(b) is computed. The output results also include the M–K curves. In addition, the moment capacity, the deflection, and the rate of deflection of the beam are also recorded for each time step.

VALIDATION OF THE MODEL

The validity of the computer model was established by comparing predicted results from the model with the measured values from fire tests for a beam tested by Lin et al. [27]. The geometric and material properties of the tested beam used in the analysis are taken from the literature and are given in Table 1. The beam was tested under ASTM E119 standard fire exposure

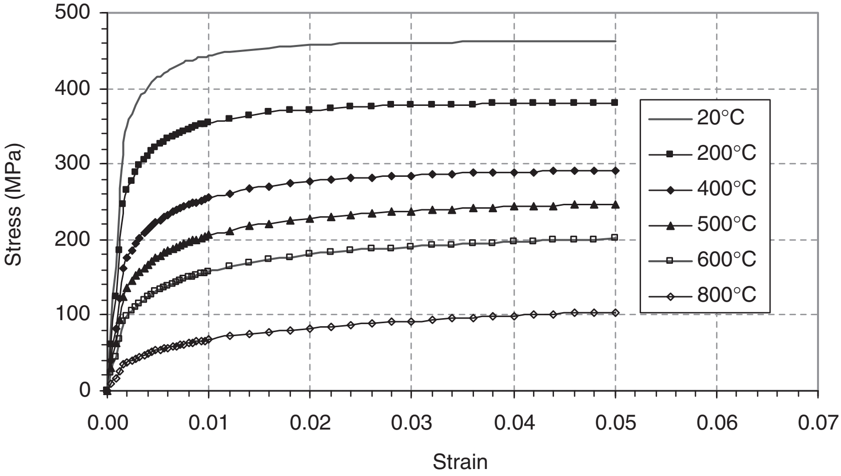

Figure 7. *Stress–strain curves of reinforcing steel at various temperatures [26].*

Table 1. Properties and analysis results for the RC beam tested by Lin et al. (1981).

Property	**Beam I**
Description	Tested by Lin et al. [27]
Cross section (mm)	305 × 355
Length (m)	6.1
Reinforcement	
2ϕ 19 mm top bars	
4ϕ 19 mm bottom bars	
f'_C (MPa)	30
f_y (MPa)	435.8
Loading ratio	0.42
Applied total load (kN)	80
Concrete cover thickness (mm)	25 (bottom) 38 (side)
Aggregate type	Carbonate
Fire resistance based on failure criterion (min)	
Rebar temperature	110
Strength	140
Deflection (BS 476)	102
Rate of deflection (BS 476)	105
Fire resistance based on ACI 216 (min)	180
Fire resistance test (min)	80

and hence the beam was also analyzed by exposing its three sides to the standard time–temperature curve specified in ASTM E119. The fire resistance of the beam is calculated based on the four sets of failure criteria previously discussed and the results are summarized in Table 1. Predicted results from the analysis are compared with measured values from fire tests in Figures 8 and 9.

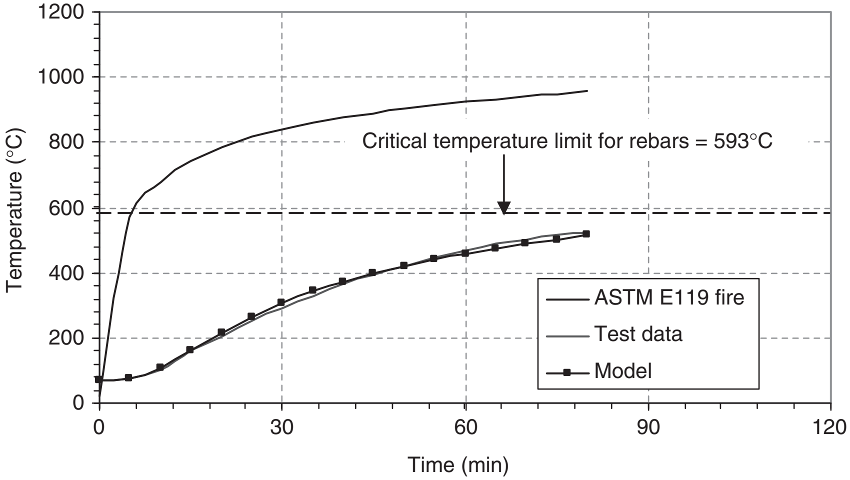

Figure 8. *Predicted and measured rebar temperatures for test beam, Beam I.*

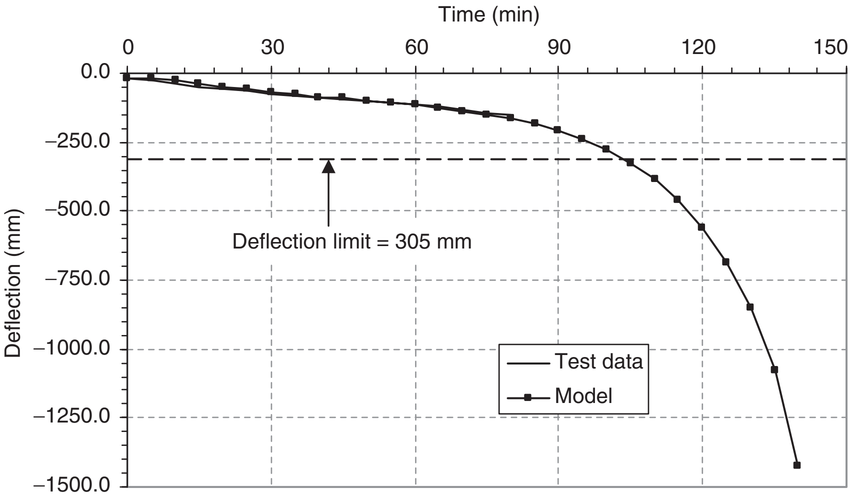

Figure 9. *Predicted and measured deflections for test beam, Beam I.*

In Figure 8, the calculated average temperatures in the rebars are compared with the measured values for Beam I, reported by Lin et al. [27]. It can be noted that there is good agreement between the predicted and measured values in the entire range of fire exposure. The steep increase in rebar temperature in the early stages of fire exposure is due to the occurrence of high thermal gradient at the beginning of fire exposure time as a result of faster increase in fire temperature (see ASTM E119 fire curve in Figure 8). A review of predicted temperatures in concrete at various depths indicated that the model predictions follow the expected trend with lower temperatures at larger depths from the fire exposed surface. However, the predicted concrete temperatures could not be compared with test data since the measured temperatures were not reported by Lin et al. [27]. Figure 9 shows predicted and measured mid-span deflections as a function of fire exposure time for Beam I tested by Lin et al. [27]. It can be seen that model predictions are in close agreement with the measured deflections, throughout the fire exposure time.

The fire resistance of this beam was evaluated based on four sets of failure criteria and their values are given in Table 1. In addition, the fire resistance of the beam was also evaluated based on ACI 216 specifications [1]. The measured fire resistance, for Beam I, is lower than that predicted by the computer model for all failure criteria. This is mainly because the test was terminated after 80 min of fire exposure, and before the beam attained complete failure, probably due to the severe conditions experienced toward the final stages in the fire tests [27]. The fire resistance of this beam would have been slightly higher if the test had been continued till the complete failure.

The fire resistance predicted based on rebar temperature (110 min) is much lower than that for strength failure criterion (140 min). This is because the rebar temperature failure criteria is based on load level of 50% of the room temperature capacity of the beam; however, the load level on this beam is <50% (~42%) and this results in higher fire resistance from strength failure criterion. Overall, the predicted fire resistance from deflection failure criteria (102 min) is a reasonable estimate to the measured value in the fire test (when the test was terminated).

The fire resistance of the beam was also estimated using ACI 216 [1] prescriptive criterion and accordingly it was 191 min. This fire resistance value is higher than that predicted by computer model for the four failure criteria. This is mainly because the fire resistance predicted by ACI 216 is based on the concrete cover thickness and the cross-sectional dimensions of the beam and does not account for important factors such as load level, strength, and deflection criteria [1].

The model was also validated against fire test results reported by Dotreppe and Franssen [9]. The predicted rebar temperatures and deflections from the analysis shows good agreement with the measured values throughout the test. The fire resistance values of tested beam were evaluated based on the thermal, strength, deflection, and rate of deflection failure criteria and were found to be 120, 145, 123, and 115 min, respectively. The measured fire resistance was 120 min. For this beam, the thermal failure criterion predicts lower fire resistance than strength failure criterion because the load ratio in the test was $<50\%$. More discussion about the validation of the model can be found in [22].

NUMERICAL STUDIES

To investigate, as well as to illustrate the influence of the main components of the performance-based fire safety design, namely load ratio, fire scenario, and failure criteria, the above numerical model is applied to analyze a set of RC beams. All the analyzed beams have the same length and cross-sectional dimensions as shown in Figure 10. The beams are assumed to be made of concrete with compressive strength of 30 MPa and reinforced with steel rebars having yield strength of 400 MPa. The fire resistance is evaluated based on the four sets of failure criteria (one thermal, one strength, and two deflection limit states). A summary of the results from the analysis is presented in Table 2.

Figure 11 shows typical M–K curves for the critical segment of the RC beam analyzed under ASTM E119 standard fire exposure (beam BFS1) at various time steps. The figure clearly shows that the moment capacity of the beam decreases with increasing time of fire exposure (increasing time steps). This is due to the deterioration in the material strength and stiffness as a result of increased temperatures in concrete and steel. The figure also shows that ultimate curvature (curvature at collapse) increases with time of fire exposure. This is mainly due to degradation of the material strength and stiffness as well as the creep strain which becomes significant prior to failure.

Effect of Fire Scenario

To investigate the effect of fire scenario on fire resistance, five RC beams, namely BFS1, BFS2, BFS3, BFS4, and BFS5, were analyzed. The first three beams were analyzed under three standard fire scenarios; namely, the ASTM E119 standard fire, hydrocarbon standard fire, and external standard fire [17,24,25]. There is no decay phase in the time–temperature curves for these standard fire scenarios. However, in realistic fires, there always exists a decay phase, since the amount of fuel or ventilation runs out

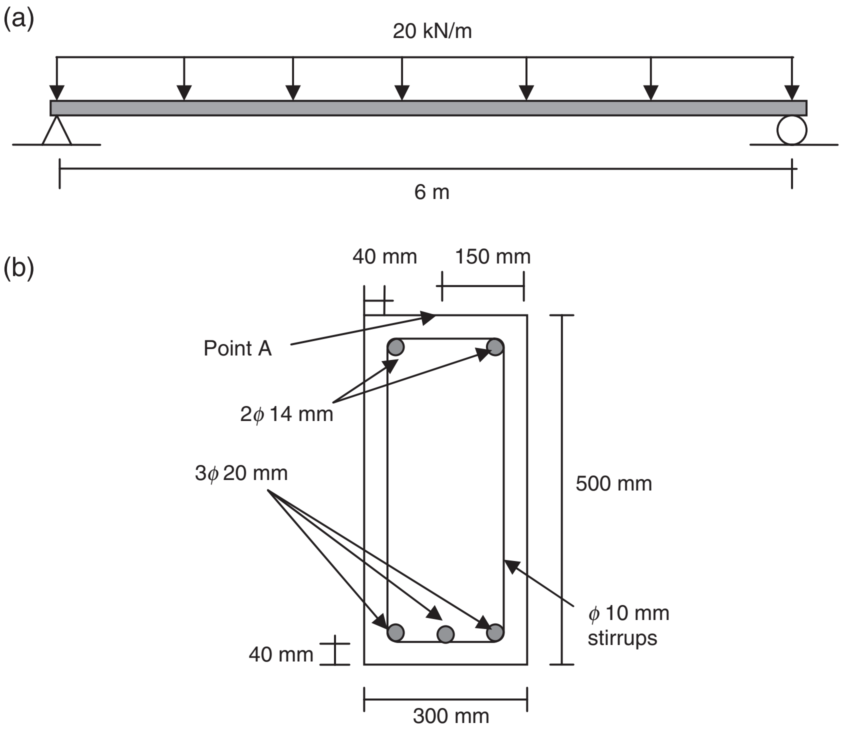

Figure 10. *Elevation and cross section of rc beam used in case studies.*

Table 2. Effect of various parameters on the fire resistance of RC beams.

			Fire resistance based on failure criterion (min)			
Beam designation	**Parameter**		**Rebar temperature**	**Strength**	**Deflection**	**Rate of deflection**
BFS1	Fire scenario*	ASTM E119	180	185	150	159
BFS2		Hydrocarbon	148	155	123	127
BFS3		External	396	375	244	370
BFS4		Design Fire I	***	***	***	***
BFS5		Design Fire II	***	***	***	***
BLR1	Load ratio** (%)	30	180	310	233	248
BLR2		40	180	240	190	201
BLR3		50	180	185	150	159
BLR4		60	180	120	110	107
BLR5		70	180	75	74	69

*Load ratio is 50%; **ASTM E119 standard fire exposure; ***no failure.

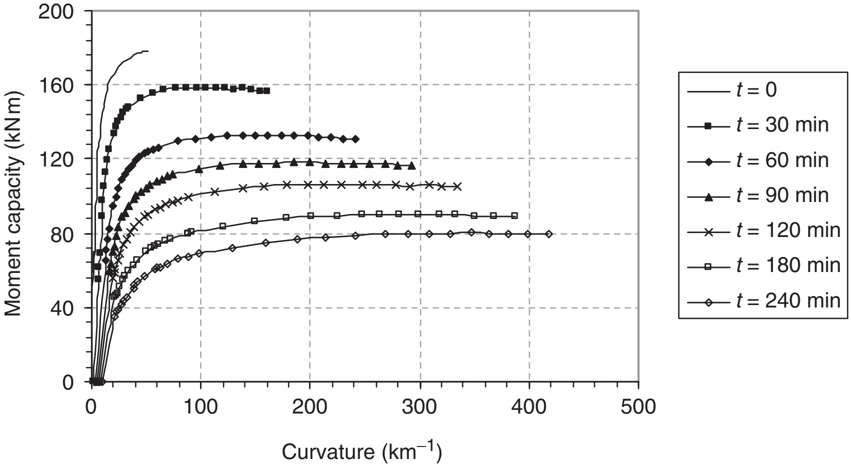

Figure 11. *Moment–curvature curves at various times for beam BFS1.*

leading to burn out of fire. Thus, the remaining two beams (BFS4 and BFS5) were analyzed under realistic (design) fire exposure.

The time–temperature curves for the two design fires (Fire I and Fire II) are developed based on the parametric fire proposed in Eurocode 1 [28] and the modification suggested by Feasey and Buchanan [29]. According to Eurocode 1, the design fire consists of a growth phase and a decay phase that is independent of the compartment properties, such as fuel load (amount of combustible materials), ventilation opening, and wall lining materials. However, it was shown that the decay phase actually depends on the compartment properties [29]. Thus, Feasey and Buchanan [29] suggested a modification for the time–temperature relationship of the Eurocode parametric fire. The modified time–temperature relationship of the parametric fire is adopted to develop the time–temperature curves of the two design fires used in the analysis.

To develop the two design fire scenarios, a fire is assumed to occur in a room with dimensions of 6 m × 4 m × 3 m. Two values of fuel load, and opening dimensions are also assumed. More details about the properties of the room for the two fires are shown in Table 3. The values were assumed in such a way that Fire I represents a severe design fire whose peak temperatures exceeds 1200°C, and Fire II represents moderate design fire whose peak temperature reaches 700°C. Fire I represents a typical real fire in a library or storage room where large amount of combustible materials and sufficient ventilation are available. Fire II represents a typical real fire in a residential room with reasonable amount of combustible material and ventilation. The time–temperature curves for the three standard fire scenarios and the two design fire scenarios are shown in Figure 1.

The analysis results show that the fire scenario has a significant influence on the temperature distribution across the beam section. As expected, the temperature at various depths of concrete, as well as in rebars, increases with the fire exposure time for the three standard fire scenarios. The results also show that the increase in concrete and rebar temperature is larger for the hydrocarbon fire than that for the ASTM E119 standard fire. This is due to the steep increase in the temperature of the hydrocarbon fire at early stages of fire exposure as shown in Figure 1. However, under the two design fire exposures, the predicted temperatures in concrete and steel rebars increase to a maximum value and then decrease. This can be attributed to the decay phase in the time–temperature curve of the design fires and thus the RC beam cross section enters the cooling phase.

The variations in the moment capacity and the deflection with fire exposure time for the five fire scenarios are presented in Figures 12 and 13,

Table 3. Assumed properties for the designed fires used in the analysis.

Design fire	Lining material	Thermal capacity of lining material ($Ws^{0.5}/(m^2 K)$)	Opening dimension (m)	Fire load (MJ/m^2 floor area)
Fire I	Gypsum board	488	2.25 × 1.5	1200
Fire II	Concrete	1900	2.85 × 1	400

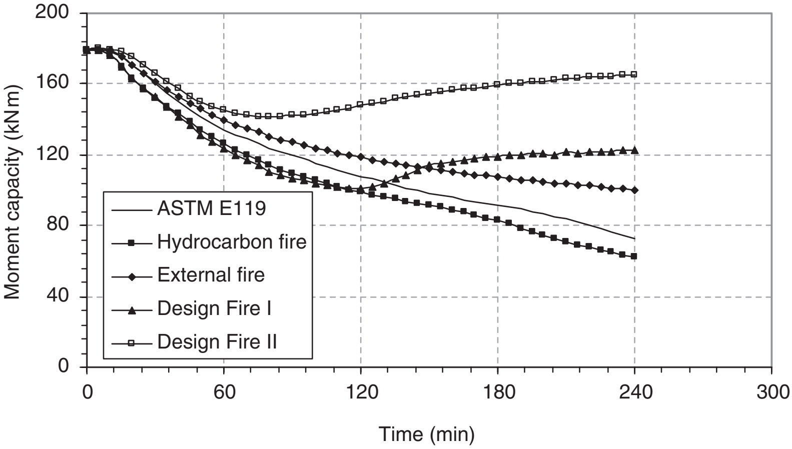

Figure 12. *Effect of fire scenario on the moment capacity of RC beams exposed to fire.*

respectively. It is clear from Figure 12 that the moment capacity for the three beams under the three standard fire exposures is always decreasing with time. However, under the exposure of the two design fires, the moment capacity decreases to a minimum value, then increases again. This is because of the decay phase in the time–temperature curve of the design fires in which the beam starts cooling and recovers part of its strength and stiffness. It can be seen from Figure 13 that the deflection and the rate of the deflection increase with time for the five beams at early stages of the fire exposure time. However, Figure 13 shows reduction (recovery) in the deflection for the two beams exposed to the design fires at later stages of the fire exposure time. This can be attributed to the recovery of parts of the beam strength and stiffness in the cooling phase discussed above. This recovery of deflection is higher for beam BFS4 exposed to severe design fire (Fire I) than for beam BSF5 exposed to moderate design fire (Fire II).

Results from the analysis show that the fire exposure has a significant effect on the fire resistance of RC beams, calculated based on different failure criteria (Table 2). It can be seen, from Table 2, that the lowest fire resistance is obtained for the beams exposed to the hydrocarbon fire, and it is about 30 min lower than that for the beam under the ASTM E119 standard fire exposure. This is due to the high increase in temperature for the hydrocarbon fire, as shown in Figure 1. It can also be seen that the fire resistance for the beam exposed to an external fire is higher than that for the beam under the exposure of the ASTM E119 standard fire. This is because the maximum fire temperature attained for external fire exposure is low when compared to that of ASTM E119 standard fire exposure.

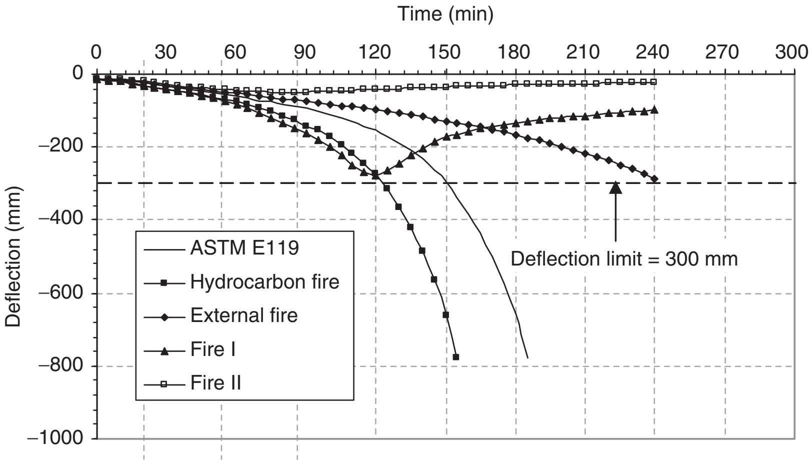

Figure 13. *Effect of fire scenario on the deflection of RC beams exposed to fire.*

Table 2 shows that none of the beams exposed to a design fire exposure attains failure, which means that none of the four failure criteria considered in the analysis is reached during the fire exposure time. Hence, in spite of the severe conditions assumed for the design fire, Fire I, no failure is attained in the beam. This result shows that, in many applications, the fire resistance values, computed based on standard fire scenarios, may be conservative if the resulting fires have a decay phase.

Effect of Load Ratio

To investigate the effect of load ratio on fire resistance, five RC beams, namely BLR1, BLR2, BLR3, BLR4, and BLR5, were analyzed with load ratio of 30, 40, 50, 60, and 70%, as shown in Table 2. In the study, the load ratio is calculated as the ratio of the applied load under fire conditions to the capacity of the beam at room temperature. Results from the analysis are shown in Figure 14 and Table 2.

The results show that load ratio has no effect on the moment capacity of RC beams since the material properties are assumed to be independent of the applied load. However, the load ratio has a significant influence on the deflection and the rate of deflection of RC beams as shown in Figure 14. The figure shows that an increase in the load ratio significantly increases the deflection and rate of deflection at any time of fire exposure. This is because an increased load ratio causes early yielding of the steel reinforcement and thus increases the plastic and creep strains. This leads to lower stiffness in the beam and results in significant increase in deflection and rate of deflection.

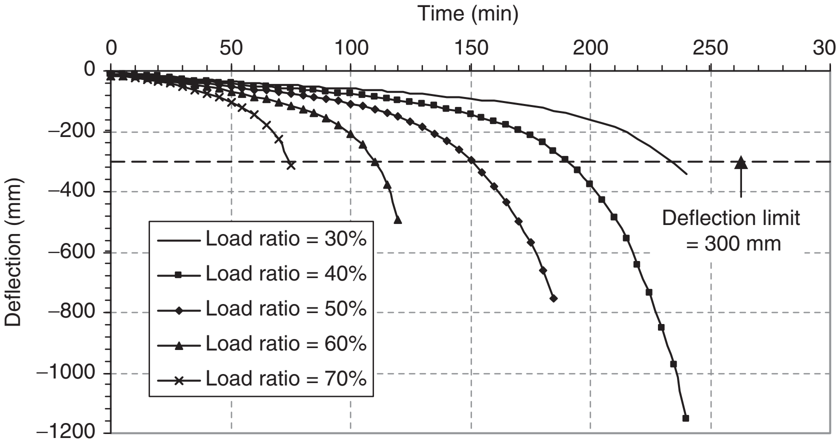

Figure 14. *Effect of Load Ratio on the Deflection of RC Beams Exposed to Fire.*

Results from the analysis also show that load ratio has no effect on the fire resistance of RC beams, if calculated based on the thermal failure criterion (Table 2). This is because the thermal limit state is based on critical temperatures which are independent of the load level. However, the load ratio has a significant influence on the fire resistance of RC beams, if calculated based on strength and deflection failure criteria. It can be seen that increasing the load ratio drastically reduces the fire resistance of RC beams. This can be attributed to the fact that high load ratio causes early softening and weakening of the constituent materials and thereby early strength and stiffness reduction of the beam. These results illustrate that fire resistance, computed based on a thermal failure criterion in standard fire tests, may not be conservative if the load ratio is $>50\%$. However, it should be noted that there is a certain level of conservatism that might be present in fire resistance tests due to the effect of some factors, such as restraints, which may increase the fire resistance in realistic scenarios.

Effect of Failure Criteria

The fire resistance for all analyzed beams was computed according to the four sets of failure criteria, incorporated in the model, and is tabulated in Table 2. The fire resistance values, predicted based on the rebar temperature and strength failure criteria, are approximately similar for most cases. However, changing the load ratio or the mechanical properties of the concrete and steel can result in large differences between the two values (rebar temperature and strength failure criteria) because the rebar-temperature failure criterion is independent of the load level and the mechanical properties of the concrete and steel.

The lowest fire resistance predicted for all beams is based on the deflection or rate of deflection failure criteria. Further, deflection and rate of deflection failure criteria predict smaller fire resistance values than those predicted by strength failure criterion for various load levels as can be seen from Table 2. Although, actual failure of the RC beam occurs when the strength limit state is reached, deflection and rate of deflection may be important in some applications to maintain the integrity of the structure, to facilitate the fire fighters work, and to safely evacuate occupants before the collapse of the structure. Therefore, for some scenarios, deflection or rate of deflection failure criterion may govern the failure of RC beams and determines their fire resistance. As explained earlier, ASTM E119 does not specify deflection or rate of deflection failure criterion, which can be a governing factor in determining the fire resistance of RC beams.

The above results clearly illustrate that the thermal failure criterion, which is often used, is insufficient to define the failure of RC beams because they do not consider important factors such as load ratio. It should be noted that the current fire resistance provisions in ASTM E119 are mainly based on a thermal failure criterion which makes them insufficient to determine the realistic fire resistance of RC beams, especially under varying load levels.

DESIGN APPLICATIONS

In North America, the current approach of evaluating fire resistance for RC beams is too prescriptive and does not reflect realistic scenarios such as loading conditions, fire scenarios, and failure criteria. This makes the current approach inapplicable for performance-based fire safety design. The proposed model is developed by accounting for realistic fire scenarios, load levels and prescriptive and performance-based failure limit states for RC beams exposed to fire.

The computer model presented here is capable of tracing the behavior of RC beams from the initial pre-fire stage to the failure of the beam under realistic fire scenarios and load level and for all possible failure criteria. Using the program, a designer can arrive at a performance-based fire safety design of an RC beam for any realistic conditions and beam properties such as fire scenario, load level, failure criteria, concrete strength, and span length. Thus, the use of this program will lead to an optimum design that is not only economical but is also based on rational design principles. Furthermore, the program can be applied to conduct parametric studies, which can then be used to develop rational fire safety design guidelines for incorporation into codes and standards.

At present, the computer program is being further expanded to account for the effect of spalling and axial restraints which are developed during exposure to fire. Also, the model is being expanded to account for other modes of failure that may result from axial and rotational restraints such as shear failure at the supports and instability of the beam.

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

- There is limited information on the fire performance of RC beams, especially under design fire, realistic loading, and failure scenarios.
- The current fire resistance provisions, developed based on limited standard fire tests under ‘standard fire scenarios’, are prescriptive and simplistic in application and thus cannot be applied for rational fire safety design under the performance-based codes.

- Load level has significant influence on the fire resistance of RC beams. Thus, the failure, and the fire resistance of an RC beam exposed to fire should be determined based on realistic load levels and load combinations.
- The type of fire exposure has significant effect on the fire resistance of RC beams. The conventional method of evaluating fire resistance, based on 'standard' fire exposure, is conservative under even severe design fire scenarios.
- The limiting criterion, used for determining failure, has significant influence on the fire resistance of RC beam. The conventional failure criterion, such as limiting rebar temperature may not be conservative under some fire scenarios. The strength, the deflection, and the rate of deflection failure criteria should be considered for realistic assessment of the fire resistance of RC beams.

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