Enhancing Fire Resistance of Concrete Beams through Sacrificial Reinforcement

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ABSTRACT

Due to the superior properties of concrete, structural members made of concrete often satisfy fire requirements specified in codes and standards without special installations or the use of external insulation. A closer examination into fire codal provisions shows that they are primarily founded for new constructions or that which does not suffer from aging or in-service trauma; such as cracking, reinforcement corrosion, creep, etc., all of which can adversely affect the structural response of concrete structures, especially under fire conditions. In order to enhance the fire resistance of concrete structures, this paper presents insights into simple and cost-effective solutions by utilizing sacrificial layer(s) of reinforcement. These solutions capitalize on the natural synergy between reinforcement and concrete and have the potential to mitigate fire-induced cracking and the development of fire-induced large deformation, thereby extending the fire resistance of reinforced concrete beams. The validity and applicability of the proposed concepts are highlighted through a highly complex three-dimensional thermo-mechanical nonlinear-based finite element model. This model was utilized in a series of parametric studies to examine critical parameters influencing the fire response of concrete beams reinforced with steel and fiber-reinforced polymer reinforcement. These parameters include sacrificial reinforcement scheme, size, and material type. It was concluded that the use of sacrificial reinforcement could be beneficial for mitigation purposes or as a repair solution for postfire events.

Keywords: Fire resistance; Reinforced concrete; beams; sacrificial reinforcement; structural members.

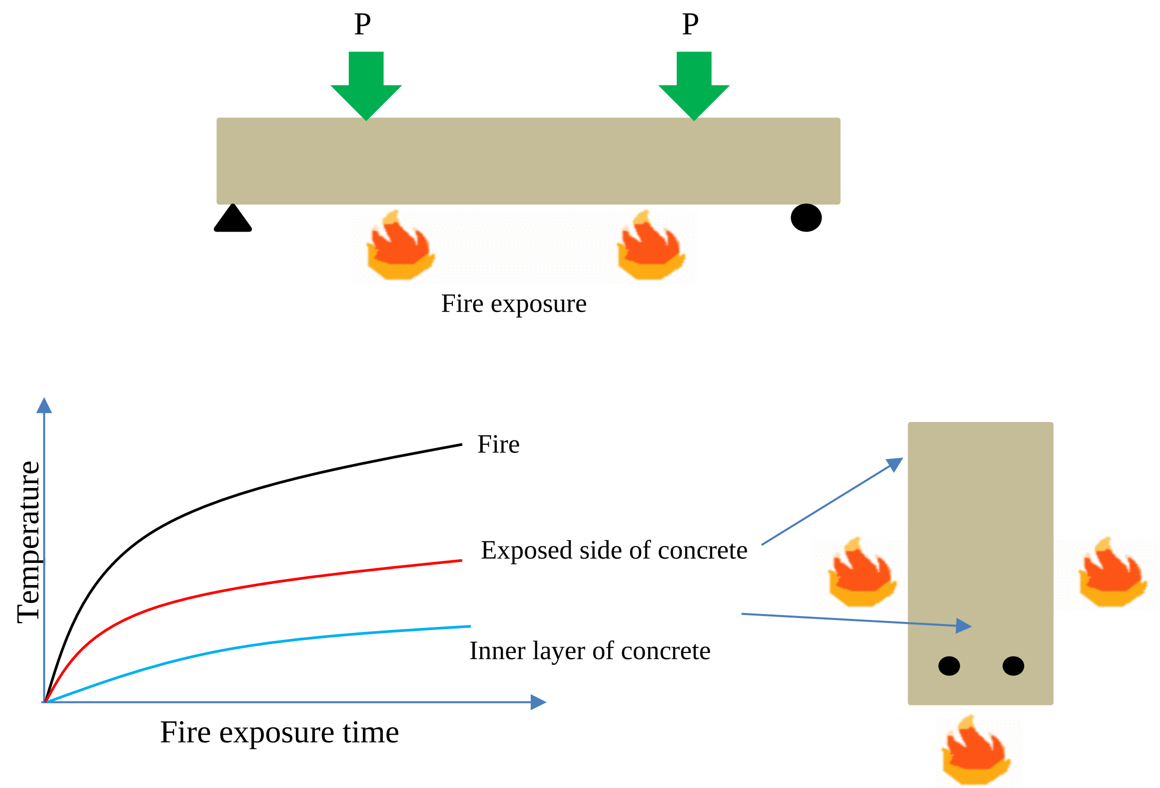
1.0 INTRODUCTION

Concrete is an inert construction material. Due to its superior properties, concrete is one of the few materials suitable for use in traumatic environments where, for instance, fire and the extreme temperature break out [1]. Despite the resilience of concrete, this material still undergoes a series of chemical and physio-mechanical changes once exposed to elevated temperatures. These effects often damage concrete's microstructure, hence adversely affecting its integrity and performance [2, 3]. As a result, predicting the thermal and structural response of concrete structures (or structural systems) becomes a challenging task.

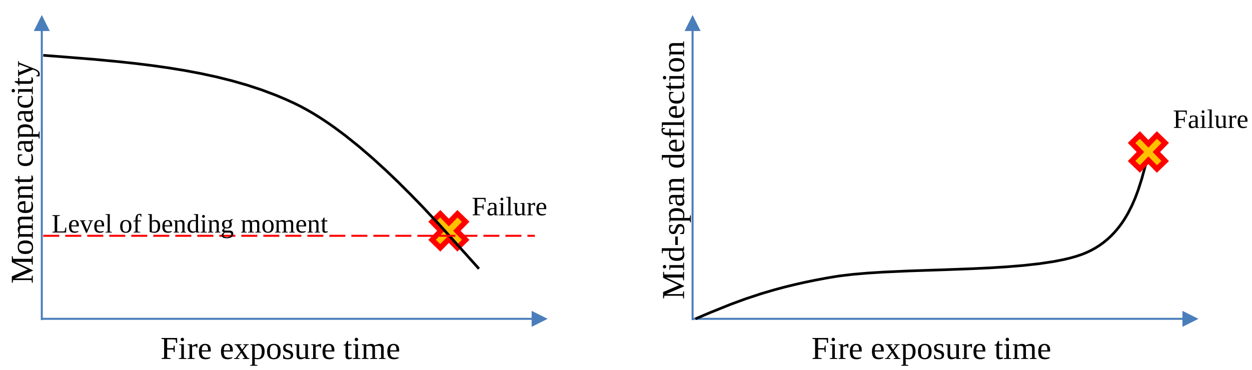
1.1 Background

When a reinforced concrete (RC) beam is exposed to fire conditions, the cross-sectional temperature rises slowly along the beam's span. This slow rise in temperature arises from the inert nature of concrete, specifically to its superior insulating properties, including 1) presence of moisture, 2) low thermal conductivity, and 3) high specific heat [4]. As a result, concrete requires a large amount of thermal energy before it can experience any temperature rise. Thus, once the temperature surrounding a RC beam starts to rise, i.e. due to a fire breaking out, the temperature of the outer surface (exposed side(s)) of concrete starts to slowly rise much before the core of concrete (which, depending on the intensity of fire, may remain relatively cool for a significant amount of time).

Consequently, a thermal gradient develops in which the temperature at the exposed surface of the concrete is much higher than that at the level of embedded reinforcement or concrete core (see Fig. 1). Once the rising temperature reaches the depth (level) at which reinforcement (rebars) is located, the temperature in these reinforcements starts to rise as well. As the area of reinforcement is very small as compared to that of concrete cross-section, the temperature in these reinforcing rebars is practically assumed to be similar to that of the surrounding concrete; despite the fact that steel is a better conductor, with much higher thermal conductivity and lower specific heat than concrete [5]. The same argument can also be drawn for the case of Fiber reinforced polymer (FRP) reinforcement [6].



a) Temperature Increase



b) Moment Degradation c) Deflection Increase

Fig. 1 Typical response of RC beams under fire conditions

The rise in temperature within the RC beam leads to deteriorating mechanical properties (i.e. strength and stiffness) of both concrete and reinforcement. This degradation, which varies according to a number of parameters, including material type and fire intensity, reduces mechanical properties to much lower magnitudes than that at ambient conditions. Such degradation translates to a reduction in flexural (i.e. moment and shear) capacity of the fire-exposed RC beams. While such temperature-induced degradation is slow, as it corresponds to the slow temperature rise in concrete, this degradation could be accelerated by a few fire-induced effects such as cracking and spalling of concrete. The development of cracks allows flames to directly attack reinforcement which speeds up reinforcement temperature rise and associated degradation of rebar mechanical properties such as elastic modulus, yield, and tensile strengths. Spalling is the breakup of concrete chunks from RC beams as a result of thermal gradients, moisture migration, and water vapor build-up to a limit exceeding the tensile strength of concrete. Spalling exposes internal reinforcement to flames and reduces cross-sectional dimensions leading to additional losses to sectional capacity. Spalling is mainly associated with high-strength concrete and concretes of dense nature. An elaborate discussion on spalling is not provided herein for brevity but can be found elsewhere [7, 8].

In any case, an increase in temperature—together with degradation in mechanical properties—causes RC beams to experience an increase in mid-span deflections (see Fig. 1). This deflection starts with a small rate and then significantly increases due to loss in sectional capacity. A RC beam is said to fail once its sectional capacity (i.e. flexural for beams) falls below the applied loading level (bending moment or shear force). At this point, the beam cannot continue to sustain the applied loading and thus fails. It is worth noting that a temperature-based failure limit state is often used in the case of RC beams. This criterion, based on prescriptive approaches, declares failure of RC beams once steel reinforcement temperature reaches 593°C. This temperature is associated with steel reinforcement losing 50% of its initial strength. It should be noted that this limit is only valid for steel reinforcement, as a well-accepted temperature limit of FRP rebars is still not well-established [9, 10].

The design and repair of RC beams affected by fire loading are analyzed in the open literature, where the standards and professional experience shaped the general design and repair strategies, which mainly depended on the affected part of the cross-section, state of reinforcement, and concrete's damage level, e.g., [11–15]. Multiple factors affect the fire resistance of RC members such as concrete type, section dimensions, reinforcement cover, state of reinforcement, etc. These factors may limit or increase the vulnerability of the member and consequently affect the structural integrity and load-bearing capacity of the structural system in a fire event. There is an innovative strategy that capitalizes on the thermal gradient across RC sections and improve their vulnerability. This paper presents insights into this simple and cost-effective solution, which utilizes sacrificial layer(s) of reinforcement embedded in the section's core to improve the fire resistance of RC beams. It further examines the parameters affecting the design of sacrificial reinforcement and their effect on the section's thermo-structural behavior.

1.2 Literature Review

Fire endurance (resistance) of beams has been of importance to engineers since the introduction of Harmathy's *Ten Rules of Fire Endurance Rating* in 1965 [16]. Later, fire tests using full scale furnaces and real-time exposure of RC beams to fire conditions became the norm. Still more recently, modelling RC structural elements and fire conditions have allowed researchers to explore complex scenarios and hypothetical designs. Based on a review of existing literature, several significant studies related to real-time testing as well as modeling of RC beams under fire have been identified and are detailed herein.

First, researchers from Coimbra University in Portugal have achieved impressive results on RC beams in fire. In study [17], the behavior of thermally restrained RC beams was explored through experimental testing. The authors tested several end restraints (axial, rotational, and combination thereof), the introduction of which always led to the increase in a critical time in terms of deformation criteria. As a result, the fire resistance of the beams also increased. Similarly, the following studies on thermally restrained RC beams from various researchers have also been published. Authors Albrifkani and Wang [18, 19] used numerical and finite element (FE) modelling to identify failure modes and conditions of unsafe design. Dwaikat and Kodur [20] also found a significant influence of end restraint on fire resistance of high-strength and normal-strength concrete. Finally, studies [21-23] used experimental results to show that moment redistribution is ideal for continuous beams' fire resistance while shear stresses are not a significant issue.

Apart from the issue of end restraint, RC beams in fire have also been studied with the goal of accounting for loss in performance (moment, shear, etc) resistance at elevated temperatures. Albuquerque et. al. [24] introduced a graphical method for fire design of RC beams using the Temperature Calculation and Design (TCD) software. The developed graphs present design solutions for more than 2300 T-beams that have proven to be more economical than traditional prescriptive (tabular) methods. Alternative approaches to the codal fire design methods (called performance-based design) of RC beams similar to that of the methods presented in the current study have become very popular. In 2007, Kodur and Dwaikat [25] presented a numerical model for tracing fire behavior over a time period from pre-fire to collapse. In 2011, the same authors published a design equation for predicting the fire resistance of RC beams [26]. In 2013, a method for determining the fire resistance of fiber reinforced polymer strengthened reinforced concrete beams was developed by Hong Kong Polytechnic University. Using advanced FE modelling, the study provided several design-oriented approaches for predicting the fire resistance of both unprotected and protected FRP-strengthened RC beams. For example, the design approach for insulated beams is presented in two parts: the first being solutions for temperature-related issues and the second being solutions to structural response analyses. Other performance-based design methods have used equivalent standard fires to relate the severity of natural fires to a standard fire. Examples of such studies include [27, 28].

Still other studies on RC beams under fire conditions have focused on reinforcement effects, also similar to that of the current research. Experiments [29, 30] studied the effects of temperature on bond degradation between concrete and rebar. Results indicated a significant influence of interfacial bond on RC beams under fire exposure. Additionally, the assumption of a perfect bond between concrete and steel was shown to be un-conservative in several scenarios. In 2019, the influence of reinforcement corrosion on fire performance was studied by researchers in China, showing a near-linear reduction in fire resistance with an increasing degree of corrosion [31]. Reinforcement of RC beams under fire has also been explored in regard to concrete cover. Sources [32, 33] indicated significant influence of bottom cover on the ultimate loading capacity of flexural members. However, they also showed a decrease in the extent of influence with increasing bottom cover thickness. Thus, it is not cost-effective or sufficiently beneficial to increase the fire resistance of RC beams by increasing its bottom cover thickness.

2.0 DEVELOPMENT OF FINITE ELEMENT MODEL

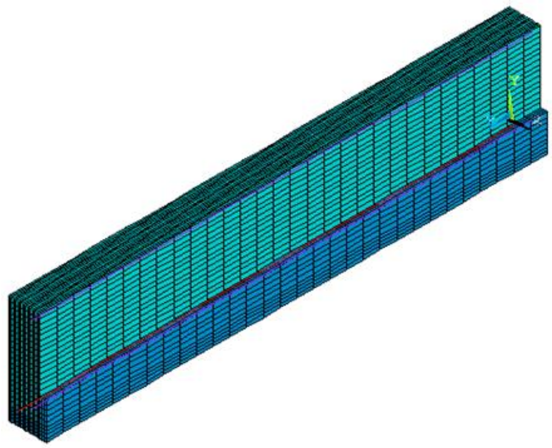
A three-dimensional FE model is developed using the FE simulation environment, ANSYS [34]. Since this model aims to examine the thermal and structural response of RC beams reinforced with steel and FRP reinforcement, this model is comprised of two components (thermal and structural), in which each is associated with the thermal and structural analysis, respectively. Hence, different thermal and structural element types are used in the development of the FE model.

2.1 Model Discretization

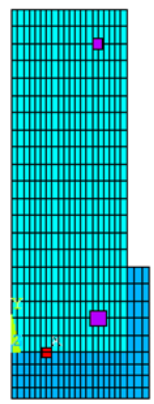
In the case of thermal analysis, both concrete and supports were modeled in the thermal simulation using SOLID70. SOLID70, which has a 3D thermal conduction capability, is made of eight nodes, each with a single degree of freedom defined as temperature. The steel (or FRP) reinforcement (whether main or skin) are modeled using the thermal link element, LINK33 [34]. This element is made of two nodes and single degree of freedom defined as temperature has uniaxial features and ability to conduct heat between its nodes. It is worth noting that both of these thermal elements are suitable for 3D steady-state or transient thermal analysis.

Similarly, a number of elements were also used in the structural (stress) simulation of the fire analysis. These elements cover, SOLID65, SOLID185, and LINK180. For a start, the concrete material was modeled using SOLID65. This element can simulate concrete behavior in tension (i.e. cracking) as well as in compression (e.g. crushing). SOLID65 element is defined by eight nodes, having three degrees of freedom at each node: translations in the nodal x, y, and z directions. In a similar manner, SOLID45 is also defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. This element is suitable of modeling rigid supports such as end boundary of beams as well as loading points and hence it is only used for these two applications. Following this simulation technique avoids development of high stress concentrations in concrete in the vicinity of loading and/or restraining supports and has been used in many other works such as those of Hawileh [35] and Omran and El-Hacha [36].

To model steel or FRP reinforcement, LINK180 is used. LINK180 is a spar uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, and large deflection capabilities. Further, the bond developing between reinforcement and surrounding concrete is also considered in this newly developed model. This bond was modeled using a set of spring elements (i.e. COMBIN14). These elements are of zero length and used to connect the nodes of the LINK180 elements to corresponding (concurrent) nodes of SOLID65 elements. COMBIN14 element requires spring stiffness values to be assigned to simulate the bond between steel (or FRP) rebars and adjacent concrete surfaces. The input stiffness is assigned in the longitudinal direction along the beam's axis to represent the shear stress stiffness, where the concurrent nodes (of LINK180 and SOLID65 elements) remain coupled in the transverse and lateral directions [34, 37]. Due to the symmetry associated with the fire-exposed RC beam, in terms of beam geometry, material composition, loading and boundary conditions, a quarter model can be used as a mean to reduce the required computational time and resources. To ensure proper application of symmetry, vertical restraints in the transverse and longitudinal planes of symmetry were applied as boundary conditions. Figure 2 showcases a detailed view of the developed FE model as well as boundary conditions.



a) Isometric view

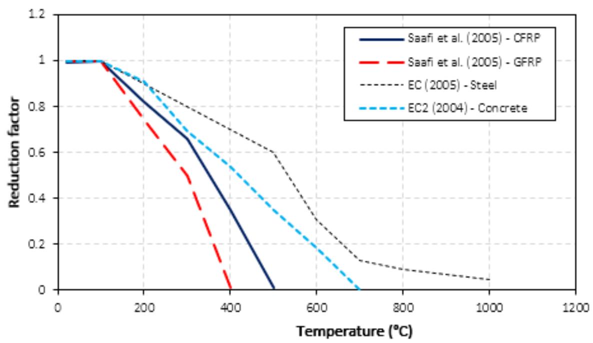


b) Cross-sectional view

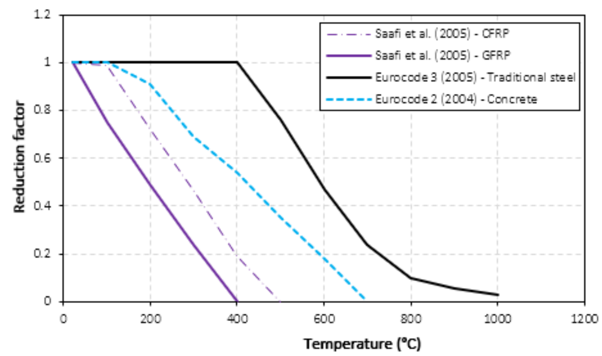
Fig. 2 Isometric and cross-sectional views of the developed FE model [dimensions are provided in the next section]

2.2 Material Constitutive Models

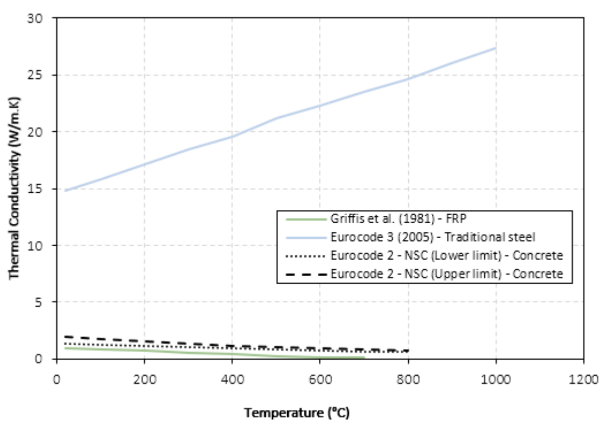
Construction materials deteriorate with rise in temperature. This degradation to the material properties is a function of material type, vulnerability to fire, the intensity of fire, as well as fire exposure time. Thus, temperature-dependent thermal and mechanical properties of constituent materials are required parameters for performing thermal and stress analysis to predict the fire response of RC beams accurately. Of interest to this work are the thermal and mechanical properties of constituent materials. The thermal properties comprise of density, thermal conductivity, specific heat, and thermal expansion. On the other hand, the mechanical properties of interest are the compressive and tensile strengths, Young’s modulus and Poisson’s ratio. Figure 3 shows the behavior of concrete, steel and FRP materials as a function of elevated temperature.



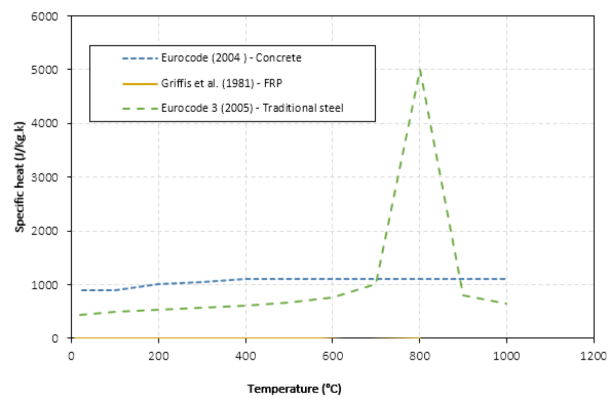
(a) Modulus property



(b) Strength property



(c) Thermal conductivity



(d) Specific heat

Fig. 3 Temperature-dependent material properties of concrete, steel, and FRP materials [38-40]

The degradation of material properties is often represented using material relations listed in fire designs and codes (i.e. Eurocode 2 [41]). It can also be found in published works disseminating small-scale material tests [1]. In this study, temperature-dependent material property relations for concrete, reinforcing steel, and carbon and glass FRP rebars were collected and then input to the developed FE model. Property relations for both concrete and steel rebars were obtained from Eurocode 2 [41]. It is interesting to note that Eurocode 2 relations account for the moisture content of concrete and the tendency of this moisture to evaporate upon reaching 100°C. This tendency to evaporation is modeled through a spike in the specific heat of concrete at around 100°C (see Fig. 3). This study assumes a moisture content of 2% by concrete weight.

Due to the lack of experimental tests carried out on thermal material data of FRP materials, thermal material properties of FRP at ambient conditions are used in the FE model. This decision has been well validated in earlier studies and is rationalized by the fact that FRP rebars are of much smaller area than that of the concrete cross-section and as such does not contribute much to the heat transfer within the RC beam [6, 42, 43]. Thus, the temperature in FRP, and to some extent steel rebars, can be safely assumed to be similar to that of surrounding concrete.

While the temperature-dependent mechanical properties of concrete and reinforcing steel were also obtained from Eurocode 2, the same properties were taken from the published work of Safii [38] and Abassi and Hogg [43] for CFRP and GFRP rebars, respectively. The variation of these properties as a function of elevated temperature is plotted in Fig. 3. This figure shows the complex behavior of aforementioned behavior and how the mechanical properties of these materials degrade at different rates and on various starting temperatures. It can be also seen that due to the inert nature of concrete, this material has favorable behavior under fire conditions compared to steel or FRP. Overall, the degradation in mechanical properties of concrete is minimal as compared to other materials. The readers should note that the Poisson's ratio for the concrete, reinforcing steel and FRP rebars was taken as 0.2, 0.3 and 0.27, respectively.

The concrete material was modeled using the nonlinear constitutive concrete material model of Williams and Warnke [44]. This model considers the nonlinearity of concrete in compression and tension by simulating the crushing and cracking of concrete to crack upon reaching their ultimate compressive and tensile strength, respectively. To model the concrete nonlinearities in compression, temperature-dependent multi-linear stress-strain curves were used. These curves were based on the material model adopted by Eurocode 2. While the tensile strength of concrete is often neglected at ambient conditions, this property can be significant in the case of exposure to fire. This is due to the fact that the degradation in tensile strength of concrete occurs slowly and as such limits the development of cracks, and in the case of normal strength concrete, can be sufficient to control and mitigate fire-induced spalling (see Fig 4). In ANSYS, and up to the first crack, concrete material is treated as an isotropic elastic material and becomes orthotropic after the initiation of cracks. Once a concrete element cracks, the modulus of elasticity is set to zero in the direction parallel to the principal tensile stress direction [34].

The concrete tensile rupture stress can crudely be taken at $0.1f'_c$, where f'_c is the compressive strength of concrete. In this study, the tensile strength of concrete is taken as $0.6\sqrt{f_c'}$. Once the concrete material reaches its tensile peak rupture stress, a tensile stiffness multiplier of 0.6 is used to simulate a sudden drop of the tensile stress to 40% of the rupture stress, followed by a linearly descending curve to zero stress at a strain value of six times the strain corresponding to the concrete rupture stress. Williams and Warnke [44] models also include two parameters, i.e. open and close crack shear transfer coefficients. Typical shear transfer coefficients are taken as zero when there is a total loss of shear transfer representing a smooth crack and 1.0 when there is no loss of shear transfer representing a rough crack. The values of open and close crack shear transfer coefficients in the developed model are assumed to be 0.2 and 0.5, respectively [34].

The bond-slip relationship between the steel (or FRP) reinforcement and concrete can be described by Eq. 1. This equation is adopted from the first segment of CEB-FIP model [45].

$$\tau = \tau_u \left(\frac{s}{s_u}\right)^{0.4} \qquad \text{Eq. 1}$$

where, τ is the bond stress at a given value of slip (s) in (MPa), τ_u the maximum bond stress in (MPa), s_u is the maximum slip in (mm). Both the values for τ_u and s_u depend on rebar type and material. Typical values for these parameters are listed in Table 1.

Table 1 Bond-slip parameters [45].

Case	$\boldsymbol{\tau_u}$**(MPa)**	$\boldsymbol{s_u}$ **(mm)**
Steel rebar	$\sqrt{f_c'}$	0.6
CFRP rebar	12.16*	0.98
GFRP rebar	8.95**	1.52

*Machined CFRP rebar, for a bonded length of *5d*

**For fine sand coated surface with helical fiber wrapping, for a bonded length ≈100 mm.

As shown in Table 1, the bond-slip parameters are a function of concrete material strength and changes according to the change in concrete strength (i.e. temperature-dependent). Once the bond-slip relations are calculated for each temperature, the secant of the bond-slip curve is obtained and input as the longitudinal stiffness (k) of the spring element (COMBIN14) as derived by Nie et al. [37] and shown in Eq. 2.

$$k = \frac{\pi}{s_u}\, p\, d\, N\, \tau_u \left(\frac{L_1 + L_2}{2}\right) \qquad \text{Eq. 2}$$

where p is the horizontal distance between reinforcing rebars in (mm), d the diameter of rebars in (mm), N the number of rebars and L_1 and $L_2$is the lengths of two adjacent reinforcement elements (LINK180) in (mm).

2.3 Loading and Failure Criteria

The developed FE model is developed to simulate the two stages associated with fire testing i.e. a transient coupled thermal-stress analysis. The first stage consists of performing thermal analysis, in which the RC beam is exposed to fire (thermal loading). This thermal loading is applied as time-steps presenting temperature-time curve that follows a standard fire such as ISO834 [46](see Eq. 3). The temperature, arising from radiation and convention effects simulating an actual fire furnace/testing facility, is applied to the RC beam at three faces (i.e. sides and soffit). In this procedure, the top face of the RC beam is exposed to ambient conditions. The radiation and convection coefficients are assumed to be 5.67×10^{-8} W/m^2 K^4 as well as 25 W/m^2 K and 4 W/m^2 K for exposed and unexposed faces, respectively. It should be noted that the emissivity of concrete was taken to be 0.7 as recommended by Eurocode 2. Failure in the thermal analysis, which uses Newton-Raphson technique, occurs once a time-step pertaining to 5°C does not converge.

$$T = 345 \log (8t + 1) +20 \qquad \text{Eq. 3}$$

where T is the furnace temperature (°C) and t is the time in minutes for ISO834.

The second stage of fire analysis consists of performing structural stress analysis to predict the performance of the RC beam under the combined effects of temperature (obtained in the first stage of analysis) as well as gravity (sustained static) loading. The thermal loads are applied to the structural model as body loads at specified load steps from the results obtained in the thermal analysis. The RC beam was modeled with simple supports (i.e., simply supported conditions). Gravity loads were applied as point loads (or uniformly distributed loading) depending on the procedure followed in the actual fire tests. The following section examines a specific discussion on the magnitude of applied loading for each case (RC beam). In the structural analysis, automatic time stepping is turned on to allow optimum control of load step size. A tolerance value of 5% was used in the nonlinear structural analysis in this study [34, 47].

3.0 VALIDATION OF THE DEVELOPED FE MODEL

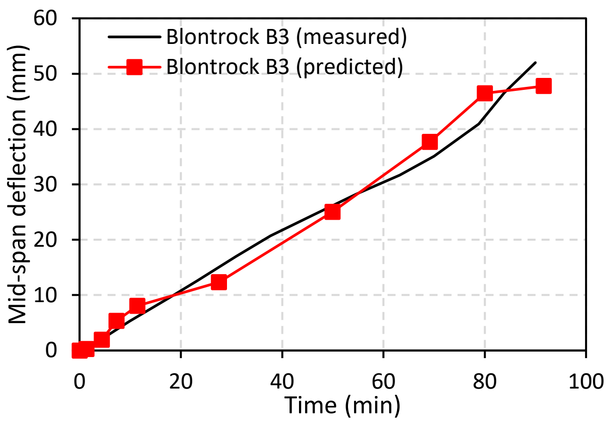
Due to lack of fire tests on concrete beams reinforced with sacrificial reinforcement, the above developed model was validated against three experimental programs in which RC beams reinforced with steel or FRP rebars were tested under standard fire conditions. These tests were carried out by Blontrock et al. [48], Palmieri et al. [49], as well as Abbasi and Hogg [43]. These tests (RC beams) were first utilized to validate the developed FE model and then used as a benchmark for carrying out a parametric study. A brief description of the tested RC beams in each of these cases is provided herein.

Blontrock et al. [48] tested several steel RC beams to investigate the fire performance of FRP-externally strengthened RC structures. In these tests, one beam, *Beam 3*, was selected for the analysis in this study as this beam was not strengthened with FRP but was rather tested under ISO 834 fire exposure as benchmark to examine the fire resistance of conventional RC beams. This beam has a height of 300 mm, width of 200 mm and a span of 3.15 m. This beam is made of siliceous-based aggregate concrete of a compressive strength of 59.47 MPa. The steel tensile reinforcement installed in this beam consists of two bars of 16 mm diameter. The concrete cover to steel reinforcement was 25 mm. The beam was subjected to a loading equivalent to 46% of its ultimate flexural capacity and failed after 95 minutes of exposure to fire.

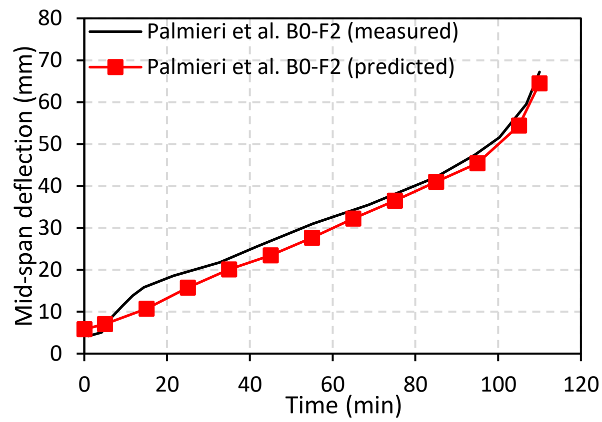
The second developed beam for analysis was that tested specimen by Palmieri et al. [49]. Similar to Blontrock et al. [48], Palmieri et al. [49] carried out an experimental investigation to examine the performance of RC beams strengthened with near-surface mounted (NSM) FRP when exposed to the ISO834 fire exposure. One of these beams, *B0-F2*, was unstrengthened and picked to serve as a benchmark specimen. This beam has a height and width of 300 and 200 mm, respectively. The beams had a clear span of 3.15 m and were reinforced with two steel rebars of a diameter of 16 mm. The compressive strength of concrete used in this beam measured at 42 MPa. During the fire test, the beam was loaded in four-point bending with a sustained load equivalent to 54% of its ultimate load capacity. This beam achieved a fire resistance of 110 minutes. It is worth noting that the beams tested by Blontrock et al. [48] and Palmieri et al. [49] were tested at the floor furnace at the WFRGent laboratory in Canada.

Abbasi and Hogg [43] conducted full scale fire tests on RC beams reinforced with GFRP rebars as their main flexural reinforcement. One of these beams, *Beam 1*, had a rectangular cross-section with height and width of 400 mm and 350 mm, respectively. The clear concrete cover to the flexural reinforcement was 75 mm. The effective span length of this beam is 4.25 m. The beam is reinforced with seven 12.7 mm diameter at the tension zone. This beam was loaded with 40 kN applied as a uniformly distributed loading at the beam’s top side. This beam achieve d a two-hour fire rating and failed at 128 min.

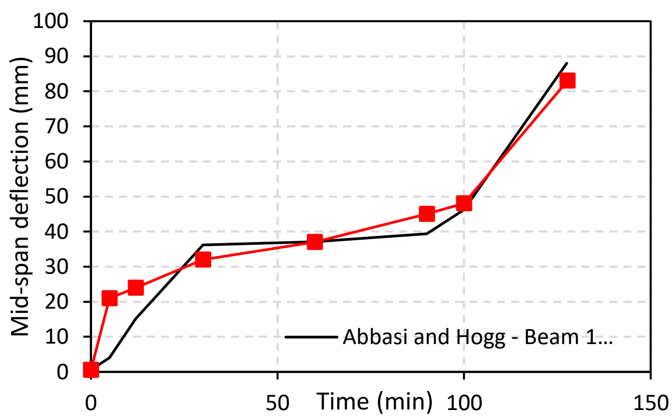
The developed FE model was first validated against the above three RC beams tested under fire conditions. The validation procedure involves comparing temperature rise in cross-section, failure mode and predicted mid-span deflection history with that measured in the fire tests. Figure 4 illustrates the validity of the developed FE model across all stages from initial loading to failure. Overall, the developed FE model seems to accurately capture both thermal and structural fire response of analyzed RC beams, with a maximum variation reaching 10% (for all three beams). It can be inferred that the developed FE model is valid and capable of tracing the response of the RC beams and could be used as a tool to predict the influence of critical response parameters to examine the feasibility of utilizing sacrificial reinforcement to improve fire response of RC beams.



(a) Beam tested by Blontrock et al. [48]



(b) Beam tested by Palmieri et al. [49]

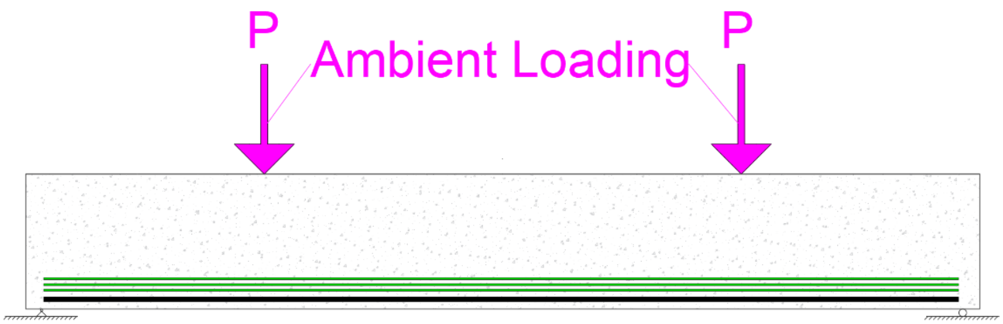


(c) Beam tested by Abbasi and Hogg [43]

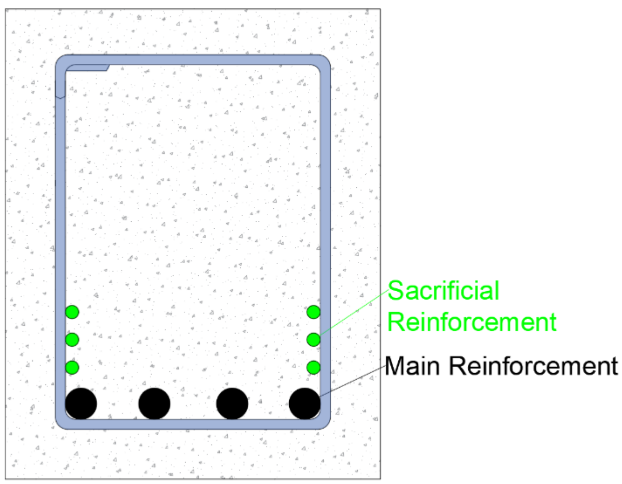
Fig. 4 Comparison between predicted and measured structural response of analyzed RC beams.

4.0 SACRIFICIAL REINFORCEMENT

Sacrificial reinforcement is the addition of small rebars parallel to the main (longitudinal) bars in a beam, as shown in Figure 5. By adding such elements (in a variety of amounts or sizes), the beam's actual load carrying capacity is increased minorly, thus also increasing its moment capacity at ambient temperature. When designing the beam to carry ambient loads, this capacity due to sacrificial reinforcement is ignored, and thus, it is only designed including the moment capacity of main bars.



a) Elevation View



b) Cross-Sectional View

Fig. 5 Elevation and Cross-Sectional View of Beam with Sacrificial Reinforcement

It seems compelling to benefit from thermal gradient between fire exposed and unexposed layers of concrete and use it to enhance the performance of RC sections under fire loading. As fire progresses, deterioration in the mechanical properties of concrete and steel occurs, concrete cracks and/or spalls, and active tension zone in the section shifts away from the exposed surface. Thus, adding additional reinforcement layers further from the beam's exposed surface will contribute to the section's fire resistance. The authors designated this added reinforcement layer(s) "Sacrificial

Reinforcement," as they are not required by the design criteria and only fully activated in extreme cases of fire exposure. The position of the reinforcing bars (their depth in the tension zone), amount of reinforcement, and type of reinforcing bars need to be examined to effectively design the sacrificial reinforcement to fulfil its aim and enhance the fire performance of RC beam elements.

5.0 PARAMETRIC STUDY

In the second part of this investigation, the developed FE model is used to examine the behavior of RC beams that were neither tested nor obtained from fire tests. This model is applied to predict the positive contribution of sacrificial reinforcement to improve fire response of RC beams. Thus, a total of nine models are built and analyzed herein to numerically investigate the effect of reinforcement scheme, size, and material type on the fire response of steel and FRP reinforced concrete beams. Whenever possible, a comparison between mid-span deflection history, failure mode and concrete crack development is presented for each case. Further details of the parametric models are presented in the subsequent subsections.

5.1 Effect of reinforcement scheme

In this section, sacrificial reinforcement was added at different heights across the depth of the beam (100 mm and 150 mm measured from the beam's soffit), number of rebars, and configuration (straight vs. angular/bent shapes). Figure 6 shows that the addition of sacrificial reinforcement was positive in all cases as this addition has reduced the amount of deformation the original beam underwent. In addition, adding sacrificial reinforcement at half the beam's depth (i.e. 150 mm from the soffit) contributed the least. This can be explained by the fact that lower tensile stresses reside at this height and hence the sacrificial reinforcement do not contribute much to lower deflection before they start losing much of their strength due to thermal effects. On the contrary, adding two layers of sacrificial reinforcement (each at 50 mm height from soffit) was proven to be the best solution to minimize deformation effects in this fire-exposed RC beam. This scheme prolonged the time to reach the failure criteria following the beam defection criteria (L/300d) by 33%, consequently affecting the damage pattern and the repair strategy.

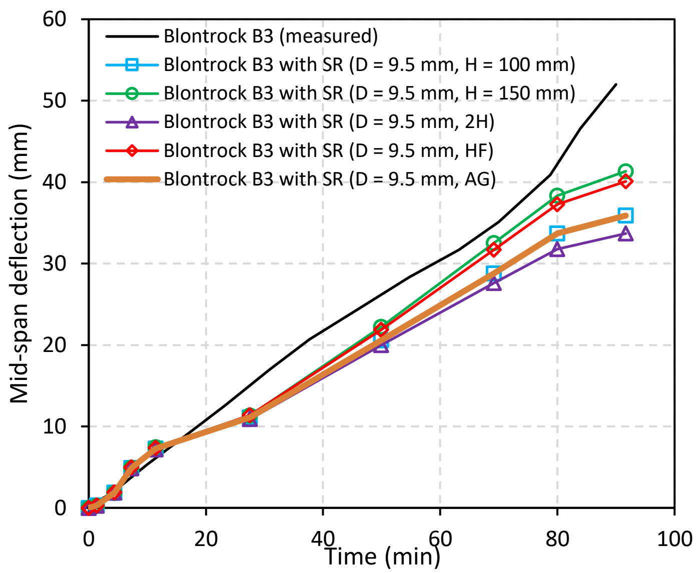


Fig. 6 Effect of additional sacrificial reinforcement [Note: HF = half height, and AG: angular/bent reinforcement]

5.2 Effect of reinforcement size

In this section, the diameter size of the sacrificial reinforcement was varied by 9.5 mm and 12.7, while keeping their position at a depth of 100 mm measured from the soffit of Beam 3 that was tested by Bloctrock et al. [48]. As plotted in Figure 7, this figure shows the addition of sacrificial reinforcement improved the deformation behavior of the fire-exposed beam. The use of one rebar (at each side) of 9.5 mm or 12.7 mm diameter reduced the overall deformation throughout all stages under fire by almost 30%. This reduction in deformation translates into an increase in failure time (by almost 50%) and possibly fire resistance of RC beams. These results indicate that the amount of reinforcement have a slightly higher impact on enhancing the behavior of the RC beams.

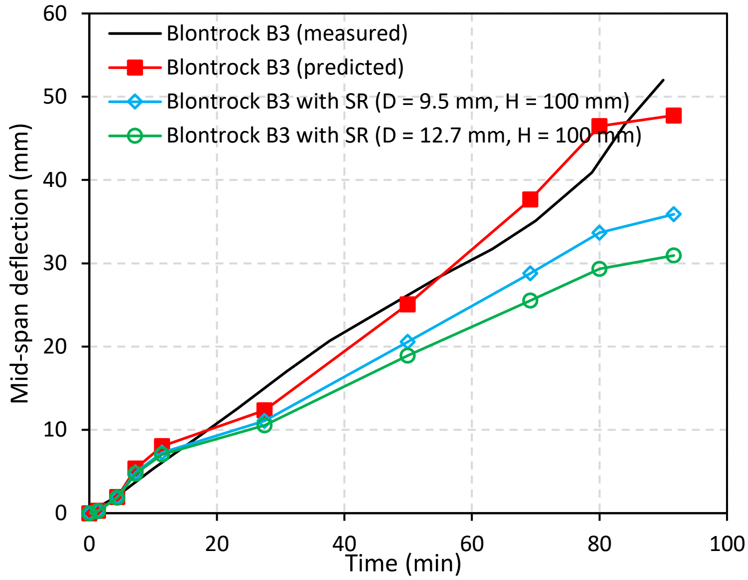


Fig. 7 Effect of diameter size of sacrificial reinforcement

5.3 Effect of reinforcement material type

The same two diameter sizes used in Sec. 5.2 are kept herein but varying the material making the sacrificial reinforcement from steel to CFRP and GFRP. This decision has been made to explore the influence of material type on the overall behavior of the fire-exposed beams. As expected, all beams with sacrificial reinforcement achieved improved performance – regardless of the type of the sacrificial reinforcement. However, a closer look in Figure 8 shows that the beam made of steel sacrificial reinforcement achieved an improved performance as opposed to that of the FRP sacrificial reinforcement. Interestingly, larger diameter FRP rebars underwent distinct behavior, while those made of the smaller diameter (9.5 mm) almost behaved similarly. This reflects upon the fact that the influence of GFRP and CFRP properties in smaller diameter rebars does not have a significant impact upon the deflection response since heating effects seem to be governing. Furthermore, CFRP bars have a slightly more substantial effect on enhancing the performance of RC section.

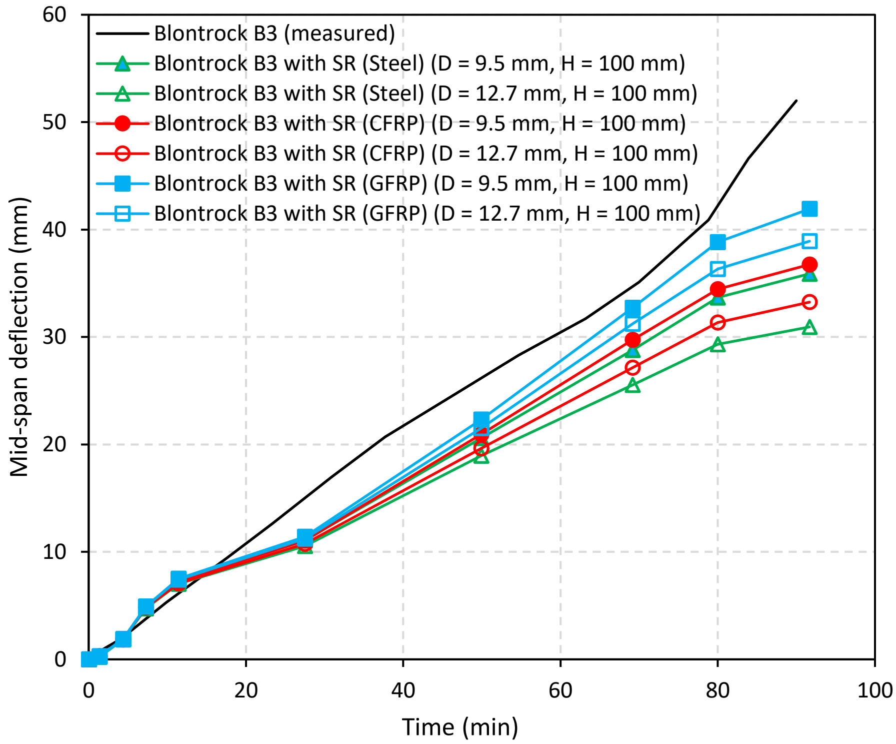


Fig. 8 Effect of material type of sacrificial reinforcement

6.0 CONCLUSIONS

This study explores the notion of adding small layers of sacrificial reinforcement to the sides of RC beams exposed to fire conditions. Despite the small amount of sacrificial reinforcement, the addition of such layers was shown to be effective in limiting stress development and deformation of RC beams. It is envisioned that such layers could be more common in practice once observations from large-scale fire tests are obtained. The following can also be concluded from the findings of this study:

- RC beams have favorable performance under fire conditions when compared to similar beams of other construction materials. However, the good behavior of such beams can be further improved once sacrificial reinforcement is added.

- The use of sacrificial reinforcement can be beneficial for mitigation purposes (i.e. during design) or as a repair solution for postfire events (especially when concrete cover is removed due to spalling).
- The reinforcement scheme, amount, and type are the design parameters for the design of sacrificial reinforcement that proved to have a significant role in affecting the performance of RC beams and improving its vulnerability to thermal loading.
- Despite the low thermal properties of FRP reinforcement, steel reinforcement was shown to achieve superior performance as sacrificial reinforcement.

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