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Numerical Analysis of Combined Effect Hybrid Fibres and Fire Insulation on the Fire Resistance Performance of SCC Beams

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Abstract

The use of self-compacting concrete in structural members has become increasingly prevalent in various construction applications. However, these structures are susceptible to one of the most hazardous disasters, which is the fire. This paper presents a numerical investigation of the fire resistance performance of self-compacting reinforced concrete (SCC) beams, as well as a parametric study to assess the impact of hybrid fibres and fire insulation on enhancing their performance under fire conditions. The study is conducted by developing a 3D finite element (FE) model using ANSYS software, where temperatures are applied according to the ISO834 standard fire. Geometric and material nonlinearities are considered in the evaluation of the behaviour of beams under fire conditions. The developed FE model is validated by comparing the predicted results with those of the experimental tests in literature. The fire resistance performance of SCC beams was compared with that of normal strength concrete (NSC) beams. The parametric study is conducted using three types of fire insulation, namely Tyfo WR-AFP, CAFCO 300, and Carboline Type-5MD. The results showed that SCC beam has lower fire resistance performance than the NSC beam. However, the incorporation of hybrid fibres allows a 17% improvement in the fire resistance of SCC beams. The use of fire insulations has increased the fire resistance time of SCC beams, and more particularly Carboline Type-5MD insulation with an increase of 28%. The combined use of hybrid fibres and fire insulation improved the fire resistance of SCC beams by 43%.

Keywords

SCC beams, fire resistance performance, hybrid fibres, fire insulation, finite element model

1 Introduction

Self-compacting concrete (SCC) is a significant advancement in concrete technology. Since it was introduced in 1988, SCC has been widely used for the construction of high-rise and industrial buildings [1]. Indeed, it is a suitable solution since it flows under its own weight and fills the moulds without any vibration or compaction even in the presence of congested reinforcements [2, 3]. However, obtaining ideal workability may result in significant brittleness and ease of production of shrinkage cracks [4]. The literature review shows that adding fibres in SCC can effectively improve the mechanical properties, and more particularly the tensile strength [5]. It is an appropriate solution to the problem of brittleness and crack propagation, where researchers confirmed the positive synergistic effect between fibre reinforcement technology and self-compacting technology [6]. These additives can improve SCC's resistance to environmental hazards when used in structural members of buildings [7]. However, fire remains one of the harshest environmental conditions to which these buildings may be exposed.

Fire causes a significant deterioration of the mechanical properties of concrete and reinforcing bars, resulting in a significant decrease in the stiffness and bearing capacity reinforced concrete (RC) members of buildings. It may cause a substantial loss of serviceability that may lead to structural collapse, constituting a threat to lives and property [8]. Several studies have been conducted, by researchers, on the behaviour of structural steel members [9–11] or RC members [12, 13] under fire conditions. Dwaikat and Kodur [14] experimentally investigated the behaviour of RC beam under fire conditions, showing that high strength concrete beams have a lower resistance and greater degrees of spalling than

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normal strength concrete (NSC). The fire resistance is significantly influenced by concrete permeability, type of fire exposure, load level and restraint conditions [14].

Yermak et al. [15] have shown that the addition of polypropylene and/or steel fibres reduces the fire damage to structural concrete members. Hou et al. [16] tested the fire resistance of four hybrid fibre reinforced reactive powder concrete beams protected by fire insulation. They concluded that the use of hybrid fibres (2% steel fibres and 0.2% PP fibres) and fire insulation at the same time is an effective method of preventing fire failure. They also show that the fire insulation can greatly improve the fire resistance performance of RC beams. Banerji et al. [17] showed, from their experimental study that ultra-high performance RC beams with polypropylene fibres exhibit better performance under fire scenarios with distinct cooling phase. The addition of 0.2% polypropylene fibers to ultra-high performance RC beams significantly enhances their fire resistance. The study that was conducted by Jin et al. [18] concluded that the addition of steel fibres to RC beams with volume fraction of 0.1% and 2% has a negligible influence on the temperature distribution. They also showed that steel fibres could reduce the spalling of concrete when heated to 400 °C.

Given the high cost of experimental studies and their time-consuming, and the study of many influencing factors, some researchers leaned towards numerical studies whose results are comparable with those of experiments. Even for the structural design of RC structures, the use of non-linear finite element (FE) model is starting to be employed in the scientific community and industry standards [19]. Kodur et al. [20] have shown that FE analysis of the residual capacity of reinforced concrete beams exposed to fire gives more realistic predictions than those predicted from simplified sectional analysis. Hou et al. [21] developed a 3D model and found that NSC beams have better fire resistance than reactive powder concrete beams. Alyaa et al. [22] investigated the structural behaviour of hybrid fibre-reinforced reactive powder concrete beams under service load and fire exposure, composed of hybrid fibres and have concluded that adding hybrid fibres would considerably improve the residual stiffness of fire-damaged beams. Ilango et al. [23] carried out a numerical simulation of the behaviour of concrete beams reinforced with carbon fibre reinforced polymer bars containing polypropylene fibres at high temperatures. They have found that the addition of polypropylene fibres to the concrete increases the fire resistance by 10 minutes. Al-Thairy et al. [24] studied the response of lightweight RC beams under elevated temperatures. They showed that after exposing the RC beam to a temperature of 800 °C, the reduction in the ultimate load capacities of lightweight RC beam is less than that of the normal weight RC beam. Ren et al. [25] developed a FE model to predict the fire resistance of hybrid fibre reinforced reactive powder concrete beams by proposing an equation of the design parameters commonly used for fire safety design.

Some researchers also recommended the use of fire insulation in structural elements to provide better protection for concrete and steel reinforcement [26, 27]. Some studies have shown that spray applied fire resistive material (SFRM) are among the best insulators owing to their advantages such as cost-effectiveness, ease of application and lightness [28]. Ren et al. [29] studied the behaviour of insulated RC beams and concluded that thermal conductivity, thickness, and setting mode of fire insulation are among the properties that strongly affect their fire resistance, while density and specific heat have little effect on their fire resistance.

The behaviour of SCC at elevated temperatures has only been addressed in a few studies, where the samples were limited to test specimens with small sizes. Fares et al. [30] carried out an experimental study to compare the performance of SCC with NSC when exposed to high temperatures, and they observed that severe spalling occurs in SCC specimens, while no spalling was observed in NSC specimens. Tao et al. [31] conducted an experimental study to evaluate the effect of high temperatures on the compressive strength of both SCC and high-strength concrete. They concluded that the compressive strength grade has a significant effect on the reduction factor of mechanical properties. Bamonte et al. [32] investigated the behaviour of NSC and SCC under high temperatures. They showed that normal strength SCC tends to behave similarly to NSC, whereas high-strength SCC is more sensitive to high temperatures than NSC. The study of the behaviour of small beams in SCC and NSC, carried out by Anand et al. [33], showed that when the grade of concrete increases, the percentage reduction in ultimate load also increases, and that beams modelled with SCC and forced cooling exhibit poorer performance than other beams.

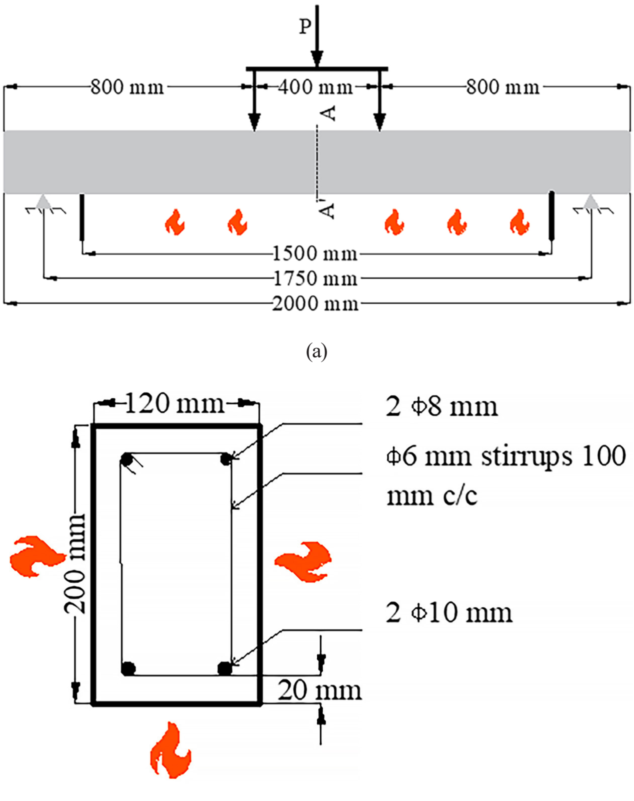
However, in order to use self-compacting concrete (SCC) in structural members and to reach a specific level of fire resistance, it is necessary to define requirements related to geometry, loading, and boundary conditions.

1.1 Objectives

Therefore, recognizing the need for further research, this paper presents a comprehensive numerical study to investigate the fire resistance performance of SCC beams. Additionally, a parametric study is conducted to assess the effect of incorporating hybrid fibres and using fire insulation in enhancing the performance of these beams under fire conditions. The study is conducted by developing a 3D FE model using ANSYS software [34] where temperatures are applied according to the ISO834 standard fire. A sequentially coupled thermo-mechanical geometrically non-linear analysis is undertaken, in which all material properties vary with temperature and stresses or strains. In this case, the thermal model is first run, and later the temperature fields are imposed in the Gauss points of the structural model, as an imposed static strain, that varies in time. The numerical model will be validated initially with a previous experimental campaign [35], in which a NSC is subjected to ISO834 fire curve.

1.2 Research significance

According to the authors best knowledge, the structural criteria and guidelines for SCC during fire design analysis are not known in the scientific community, and most studies are related to experimental campaigns for limited geometries, loads, and types of fire protection. The use of extensive numerical thermo-mechanical models to parametrically study the efficiency of SCC during a fire event is, at the moment, almost null.



(a)

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Fig. 1 Dimensions, reinforcement, loading, and boundary conditions details of the studied beams, a) Elevation, b) Section A-A'

2 Case of study

The case study involves seven beams with the same dimensions and boundary conditions, each with a cross-section of (120 × 200) mm^2 and a total length of 2000 mm. These beams are reinforced with two 10 mm diameter bars for tensile reinforcement, two 8 mm diameter bars for compressive reinforcement, and shear reinforcement in 6 mm diameter stirrups spaced 100 mm apart, Fig. 1. The first beam is made of NSC, while the other six are made of SCC. One of the SCC beams without fire insulation and hybrid fibres is used as a reference, while the remaining five beams are treated with different fire insulations, such as Tyfo WR-AFP, CAFCO 300, and Carboline Type-5MD, including one containing hybrid fibres and Carboline Type-5MD fire insulation. The designations and characteristics of all the studied beams are detailed in Table 1. The beams are subjected to combined thermal and mechanical loads. The thermal load is applied to three longitudinal sides according to the ISO834 standard fire model, as well as a constant mechanical load set at 35% of the load bearing capacity. The use of fire insulation is only at the bottom of the studied beams, with a 3 mm thickness, as shown in Fig. 2.

Table 1 Designations and details of studied beams

Beam	Concrete type	Fire insulation	Elastic modulus (GPa)	Compressive strength (MPa)	Tensile strength (MPa)	Thermal conductivity (W/mK)	Specific heat (J/kg K)	Density (kg/m^3)
B_1	NSC	without	30.22	46.52	2.39	1.33	900	2350
B_2	SCC	without	40.88	60	5.5	3.03	1029.78	3000
B_3	HFRSCC	without	41.24	80.31	6.29	3.03	1029.78	3000
B_4	SCC	Tyfo WR-AFP	40.88	60	5.5	3.03	1029.78	3000
B_5	SCC	CAFCO 300	40.88	60	5.5	3.03	1029.78	3000
B_6	SCC	Carboline Type-5MD	40.88	60	5.5	3.03	1029.78	3000
B_7	HFRSCC	Carboline Type-5MD	41.24	80.31	6.29	3.03	1029.78	3000

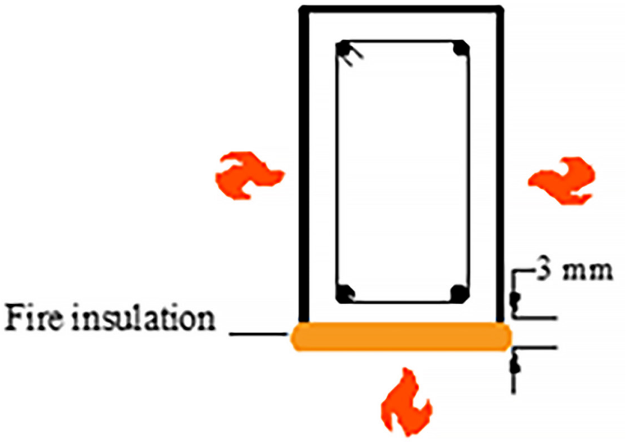

Fig. 2 Fire Insulation placement in SCC Beams

3 Numerical simulation and material models

The case study explained in the previous section was simulated by ANSYS software [34]. The sequential thermal-mechanical coupling technique is utilized which begins with thermal analysis by subjecting the beams to a time-varying thermal load according to the standard ISO 834 fire and the thermal contours are recorded at each time step. These thermal contours are then utilized after switching from thermal to structural analysis as both a variable load beside applying constant mechanical load. In the development of 3D FE model taking into account the following assumptions:

- The mechanical properties of concrete and steel reinforcement at different temperatures are considered isotropic and homogeneous.
- Spalling is neglected in this study because the compressive strength of SCC and NSC is less than 70 MPa and SCCH contains polypropylene fibres [36].
- A full bond is assumed between the concrete and the steel reinforcement and the total stress in the reinforcement is similar to that in the concrete [36].

3.1 Finite element models

Five FE are used to evaluate the thermal and structural analysis of the studied beams. For the thermal analysis, LINK33 is to simulate the reinforcement bars and SOLID70, for the concrete and fire insulation. LINK33 is a uniaxial element that consists of two nodes with one degree of freedom and temperature assigned to each node [34]. SOLID70, having 3-D thermal conduction capabilities, is composed of eight nodes, each with a single degree of freedom for temperature [34]. For the structural analysis, LINK180, SOLID65 and SOLID185 have been chosen to simulate reinforcement bars, concrete and rigid plates, respectively. The rigid plates were used at both ends to prevent localized concentrations of tensile stresses in concrete resulting from the localized effects of concentrated loading. LINK180 is a 3D bar having a uniaxial tension-compression with two nodes and three degrees of freedom at each node [34]. SOLID65 is capable of simulating both cracking in tension and crushing in compression, defined by its eight nodes and three degrees of freedom at each node [34]. This element incorporates open and close crack shear transfer coefficients, with the values for this simulation set at 0.4 and 0.8, respectively [39]. Additionally, the simulation considers a tensile crack factor (TCF) of 0.6 [40], which is a crucial parameter directly influences the fracture energy of concrete. SOLID185 are defined by eight nodes and three degrees of freedom at each node [34], and eight Gauss points for full integration.

3.2 Material properties models

In this section, the material properties of all materials used in the numerical models are presented, including the non-linear parameters that may lead to cracking and yielding of the concrete and steel respectively. For the concrete, the multilinear isotropic hardening plasticity (MISO) present in the ANSYS material library was used. For the steel, multilinear isotropic based on Von Mises formulation was applied. The MISO model in ANSYS Mechanical APDL is a rate-independent plasticity model characterized by a Von Mises yield criterion, an associative flow rule, and isotropic hardening. It is evident from the existing literature that numerous studies have investigated the efficacy of employing the MISO model in materials modeling [41, 42]. Notably, the selection of the MISO model for this study was informed by previous research demonstrating its validity in simulating RC beams [39, 43].

3.2.1 Concrete

The main concrete properties used for the mechanical analysis are presented in Table 1, but these are for ambient temperature. For this numerical analysis all thermal and mechanical properties of NSC will be affected by temperatures according to the variation proposed in Eurocode 2 Part 1–2 [37]. For the concrete ANSYS uses standard tensile fracture energy values, by indirectly referencing the variable a tensile crack factor (TCF) of 0.6 [40]. With Regard to SCC, the relationships proposed by Khaliq and Kodur [38] concerning the variation of thermal conductivity, specific heat and thermal elongation as a function of temperature, whose curves are shown in Fig. 3, were adopted in our simulations. Its density was taken according to Eurocode 2 part 1–2 [37].

The variation of mechanical properties with temperature of the NSC was adopted according to Eurocode 2 Part 1–2 [37], and the stress-strain curves are depicted in Fig. 4(a).

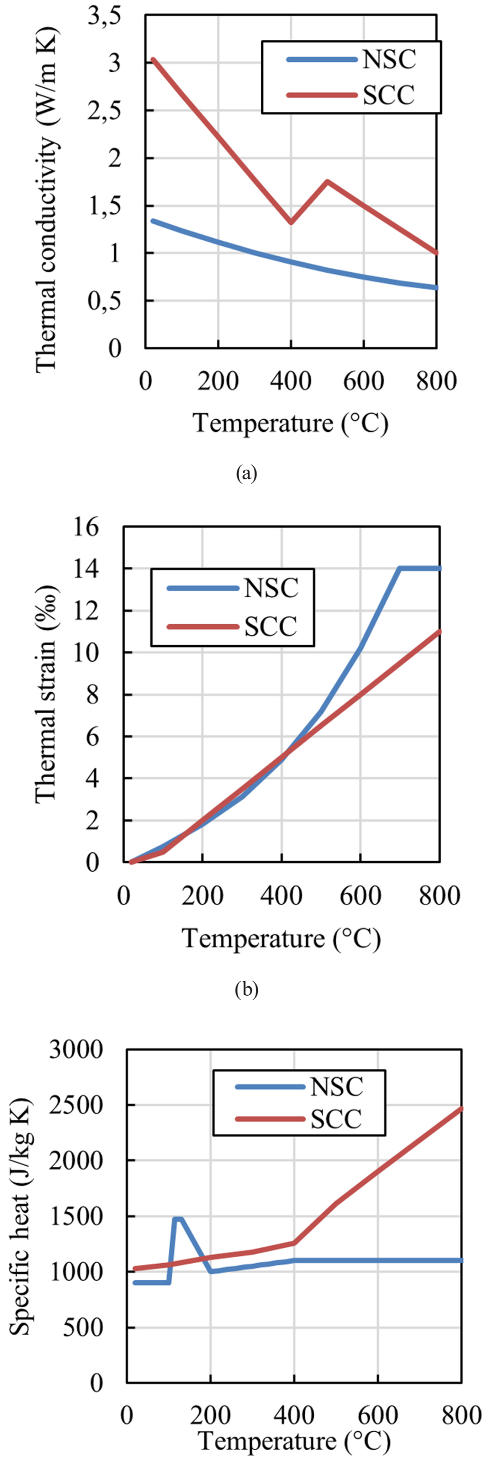

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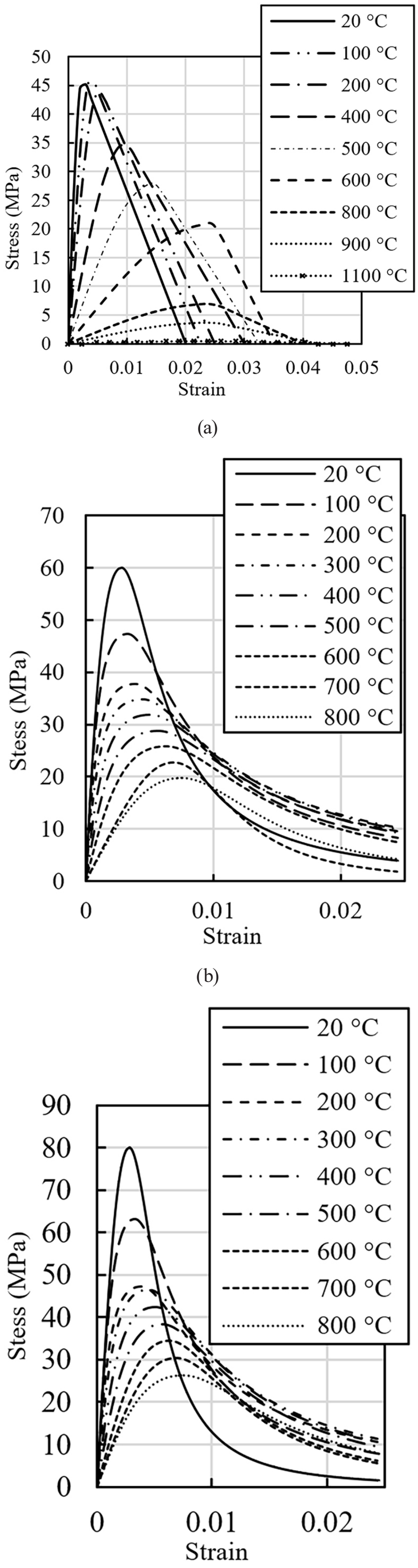
Fig. 3 Variation of thermal properties of concrete as a function of temperature [37, 38] a) thermal conductivity, b) specific heat, and c) thermal strain



(a)

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Fig. 4 Stress-strain curves at different temperatures of a) NSC [37], b) SCC and c) HFRSCC

The constitutive laws of SCC proposed by Aslani and Samali [44], taking into account the reduction factors of mechanical properties as a function of temperature suggested by Khaliq and Kodur [38], were used by adopting the stress-strain curves of SCC at different temperatures, Fig. 4(b).

3.2.2 Steel reinforcement

The evolution of thermal properties, such as thermal conductivity, specific heat, and thermal strain as a function of temperature, is shown in Fig. 5 where adopted from Eurocode 2 Part 1–2 [37]. The density of steel is assumed to be 7850 kg/m^3, also derived from Eurocode 2 Part 1–2 [37]. The mechanical properties of steel as a function of temperature are used in this study in accordance with Eurocode 2 Part 1–2 [37] and their stress-strain curves are shown in Fig. 6.

3.2.3 Hybrid fibres

The addition of hybrid fibres to SCC has a negligible effect on the variation of thermal properties with temperature [38] and therefore was neglected in this study. The stress-strain properties of SCC with addition of hybrid fibres at different temperatures are evaluated using Aslani and Nejadi [45] constitutive laws, considering the impact of hybrid fibres on compressive and tensile strength through the suggested relationships by Xu et al [46, 47]. including the reduction factor of mechanical properties proposed by Khaliq and Kodur [38]. The details of characteristics of polypropylene and steel fibres used in simulations are represented in Table 2, and the stress-strain curves of HFRSCC are illustrated in Fig. 4(c).

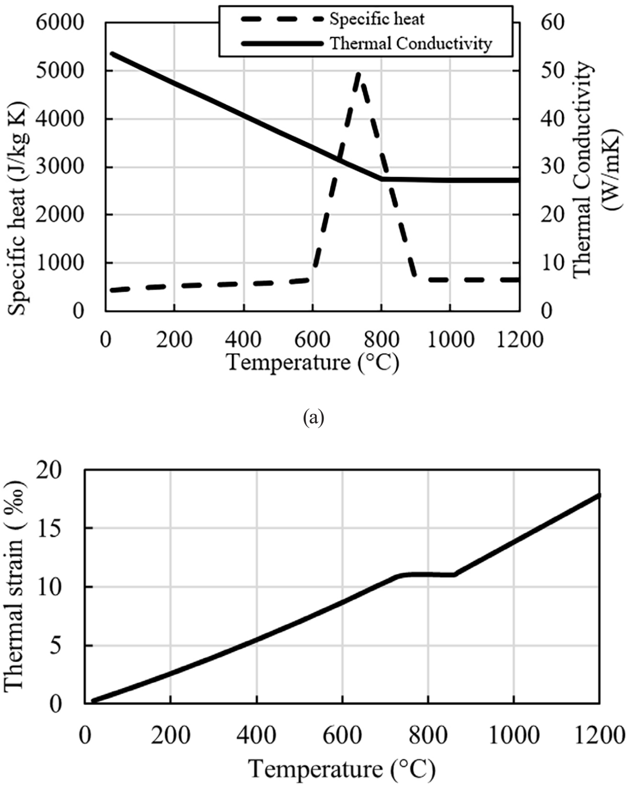

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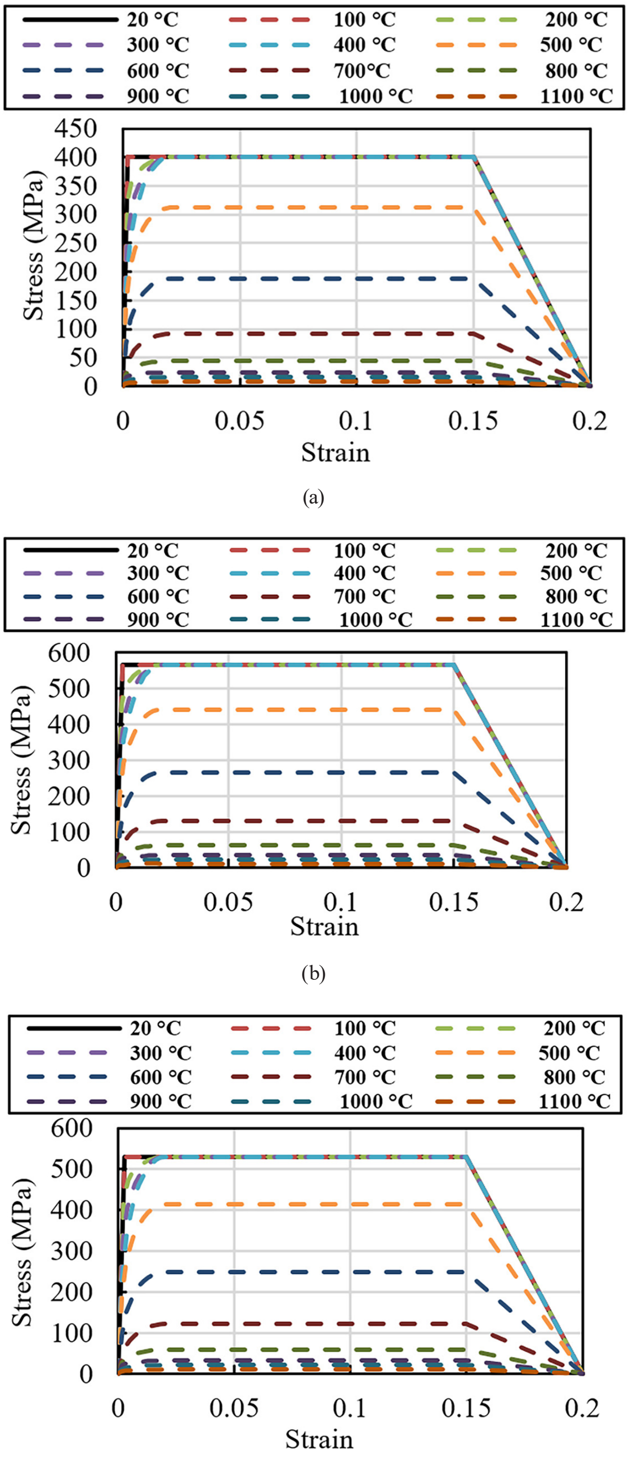
Fig. 5 Evolution of a) thermal conductivity, specific heat and b) thermal strain at elevated temperatures of steel reinforcement [37]



(a)

(b)

(c)

Fig. 6 Stress-strain curves at different temperatures of a) stirrups, b) compressive and c) tensile reinforcements [37]

Table 2 Mechanical and physical properties of fibres

Fibre type	Density (Kg/m^3)	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
Steel	7850	60	0.75	1050	200
Polypropylene	905	65	0.85	250	3

3.2.4 Fire insulation

The Spray Applied Fire Resistive Materials (SFRM) system is a passive fire protection method used to enhance the fire resistance of structural elements such as beams, columns, and ceilings. SFRM involves spraying a specialized material onto surfaces to provide thermal insulation and protection against fire. Kodur and Shakya [48] suggested relationships for the variation of thermal properties as a function of temperature of fire insulation by SFRM of the three types and their curve was given in Fig. 7, were used in this study.

3.3 Mesh and boundary condition

Temperature-induced reduction in material properties leads to many convergence problems in fire resistance analysis due to significant changes in stiffness. Such a decrease can led to the global stiffness matrix becoming ill conditioned, which can result in a non-convergence at a given time step. The time step is refined with smaller time increments to aid convergence, when the analysis does not converge after a specified number of iterations due to a combination of material and geometric non-linearity. A mesh size of 20 mm for concrete, steel reinforcements and fire insulation is chosen to be the optimum for achieving convergence and efficacy as shown in Fig. 8. Also, it was later demonstrated in Section 5, that these element dimensions and chosen geometries presented no mesh dependency. To simplify the mesh generation, an equivalent square area was used for the steel reinforcement, therefore allowing a full node connection between the concrete, the longitudinal rebars, and the stirrups.

The heat due the fire is applied according to the ISO 834 fire model and transferred to the beam surfaces in the three

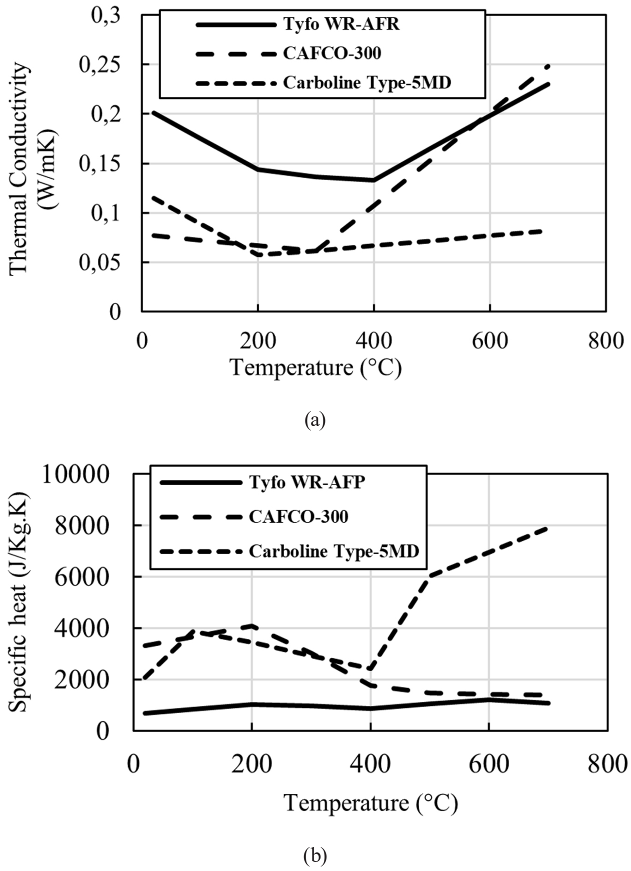


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Fig. 7 Variation of thermal properties of fire insulations as a function of temperature a) thermal conductivity, b) specific heat [48]

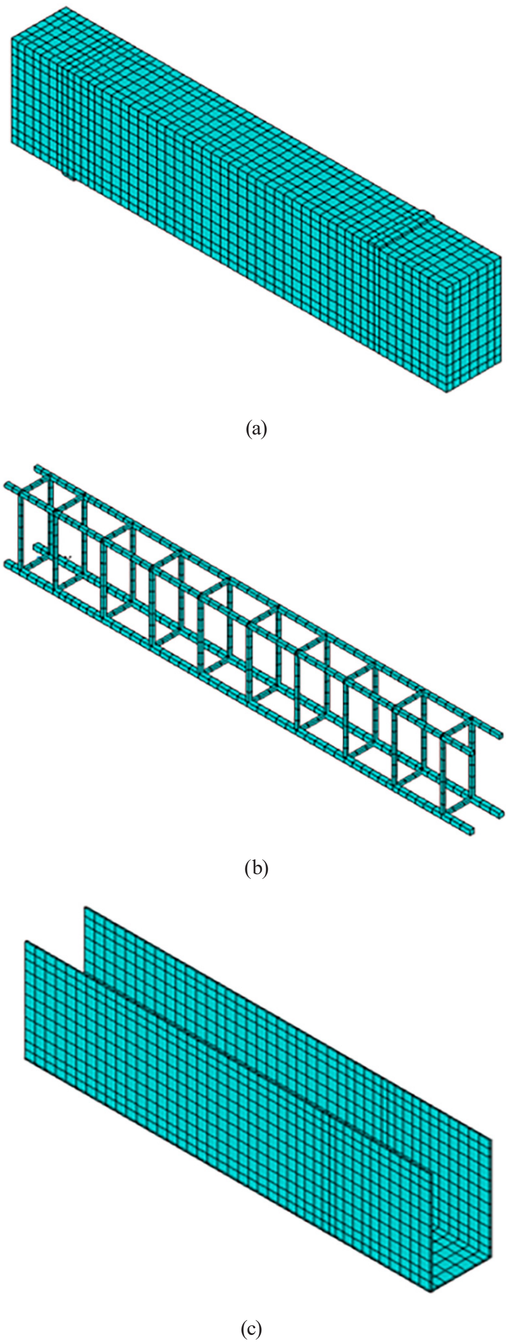

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Fig. 8 Finite element meshing for a) concrete, b) rebar and c) fire insulation longitudinal sides by convection and radiation taking the film coefficient equal to 25 W/m^2, the surface emissivity of the member equal to 0.7, the Boltzmann constant equal to 5.67×10^{-8} W / m^{2}K4, and the emissivity of the fire equal to 1. The unexposed side is subjected to the room temperature of 20 °C a film coefficient of 9 W/m^2. The thermal boundary conditions (convection and radiation) are shown in Fig. 9. The pinned and roller supports are positioned at the bottom of the rigid plate, specifically at the middle nodes. Mechanical loads are applied to the top of the rigid plate at all the center nodes, as shown in Fig. 10.

3.4 Type of analysis

Due to the non-linear material and geometrical non-linear analysis, it is necessary to use a predictor-corrector methodology, in which the iterative Newton-Raphson method was applied for the mechanical model using force control. For the thermal model, since all material thermal parameters are temperature-dependent, a Newton-Raphson method is also used.

4 Failure criteria

When designing the fire resistance of the researched beams, the failure criteria must be applied to the structural analysis of the relevant collapse limit states. The failure of the beams occurs when they are unable to sustain the applied loading during fire conditions, and this happens when the midspan displacement increases quickly. Under high temperatures due to the fire, an increase in the mid-deflection of the beams occurs due to the degradation in the strength and stiffness properties of concrete and reinforcing steel. This type of analysis is only possible to perform using non-linear models, therefore the need of using the thermos-mechanical FE models. For a more realistic assessment of failure, deflection limit state is used to evaluate failure during fire exposure, and this one occurs under the deflection limit state when the maximum deflection in the beam exceeds L/20 at any fire exposure time as specified in British Standard (BS) code [49], where L = span length of the beam, in mm.

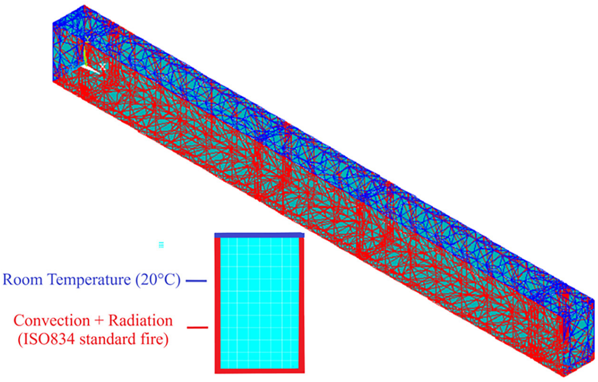


Fig. 9 Thermal boundary conditions

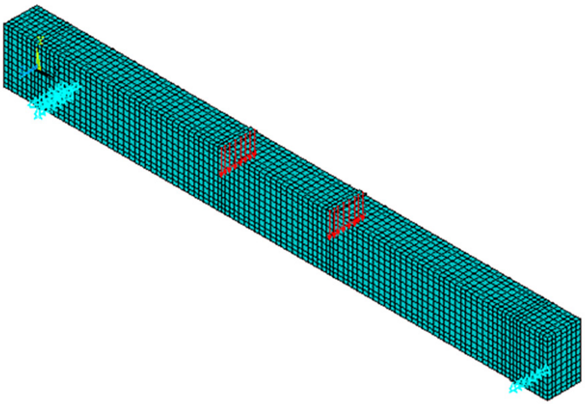


Fig. 10 Location of loading and supports in beam

5 Model validation

To validate the results of the developed FE model, they were compared against experimental test data. The beam BRS1 tested by Rafi et al. [50], was specifically chosen for the model validation, due to an accurate assessment of the mechanical FE model results. Fig. 11 presents a comparison between the measured and predicted results. In order to inquirer there was no mesh dependency [51], the size of the FE was changed from 40 mm to 20 mm. Notably, convergence was achieved when using meshes with size element below 20 mm, resulting in outcomes closely mirroring those of the experimental tests.

Similarly, the beam BESS20-1 examined by Rafi et al. [35] was selected to verify the accuracy of thermal and thermomechanical results predicted by the FE model and Fig. 12. illustrates this comparison. From Fig. 12 (a), it is can be observed a favourable agreement between the measured and predicted results in except small difference can be attributed to the neglected some factors such as the bond

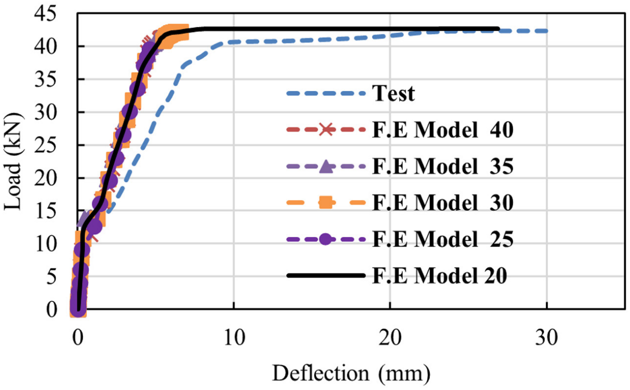
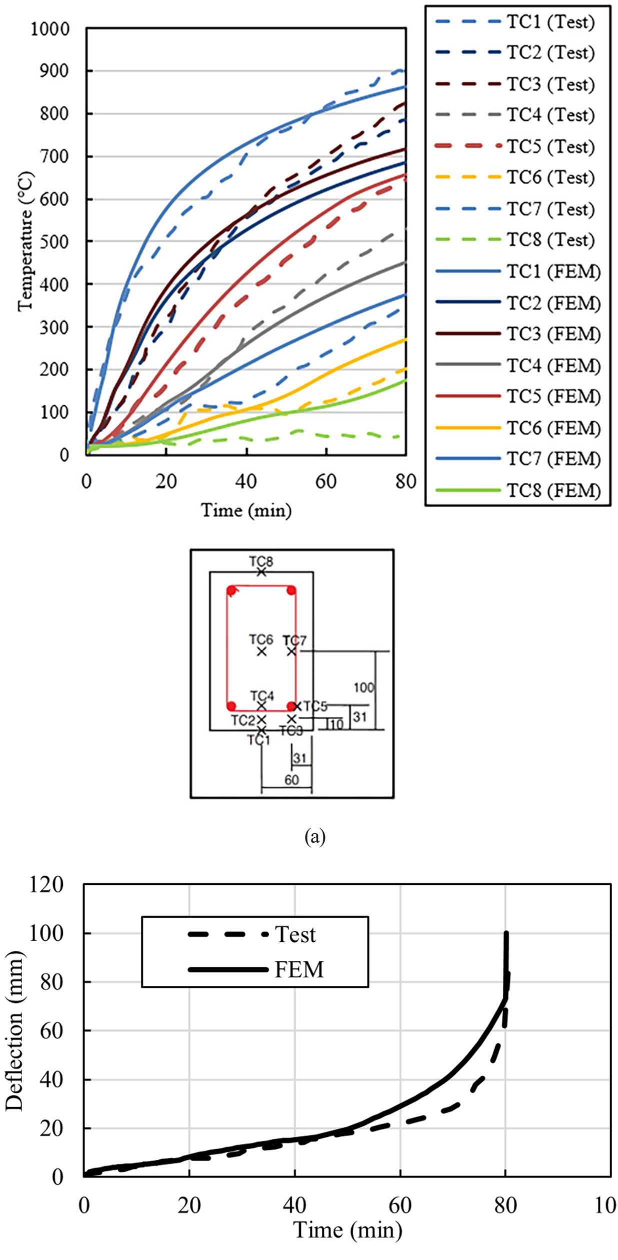


Fig. 11 Comparison between the predicted FE model results with varying mesh sizes and measured test results: Load vs. deflection behaviour at ambient temperature of BRS1 beam

between the reinforcement steel and the concrete as well as moisture content. Regarding the structural response Fig. 12 (b), it can be observed that the predicted mid-span deflection closely matches that measured during the test until 50 minutes, and then progresses slightly faster to reach the same beam failure time and deformation. However, when considering the beam failure time, there is a clear agreement between the predicted results from the FE model and the measured results. These findings underscore the precision of the developed FE model in accurately forecasting the fire resistance performance of RC beams.



(a)

(b)

Fig. 12 Comparison between the predicted and measured results: Temperature vs. defection of BESS20-1 beam, a) thermal response and b) structural response

It is also important to point, that the limit L/20 for failure described in Section 4, which for the reference span is around 87.5 mm, is also verified in this model, therefore, also validating it with an analytical prediction.

6 Results and discussion:

6.1 Fire resistance performance of SCC beams

To conduct a comprehensive investigation into the fire resistance performance of SCC beams, a comparison was made between beam made of SCC and NSC. The evolution of the mid-span deflection of the two beams B_2 in SCC and B_1 in NSC, during fire conditions, is shown in Fig. 13. It can be observed that the mid-span deflection of the B_2 beam progresses more rapidly than that of the B-1 beam. The fire resistance time limit of the B_2 beam is 72 minutes, which is 8% less than that of B_1 beam. This difference may be due to the rapid deterioration of the mechanical properties of SCC compared to NSC at elevated temperatures owing its higher thermal conductivity, leading to faster heat transfer in both the reinforcement and the concrete, as shown in Fig. 14. This leads to a more rapid decrease in the strength and stiffness of SCC beams.

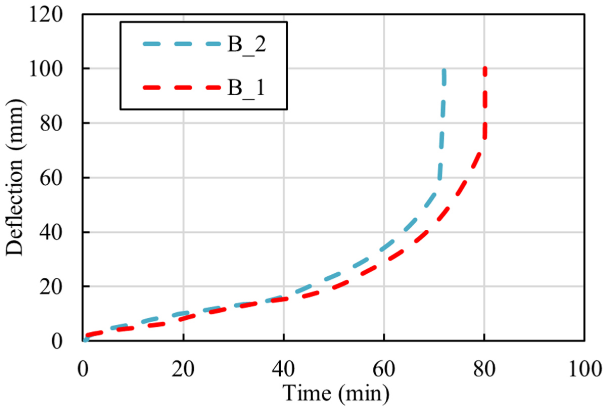


Fig. 13 Mid-span deflection evolution of NSC and SCC beam under fire conditions

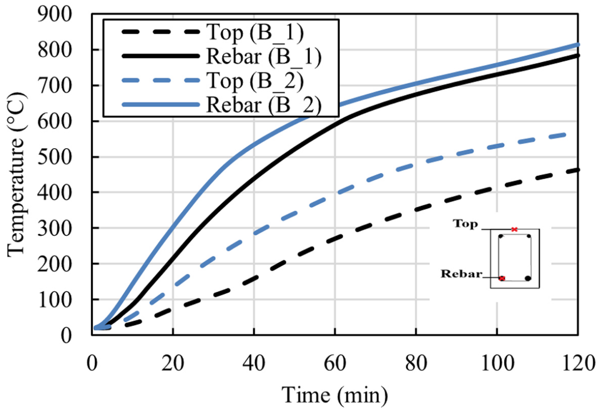


Fig. 14 Temperature evolution as a function of time in the rebar and top of NSC and SCC beams

6.2 Effect of hybrid fibres

The results of the study revealed that the addition of hybrid fibres has a very significant impact on the fire resistance performance of SCC beams studied. Fig. 15 shows that the mid-span deflection of B_3 beam with hybrid fibres progresses more slowly compared to the B_2 beam without fibres, with an improvement in fire resistance of 17% and a time limit of 84 minutes. This is due to the combined effect on the SCC, where the polypropylene fibres slow the deterioration of strength and elastic modulus at elevated temperatures, while steel fibers enhance tensile stress at various temperature levels, Fig. 16. illustrates the distribution of deformation in the bars of tensile reinforcement for both beams (B_2 and B_3) at 72 minutes (the failure time of B_2). This figure reveals that the bars of tensile reinforcement in the B_3 beam experienced significantly less deformation. This observation suggests that HFRSCC demonstrated greater resistance to tensile stress compared to SCC.

6.3 Effect of fire insulation

The effect of fire insulation on the fire resistance performance of SCC beams was assessed comparing different insulated and non-insulated beams, as shown in Fig. 17.

The beams with fire insulation showed a slower progression of deflection at mid-span and a longer fire resistance duration. This behaviour is attributed to the low thermal conductivity of the insulation, which reduces heating rates at the beam surface, as depicted in Fig. 18. Consequently, the temperature penetration across the beams cross-section decreases thus effectively decelerating the deterioration of strength and stiffness in the insulated beams.

The beam B_6, which employed Carboline Type-5MD fire insulation, exhibited a fire resistance time of 92 minutes and both beams B_4 and B_5 with Tyfo WR-AFP and CAFCO 300 fire insulations, respectively achieved a fire resistance time of 82 minutes. This difference in fire resistance time between beams is due to the low thermal conductivity of insulations, as shown in Fig. 7.

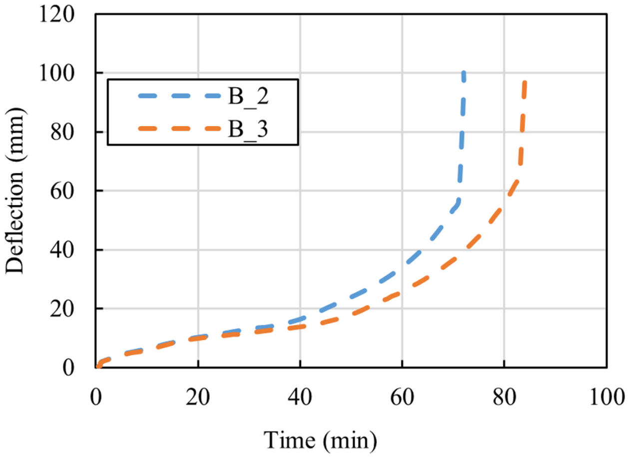


Fig. 15 Effect of hybrid Fibres on mid-span deflection of SCC Beams under fire conditions

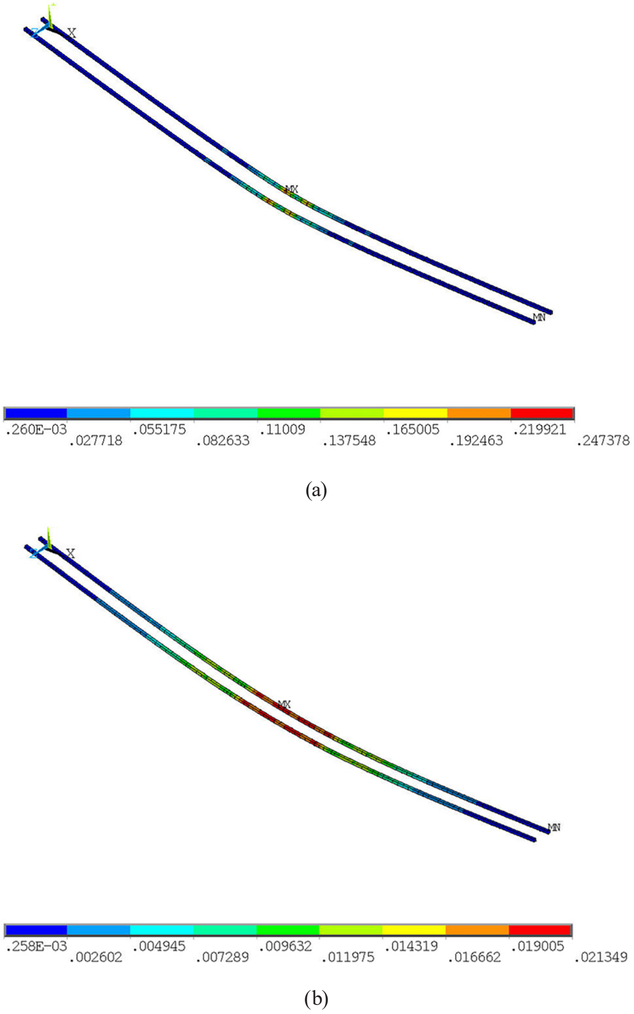


Fig. 16 Strain distribution in the tensile reinforcement bars of a) B_2 and b) B_3 at 72 minutes

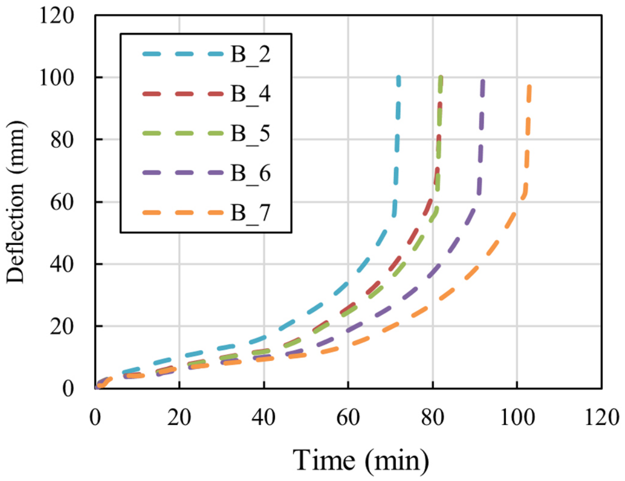


Fig. 17 Effect of fire insulation on mid-span deflection of SCC beams under fire conditions

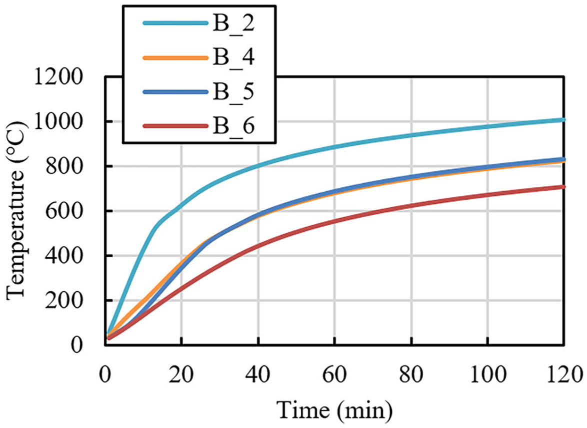


Fig. 18 Temperature evolution as function of time in the bottom of studied beams

The use of fire insulation Carboline Type-5MD on SCC beams improves their fire resistance by 28%. The B_7 beam achieved the longest fire resistance time of 103 minutes, which was 43% longer than the B_2 beam, benefiting from the combined effect of hybrid fibres and fire insulation.

7 Conclusion

Based on the results of the numerical investigation on the fire resistance performance of self-compacting concrete beams and the assessment of the effect of adding hybrid fibres and fire insulation to enhance their performance, the following conclusions were drawn:

- The actual validation for both thermal and thermomechanical produced results which confronted experimental data and FE model predictions and have shown close agreement, with slight discrepancies attributed to neglected factors as bond between reinforcement steel and concrete, and moisture content.
- The comparison of fire resistance performance between SCC beams and NSC beams revealed that SCC beams exhibited faster mid-span deflection progression during fire exposure. The fire resistance time of SCC beam was 8% lower than that of NSC beam.
- The addition of hybrid fibres to SCC beams improves their fire resistance performance by 17%.
- The SCC beam insulated with Carboline Type-5MD showed a fire resistance duration of 12% longer than the SCC beams with Tyfo WR-AFP and CAFCO 300 fire insulations and 28% longer than the uninsulated SCC beam.
- The use of hybrid fibres and fire insulation at the bottom side on SCC beams can be enhanced their fire resistance by 43%.

In this study, well calibrated FE models have been developed and depicted with good accuracy fire resistance for the assessment of the effect, of adding hybrid fibres and the fire insulation in enhancing the performance of SCC beams under fire condition. These advanced numerical models will provide, through further parametric analysis, new design rules to ease the fire resistance SCC beams calculus.

8 Future work and further developments

This study focuses on understanding the behaviour of self-compacting concrete (SCC) beams and evaluating solutions to enhance fire resistance. Future work should concentrate on proposing foundational laws to address gaps in design codes, providing a more comprehensive framework for designing fire-resistant SCC beams. This research aims to contribute to the advancement of SCC beam design by establishing essential principles that strengthen existing knowledge and guide future design guidelines.

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References

[1] Okamura, H., Ouchi, M. "Self-compacting concrete", Journal of Advanced Concrete Technology, 1(1), pp. 5–15, 2003. https://doi.org/10.3151/jact.1.5

[2] Meko, B., Ighalo, J. O., Ofuyatan, O. M. "Enhancement of self-compactability of fresh self-compacting concrete: A review", Cleaner Materials, 1, 100019, 2021. https://doi.org/10.1016/j.clema.2021.100019

[3] Iqbal, S., Ali. A., Holschemacher, K., Ribakov, Y., Bier, T. A. "Effect of fly ash on properties of self-compacting high strength lightweight concrete", Periodica Polytechnica Civil Engineering, 61(1), pp. 81–87, 2017. https://doi.org/10.3311/PPci.8171

[4] Loser, R., Leemann, A. "Shrinkage and restrained shrinkage cracking of self-compacting concrete compared to conventionally vibrated concrete", Materials and Structures, 42, pp. 71–82, 2009. https://doi.org/10.1617/s11527-008-9367-9

[5] Karatas, M., Gunes, A. "Engineering properties of self-compacting concrete produced by polypropylene and steel fiber", Periodica Polytechnica Civil Engineering, 59(2), pp. 95–102, 2015. https://doi.org/10.3311/PPci.7348

[6] Yehia, S., Douba, A., Abdullahi, O., Farrag, S. "Mechanical and durability evaluation of fiber-reinforced self-compacting concrete", Construction and Building Materials, 121, pp. 120–133, 2016. https://doi.org/10.1016/j.conbuildmat.2016.05.127

[7] Lublóy, É. "The influence of concrete strength on the effect of synthetic fibres on fire resistance", Periodica Polytechnica Civil Engineering, 62(1), pp. 136–142, 2018. https://doi.org/10.3311/PPci.10775

[8] Qin, D., Gao, P., Aslam, F., Sufian, M., Alabduljabbar, H. "A comprehensive review on fire damage assessment of reinforced concrete structures", Case Studies in Construction Materials, 16, e00843, 2022. https://doi.org/10.1016/j.cscm.2021.e00843

[9] Akcay, B., Tasdemir, M. A. "Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete", Construction and Building Materials, 28(1), pp. 287–293, 2012. https://doi.org/10.1016/j.conbuildmat.2011.08.044

[10] Kada, A., Lamri, B. "Numerical analysis of non-restrained long-span steel beams at high temperatures due to fire", Asian Journal of Civil Engineering, 20(2) pp. 261–267, 2019. https://doi.org/10.1007/s42107-018-0103-7

[11] Król, P. A. "Random parameters and sources of uncertainty in practical fire safety assessment of steel building structures", Periodica Polytechnica Civil Engineering, 63(1), pp. 398–411, 2017. https://doi.org/10.3311/PPci.9833

[12] Kodur, V., Kumar, P., Rafi, M. M. "Fire hazard in buildings: review, assessment and strategies for improving fire safety", PSU Research Review, 4(1), pp. 1–23, 2020. https://doi.org/10.1108/PRR-12-2018-0033

[13] Zitouni, M., Lamri, B., Kada, A. "Fire resistance performance of glass fiber reinforced concrete columns", In: CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure, Singapore, 2021, pp. 275–283. ISBN 978-981-16-7160-9 https://doi.org/10.1007/978-981-16-7160-9_27

[14] Dwaikat, M., Kodur, V. "Response of restrained concrete beams under design fire exposure", Journal of Structural Engineering, 135(11), pp. 1408–1417, 2009. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000058

[15] Yermak, N., Pliya, P., Beaucour, A.-L., Simon, A., Noumowé, A. "Influence of steel and/or polypropylene fibres on the behaviour of concrete at high temperature: Spalling, transfer and mechanical properties", Construction and Building Materials, 132: pp. 240–250, 2017. https://doi.org/10.1016/j.conbuildmat.2016.11.120

[16] Hou, X., Ren, P., Rong, Q., Zheng, W., Zhan, Y. "Effect of fire insulation on fire resistance of hybrid-fiber reinforced reactive powder concrete beams", Composite Structures, 209, pp. 219–232, 2019. https://doi.org/10.1016/j.compstruct.2018.10.073

[17] Banerji, S., Kodur, V., Solhmirzaei, R. "Experimental behavior of ultra high performance fiber reinforced concrete beams under fire conditions", Engineering Structures, 208, 110316, 2020. https://doi.org/10.1016/j.engstruct.2020.110316

[18] Jin, L., Zhang, R., Li, L., Du, X., Yao, Y. "Impact behavior of SFRC beams at elevated temperatures: Experimental and analytical studies", Engineering Structures, 197, 109401, 2019. https://doi.org/10.1016/j.engstruct.2019.109401

[19] Arruda, M. R. T., Deividas, M., Vadimas, K. "State of the art on structural reinforced concrete design guidelines with non-linear analyses", Mechanics of Advanced Materials and Structures, pp. 1–15. https://doi.org/10.1080/15376494.2023.2192214

[20] Kodur, V. K. R., Agrawal, A. "An approach for evaluating residual capacity of reinforced concrete beams exposed to fire", Engineering Structures, 110, pp. 293–306, 2016. https://doi.org/10.1016/j.engstruct.2015.11.047

[21] Hou, X., Ren, P., Rong, Q., Zheng, W., Zhan, Y. "Comparative fire behavior of reinforced RPC and NSC simply supported beams", Engineering Structures, 185, pp. 122–140, 2019. https://doi.org/10.1016/j.engstruct.2019.01.097

[22] Al-Attar, A. A., Abdulrahman, M. B., Hamada, H. M., Tayeh, B. A. "Investigating the behaviour of hybrid fibre-reinforced reactive powder concrete beams after exposure to elevated temperatures", Journal of Materials Research and Technology, 9(2), pp. 1966–1977, 2020. https://doi.org/10.1016/j.jmrt.2019.12.029

[23] Ilango, S., Mahato, S. "Behaviour of polypropylene fibre-reinforced concrete beam with CFRP reinforcement under elevated temperature", Asian Journal of Civil Engineering, pp. 1–18, 2020. https://doi.org/10.1007/s42107-020-00230-6

[24] Al-Thairy, H., Al-Jasmi, S. K. "Numerical investigation on the behavior of reinforced lightweight concrete beams at elevated temperature", Iranian Journal of Science and Technology, Transactions of Civil Engineering, 45, pp. 2397–2412, 2021. https://doi.org/10.1007/s40996-021-00580-4

[25] Ren, P., Hou, X., Cui, Z., Xie, H., Abid, M. "Fire resistance evaluation and minimum reinforcement ratio for hybrid fibre-reinforced RPC beams under fire exposure", Journal of Building Engineering, 44, 103216, 2021. https://doi.org/10.1016/j.jobe.2021.103216

[26] Williams, B., Bisby, L., Kodur, V., Green, M., Chowdhury, E. "Fire insulation schemes for FRP-strengthened concrete slabs", Composites Part A: Applied Science and Manufacturing, 37(8), pp. 1151–1160, 2006. https://doi.org/10.1016/j.compositesa.2005.05.028

[27] Khoury, G. A. "Effect of fire on concrete and concrete structures", Progress in Structural Engineering and Materials, 2(4), pp. 429–447, 2000. https://doi.org/10.1002/pse.51

[28] Kodur, V., Arablouei, A. "Effective properties of spray-applied fire-resistive material for resistance to cracking and delamination from steel structures", Construction and Building Materials, 84, pp. 367–376, 2015. https://doi.org/10.1016/j.conbuildmat.2015.03.022

[29] Ren, P., Hou, X., Rong, Q., Zheng, W. "Quantifying fire insulation effects on the fire response of hybrid-fiber reinforced reactive powder concrete beams", Fire Technology, 56(4), pp. 1487–1525, 2020. https://doi.org/10.1007/s10694-019-00937-2

[30] Fares, H., Noumowe, A., Remond, S. "Self-consolidating concrete subjected to high temperature: Mechanical and physicochemical properties", Cement and Concrete Research, 39(12), pp. 1230–1238, 2009. https://doi.org/10.1016/j.cemconres.2009.08.001

[31] Tao, J., Yuan, Y., Taerwe, L. "Compressive strength of self-compacting concrete during high-temperature exposure", Journal of Materials in Civil Engineering, 22(10), pp. 1005–1011, 2010. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000102

[32] Bamonte, P., Gambarova, P. G. "High-temperature behavior of SCC in compression: Comparative study on recent experimental campaigns", Journal of Materials in Civil Engineering, 28(3), 04015141, 2016. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001378

[33] Anand, N., Andrushia, A. D., Mathews, M. E, Kiran, T., Chandramohan, D. L., Carmichael, M. J. "Effect of cover thickness on flexural behaviour of conventional and self compacting concrete beams subjected to elevated temperature", Materials Today: Proceedings, 60, pp. 173–180, 2022. https://doi.org/10.1016/j.matpr.2021.12.294

[34] ANSYS "ANSYS Student® Academic research, R 2.", 2023. Available at: https://www.ansys.com/academic/students/ansys-student [Accessed: 20 December 2023]

[35] Rafi, M., Nadjai, A., Ali, F., O'Hare, P. "Evaluation of thermal resistance of FRP reinforced concrete beams in fire", Journal of Structural Fire Engineering, 2(2), pp. 91–107, 2011. https://doi.org/10.1260/2040-2317.2.2.91

[36] Kodur, V. K. R., Dwaikat, M. "A numerical model for predicting the fire resistance of reinforced concrete beams", Cement and Concrete Composites, 30(5), pp. 431–443, 2008. https://doi.org/10.1016/j.cemconcomp.2007.08.012

[37] EN_1992-1-2. "Eurocode 2: Design of concrete structures. Part 1-2: General rules structural fire design", Brussels: CEN-European Committee for Standardization. 2004. [online] Available at: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.2.2004.pdf [Accessed: 20 December 2023]

[38] Khaliq, W., Kodur, V. "Thermal and mechanical properties of fiber reinforced high performance self-consolidating concrete at elevated temperatures", Cement and Concrete Research, 41(11), pp. 1112–1122, 2011. https://doi.org/10.1016/j.cemconres.2011.06.012

[39] Džolev, I. M., Cvetkovska, M. J., Lađinović, Đ. Z., Radonjanin, V. S. "Numerical analysis on the behaviour of reinforced concrete frame structures in fire", Computers and Concrete, 21(6), pp. 637–647, 2018. https://doi.org/10.12989/cac.2018.21.6.637

[40] Taufik, S., Anggarini, E., Setiawan, I. "ANSYS numerical modeling of confined deep beam with high strength concrete", International Journal of Structural Glass and Advanced Materials Research, 4, pp. 41–55, 2020. https://doi.org/10.3844/sgamrsp.2020.41.55

[41] Jiménez Rios, O'Dwyer, D. "FEM non-linear modelling of cob using ANSYS", In: 9th International Conference on Computational Methods, Rome, Italy, 2018, pp. 285–298. ISBN: 978-0-9985082-2-1 Available at: https://www.sci-en-tech.com/ICCM2018/PDFs/3235-10939-1-PB.pdf [Accessed: 20 December 2023]

[42] Arriaga, A., Pagaldai, R., Zaldua, A. M., Chrysostomou, A., O'Brien, M. "Impact testing and simulation of a polypropylene component. Correlation with strain rate sensitive constitutive models in ANSYS and LS-DYNA", Polymer Testing, 29(2), pp. 170–180, 2010. https://doi.org/10.1016/j.polymertesting.2009.10.007

[43] Pandimani, Ponnada, M. R., Geddada, Y. "Numerical nonlinear modeling and simulations of high strength reinforced concrete beams using ANSYS", Journal of Building Pathology and Rehabilitation, 7(1), pp. 22, 2021. https://doi.org/10.1007/s41024-021-00155-w

[44] Aslani, F., Samali, B. "Constitutive relationships for self-compacting concrete at elevated temperatures", Materials and Structures, 48(1), pp. 337–356, 2015. https://doi.org/10.1617/s11527-013-0187-1

[45] Aslani, F., Nejadi, S. "Self-compacting concrete incorporating steel and polypropylene fibers: Compressive and tensile strengths, moduli of elasticity and rupture, compressive stress–strain curve, and energy dissipated under compression", Composites Part B: Engineering, 53, pp. 121–133, 2013. https://doi.org/10.1016/j.compositesb.2013.04.044

[46] Xu, L., Li, B., Chi, Y., Li, C., Huang, B., Shi, Y. "Stress-strain relation of steel-polypropylene-blended fiber-reinforced concrete under uniaxial cyclic compression", Advances in Materials Science and Engineering, 2018. https://doi.org/10.1155/2018/9174943

[47] Xu, L., Huang, L., Chi, Y., Mei, G. "Tensile behavior of steel-Polypropylene hybrid fiber-reinforced concrete", ACI Materials Journal, 113(2), pp. 219–229, 2016. [online] Available at: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51688641 [Accessed: 26 May 2024]

[48] Kodur, V. K. R., Shakya, A. M. "Effect of temperature on thermal properties of spray applied fire resistive materials", Fire Safety Journal, 61, pp. 314–323, 2013. https://doi.org/10.1016/j.firesaf.2013.09.011

[49] Standard, B. "Fire tests on building materials and structures-Part 20: Method from determination of the fire resistance of elements of construction (general principles)", BS 476–20, London, UK, 1987. [online] Available at: https://allcivilstandard.com/wp-content/uploads/2019/02/BS-00476-20-1987-2014-1.pdf [Accessed: 20 December 2023]

[50] Rafi, M. M., Nadjai, A., Ali, F. "Experimental testing of concrete beams reinforced with carbon FRP bars", Journal of Composite Materials, 41(22), pp. 2657–2673, 2007. https://doi.org/10.1177/0021998307078727

[51] Lopes, B., Arruda, M. R. T., Almeida-Fernandes. L., Castro. L., Silvestre, N., Correia, J. R. "Assessment of mesh dependency in the numerical simulation of compact tension tests for orthotropic materials", Composites Part C: Open Access, 1, 100006, 2020. https://doi.org/10.1016/j.jcomc.2020.100006