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Numerical Investigation into the Mechanical Performance of Hybrid Fiber-Reinforced Self-Compacting Concrete Beams at High Temperature

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ABSTRACT: The use of self-compacting concrete (SCC) in structural elements has significantly increased in recent years due to its superior fresh properties, including high flowability, ease of placement, and ability to consolidate without vibration, making it particularly suitable for complex and densely reinforced structures. However, despite these advantages, SCC presents certain limitations when exposed to fire, which is considered one of the most severe threats to structural safety. This is mainly due to the lack of comprehensive understanding and design guidelines regarding its behaviour under elevated temperatures, particularly at the structural element level. This paper presents a numerical investigation of the mechanical behaviour of hybrid fibres reinforced self-compacting concrete (HFSCC) beams under high temperatures due to fire using a finite element (FE) model. Three beams are analysed, one without fibres (SCC), and the others, with hybrid fibres, having the fixed volume fraction (VF) of polypropylene fibre of 0.1% and a VF of steel fibres of 1% and 2%. All beams are simulated using ANSYS software and analysed at ambient and elevated temperatures at 400°C, 600°C, and 800°C. The numerical study is carried out to evaluate the behaviour of beams, considering geometric and material nonlinearities. The numerical results suggest that at room temperature (20°C), adding hybrid fibres, 0.1% VF of polypropylene, and VF of 1% steel to SCC beams increases ultimate load capacity by 17.9%, and with an increase in the VF of steel fibres to 2%, the load capacity further improves to 30.8%. At elevated temperatures (400°C, 600°C, and 800°C), the addition of hybrid fibres reduces the rate of reduction of ultimate load capacity of SCC beams, particularly significant when 2% VF of steel fibres are used.

KEYWORDS: Mechanical behaviour; self-compacting concrete; hybrid fibres; high temperature; finite element

1 Introduction

The use of fibre-reinforced self-compacting concrete (FRSCC) in structural members has recently offered a new alternative to the current trend in concrete preparation advance, because it combines positive aspects of fresh properties of self-compacting concrete (SCC) with improved characteristics of hardened concrete with fibre addition [1,2]. SCC is characterized by its ability to flow under its own weight without requiring any vibration for placement and compaction, even in the presence of congested reinforcement [3]. Since its introduction by Okamura and Ouchi [4], SCC has offered a crucial solution for achieving concrete that self-levels without mechanical vibration. This technology has been widely applied in buildings and structural projects in various countries, including Japan, Canada, and the United States [5,6]. Furthermore, the use of fibres, such as steel and polypropylene, in SCC enhances the mechanical properties, particularly

the tensile strength [7–9]. This combination effectively addresses the issue of concrete fragility and crack propagation, as the literature review demonstrates the beneficial synergy between fibre reinforcement and self-compacting technology, making it highly suitable for use in buildings [7,10–13]. Additionally, a recent study by Mustafa Abdullah and Haido [14] showed that the addition of recycled PET fibres enhances concrete ductility, reduces brittleness, and improves crack resistance. However, fire remains one of the most perilous threats to buildings' safety [15]. Appropriate fire safety measures should therefore be provided for structural members to achieve adequate design [16–20].

Most of the research studies on the behaviour of steel and concrete structures exposed to fire dealt with individual members, considering mainly temperature-dependent properties [20–24]. In a numerical investigation, Mohamed et al. [25] explored the performance of reinforced concrete (RC) columns reinforced with glass fibres when subjected to elevated temperatures from fire and axial loading. Their findings indicate that augmenting the volume fraction of glass fibres leads to heightened final axial displacement and expansion of the columns. Kodur and Agrawal [26] undertook an investigation aimed at evaluating the residual capacity of fire-exposed RC beams. Their study revealed that finite element analysis provides more accurate predictions of residual capacity compared to those derived from simplified sectional analysis. Antonius et al. [27] examine the flexural behaviour of RC beams at temperatures up to 900°C with 0.5% steel fibre reinforcement, finding that double reinforcement systems outperform single ones. Despite high temperatures, longitudinal reinforcement retains 83% of its initial yield stress, supported by steel fibre stress-strain models. Thanaraj et al. [28] made an experimental study to investigate the behaviour of RC beams of different strengths subjected to standard fire. They concluded that the ultimate loads of M20 and M50 grades of RC beams exposed to fire for a duration of 240 min were reduced by about 75% and 71%, respectively.

Al-Thairy and Al-Jasmi [29] studied numerically the response of lightweight RC beams under elevated temperatures numerically and concluded that after their exposure to 800°C, the reduction in the ultimate load capacities is less than that of normal weight RC. Hager and Mróz [30] and Zhang et al. [31] have shown that the addition of polypropylene and/or steel fibres may reduce the fire damage to structural concrete members. Banerji et al. [32] conducted experimental research concerning the performance of ultra-high-performance fibre RC beams when exposed to fire. They observed that beams reinforced with polypropylene fibres demonstrate enhanced performance during fire exposure, particularly during the distinct cooling phase. Alyaa et al. [33] explored the structural response of reinforced reactive powder concrete beams, which incorporated a combination of fibres (50% polypropylene and 50% steel fibres), under both service load and fire conditions. Their findings suggest that incorporating hybrid fibres significantly enhances the residual stiffness of beams damaged by fire. Jin et al. [34] studied the performances of steel fibre RC beams with volume fractions of fibres of 0.1% and 2% at elevated temperatures. They have indicated that the steel fibres have an ignorable influence on the distribution of temperatures when their volume fraction is no larger than 2%. These fibres can reduce the spalling of concrete during heating at 400°C. Ilango and Mahato [35] show in their numerical study that the addition of polypropylene fibres to RC beams strengthened with carbon fibre reinforced polymer (CFRP) bars improved their fire resistance by 16%.

The literature review on the behaviour of SCC at elevated temperature has revealed that some research works focused only on experiments using small-sized samples. Fares et al. [36] conducted an experimental study comparing the performance of SCC and NSC under high temperatures. They found that SCC specimens experienced severe spalling, whereas NSC specimens did not exhibit any spalling. Tao et al. [37] performed an experimental study to assess the impact of high temperatures on the compressive strength of SCC and high-strength concrete. They concluded that the compressive strength grade significantly influences the reduction factor of mechanical properties. Bamonte and Gambarova [38] studied the behaviour of NSC and SCC at high temperatures. Their findings revealed that normal-strength SCC behaves similarly to NSC,

while high-strength SCC is more sensitive to high temperatures than NSC. Anand et al. [39] studied the behaviour of small beams made from SCC and NSC. Their findings indicated that as the concrete grade increases, the percentage reduction in ultimate load also increases. Additionally, beams made with SCC and subjected to forced cooling performed worse than other beams.

The literature review on SCC has revealed that some research works focused only on testing small samples with the objective of providing information on the stress-strain behaviour law of the material at elevated temperatures [13,36,39–41]. However, there is still no information on the behaviour of SCC structural elements under fire conditions.

Therefore, for the use of self-compacting concrete (SCC) in structural elements and to achieve specific fire resistance standards, it is imperative to establish criteria regarding geometry, loading, and boundary conditions. Therefore, considering there is a need for more research, this paper presents a parametric numerical study using a finite element (FE) model via ANSYS software to simulate the behaviour of hybrid fibres, steel, and polypropylene, reinforced self-compacting concrete (HFSCC) beams under elevated temperatures due to fire. The effect of adding hybrid fibres with a variation in the volume fraction of steel fibres is studied. Geometric and material nonlinearities are considered in the evaluation of the behaviour of beams.

2 Materials and Methods

2.1 Case of Study

To assess the overall effectiveness of incorporating hybrid fibres and specifically evaluate the influence of steel fibres on enhancing the behaviour of SCC beams, the case study comprises three RC beams: one in SCC without fibres and the others in HFSCC, with the fixed volume fraction (VF) of polypropylene fibres and varying VF of steel fibres. The selection of VF for fibres is based on optimal values reported in the literature. Detailed information regarding the chosen VF is provided in Section 2.2.2. The labelling and parameters of the studied beams are represented in Table 1. SCC generally exhibits higher 28 day compressive strength (often 30–50 MPa). Therefore, in this numerical study, a concrete compressive strength value of 40 MPa was selected to represent typical normal-strength SCC according to EN 1994-1-2 [42] and Inayathulla et al. [43]. The geometry and properties of the hybrid fibres used in this study are the same as those of Aslani and Nejadi [13]. All beams are simply supported with a span of 3.2 m, having a rectangular cross-section of 250 mm × 350 mm. Fig. 1 shows the dimensions and reinforcement details, loading, and boundary conditions of the studied beams. The yield strength and modulus of elasticity of rebars have 420 MPa and 205 GPa, respectively.

Table 1: Beams specifications.

Designation of Beams	VF Polypropylene (%)	VF Steel (%)	Compressive Strength of Concrete (MPa)
B0	0	0	40
B1	0.1	1	48
B2	0.1	2	54

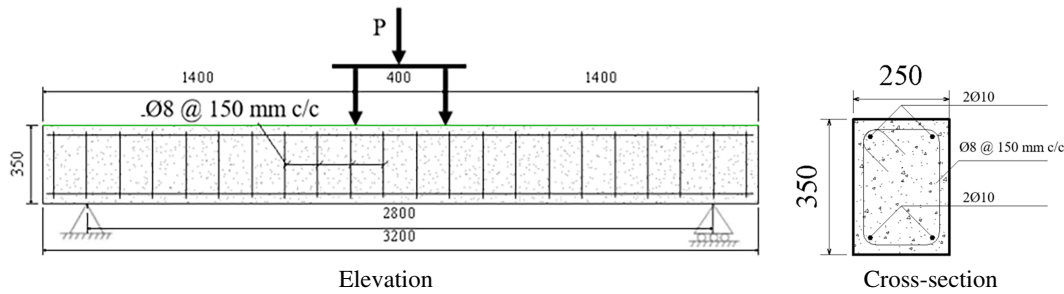


Figure 1: Dimensions and reinforcement details of the studied beams.

To investigate the influence of steel fibre content on the mechanical behaviour of HFSCC beams under elevated temperatures, a parametric analysis is conducted by varying the volume fraction (VF) of steel fibres from 0% to 2%. Specifically, three cases are considered: a reference beam without fibres (B0), and two hybrid fibre-reinforced beams incorporating a constant polypropylene fibre content of 0.1% combined with steel fibre volume fractions of 1% (B1) and 2% (B2). An increasingly concentrated load is applied at the mid-span of each beam until failure, under both ambient temperature (20°C) and elevated temperatures of 400°C, 600°C, and 800°C (Fig. 1). This approach allows for a direct assessment of the effect of increasing steel fibre content on the load-carrying capacity and overall mechanical response of the beams under fire conditions.

2.2 Numerical Modelling

Finite Elements (FE) models are developed using the software ANSYS [44] to simulate and analyse beams under applied ambient and high temperatures of 400°C, 600°C, and 800°C to determine the ultimate mechanical load for each case. It is important to point out that the robustness of this numerical model, to undertake non-linear thermal-mechanical analysis for SCC beams subject to fire, was already verified and studied in the work of Zitouni et al. [45].

The LINK180, SOLID65, and SOLID185 elements from the ANSYS library are used to simulate reinforcement, concrete, and steel plates, respectively [44]. The LINK180 element, characterized by two nodes with three translational degrees of freedom at each node, can withstand uniaxial tension or compression. It simplifies the reinforcement modelling process by focusing on the axial forces, which are the primary forces experienced by the reinforcement in RC structures. SOLID65 and SOLID185 employ full integration and consist of eight nodes, with each node having three degrees of freedom. SOLID65 can model cracking in tension and crushing in compression, which is crucial for accurately predicting the failure modes and mechanical response of concrete under various loading conditions. SOLID185 is a versatile element that can handle various material properties, including plasticity, creep, and large deflection capabilities, making it suitable for simulating steel plates that may undergo significant deformation under high temperatures. ANSYS applies standard values for tensile fracture energy in concrete, indirectly accounting for this through a tensile crack factor (TCF) set at 0.6.

The following assumptions have been adopted:

- To define the material stress–strain relationship used as input in this study, the constitutive model presented in Eq. (4), as proposed by Aslani et al. [13,40], was adopted, incorporating the reduction factors suggested by Khaliq and Kodur [41]. In addition, the equations proposed by Xu et al. [46,47] were used to simulate the effect of hybrid fibres on the mechanical properties of the concrete.
- The descending part of the ideal stress-strain curve of concrete, which indicates strain softening, was neglected, as recommended in earlier studies [48].

- Full adhesion is assumed between the concrete and the steel reinforcement, indicating that there is no slip, and therefore no special contact element is assigned. Excluding the contact element from the model has two advantages: the first is the simplicity of the model, and the second is to facilitate the convergence process.
- Spalling is not considered in this study because the compressive strength of SCC is below 70 MPa, and the SCC used contains polypropylene fibres [49].

2.2.1 Mesh, Loading, and Boundary Condition

To ensure there is no mesh dependency, various mesh sizes of 40, 35, 30, 25, 20, and 15 mm, an optimal size of 20 mm was chosen, and the modelled beam is shown in Fig. 2, for both concrete and steel reinforcement. This element size and geometry exhibited mesh independence, indicating that further mesh refinement would not significantly impact the results. To simplify mesh generation, an equivalent square area of steel reinforcement was employed, facilitating full node connections between the concrete, longitudinal rebars, and stirrups. This simplification is valid for the numerical analysis, since no slip-bond is simulated.

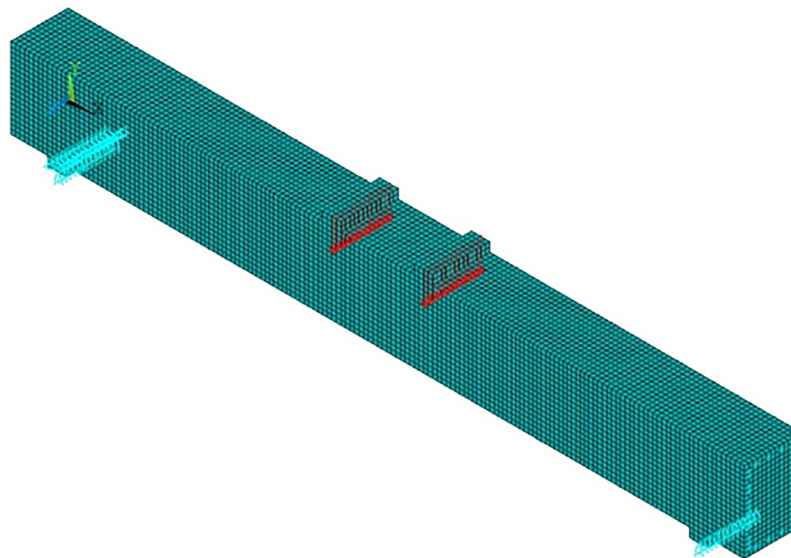


Figure 2: Mesh and boundary conditions of the studied beams.

Regarding loading and boundary conditions, the numerical simulation was executed using a steady-state thermal-mechanical analysis approach. The analysis was conducted in two sequential stages:

- **Thermal State Application:** A uniform constant temperature (400°C, 600°C, or 800°C) was applied as a thermal body load across the entire cross-section of the beam. This procedure ensures that all internal integration points reach the target temperature simultaneously.
- **Mechanical Loading Stage:** Upon reaching thermal equilibrium at the target temperature, a monotonically increasing mechanical load was applied. The load was increased incrementally until the structural member reached its ultimate limit state.

The beam was modeled with a simply supported configuration. Pinned and roller supports were located at the bottom of the rigid plates, positioned precisely at the central nodes to ensure uniform reaction distribution. The mechanical loads were applied at the top of the rigid plates across all central nodes, as illustrated in Fig. 2. This steady-state methodology provides a controlled environment to isolate the influence

of high temperature on the residual mechanical capacity and stiffness of the fiber-reinforced concrete without the interference of transient temperature gradients.

2.2.2 Materials Properties

A non-linear analysis, for the behaviour of SCC, is carried out using mechanical properties as specified in the assumptions. The density of SCC is as specified in EN 1994-1-2 [42].

Incorporating hybrid fibres into SCC significantly enhances its mechanical properties, resulting in superior ductility. Xu et al. [46] and Xu et al. [47] proposed Eqs. (1)–(3) to characterize their effect on tensile strength and to describe their influence on compressive strength and deformation.

$$\sigma_c = \sigma_{c0} (1 + 0.17\lambda_s + 0.341\lambda_p) \quad (1)$$

$$\varepsilon_c = \varepsilon_{c0} (1 + 0.55\lambda_s + 0.341\lambda_p) \quad (2)$$

$$f_{ft} = f_{mt} (1 + \alpha\lambda_s + \beta\lambda_p) \quad (3)$$

With $\alpha = 0.379$ and $\beta = 0.02$.

Where σ_{c0} and ε_{c0} represent the maximum stress and the maximum strain for concrete without fibres, respectively. λ_s and λ_p represent the characteristic parameters of steel and polypropylene fibres, respectively. The parameters f_{ft} and f_{mt} denote the uniaxial tensile strength of concrete with and without fibres, respectively. The characteristics of the hybrid fibres used are detailed in Table 2.

Table 2: Characteristics details of hybrid fibres.

Fiber Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (%)	Length (mm)	Diameter (mm)
Polypropylen	250	3	905	65	0.85
steel	0.1	200	7850	60	0.75

Khaliq and Kodur [41] proposed relationships for the reduction factors in mechanical properties of SCC and HFSCC at high temperatures, and their curves are plotted in Fig. 3, where the reductions of compressive strength, tensile strength, and elastic modulus of concrete with temperature are defined by coefficients $K_{c,T}$, $K_{t,T}$ and $K_{E,T}$, respectively. It should be noted that the degradation of fibre contribution at high temperatures is implicitly included within these reduction factors, as hybrid fibres primarily influence the tensile strength and elastic modulus of concrete. Therefore, the temperature-induced reduction in fibre effectiveness is reflected in the corresponding curves shown in Fig. 3.

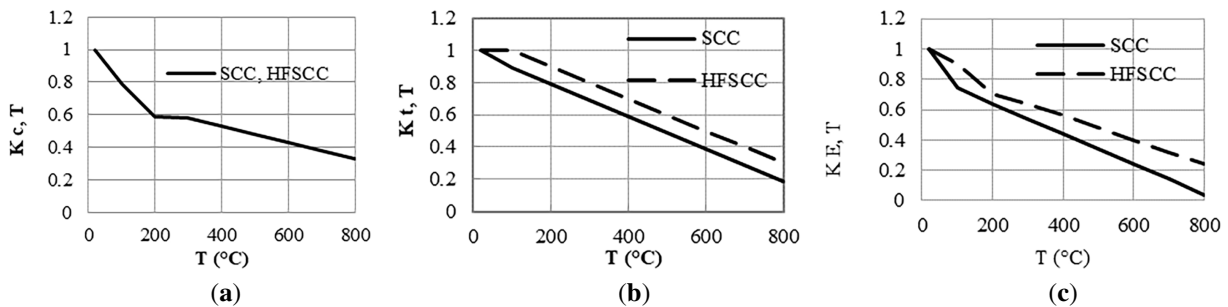


Figure 3: Reduction factors of concrete with temperature, (a) compressive strength, (b) tensile strength, and (c) elastic modulus, and boundary conditions of the studied beams.

Eq. (4) proposed by Aslani and Samali [40] is used to simulate the response of concrete under compressive stress at elevated temperatures.

$$\frac{\sigma_{c,T}}{f'_{c,T}} = \frac{\left(\frac{\varepsilon_{c,T}}{\varepsilon_{max}}\right)}{n - 1 + \left(\frac{\varepsilon_{c,T}}{\varepsilon_{max}}\right)^n} \quad (4)$$

$$\text{where } n = \left[1.02 - 1.17 \left(\frac{E_{sec}}{\varepsilon_{c,T}}\right)\right]^{(-0.74)} \quad \text{with } E_{sec} = \frac{f'_{c,T}}{\varepsilon_{max}}.$$

Where $\sigma_{c,T}$ is the concrete stress, $f'_{c,T}$ is the maximum compressive strength of concrete, n is the material parameter that depends on the shape of the stress–strain curve, $\varepsilon_{c,T}$ is the concrete strain, ε_{max} is the strain corresponding with the maximum stress, $f'_{c,T}$, $E_{c,T}$ is the modulus of elasticity, and E_{sec} is the secant modulus of elasticity.

According to the study of Hager and Mróz [30], the addition of 0.1% polypropylene (PP) fibres significantly reduces the extent of spalling; therefore, this VF was chosen for this study. Additionally, Yazıcı et al. [50] concluded that incorporating 1% to 1.5% steel fibres by VF in concrete markedly enhances its flexural strength. Consequently, in this study, a 1% steel fibre content was selected, and a 2% steel fibre content was additionally tested to evaluate their impact on SCC beams. The stress-strain curves according to Eqs. (1), (2) and (4), considering the reduction factors of the mechanical properties, are plotted and shown in Fig. 4.

The compressive stress–strain behavior of the concrete at elevated temperatures was implemented in ANSYS using the Multilinear Isotropic Hardening (MISO) model. The numerical implementation utilizes a peak-limit approach to ensure numerical stability during the non-linear solution process. In the material input, the constitutive relationship is defined by discrete data points following the non-linear hardening branch accurately up to the maximum compressive strength $f'_{c,T}$. To facilitate numerical convergence and prevent instability issues common in non-linear FEA of reinforced concrete structures, the descending (softening) part of the curve was omitted. The simulation is configured to terminate at the peak stress point, avoiding the “negative stiffness” errors that typically trigger premature divergence in the Newton-Raphson solver. This simplification is a recognized practice in numerical campaigns where the research focus is on the ultimate load-bearing capacity and peak structural response rather than the post-peak residual behavior. This approach is supported by established literature, which recommends utilizing the peak-limit formulation to achieve robust and reliable results in the assessment of the ultimate limit states of RC members under extreme loading conditions [48,51].

The total strain of steel at elevated temperatures includes two parts: the free thermal strain ε_{th} and the stress-induced strain ε_{σ} . both are defined in the present FE model according to EN 1994-1-2 [42].

2.3 Model Validation

To validate the numerical model developed in this study, two RC beams tested by Dwaikat and Kodur [21] (designated B1) and Hou et al. [52] (designated RPCL-1) were selected and simulated. The results predicted by the developed model were then compared with the corresponding experimental measurements. These beams were chosen for validation due to the availability of detailed information on their material properties, geometry, and test conditions, which facilitates accurate finite element modelling.

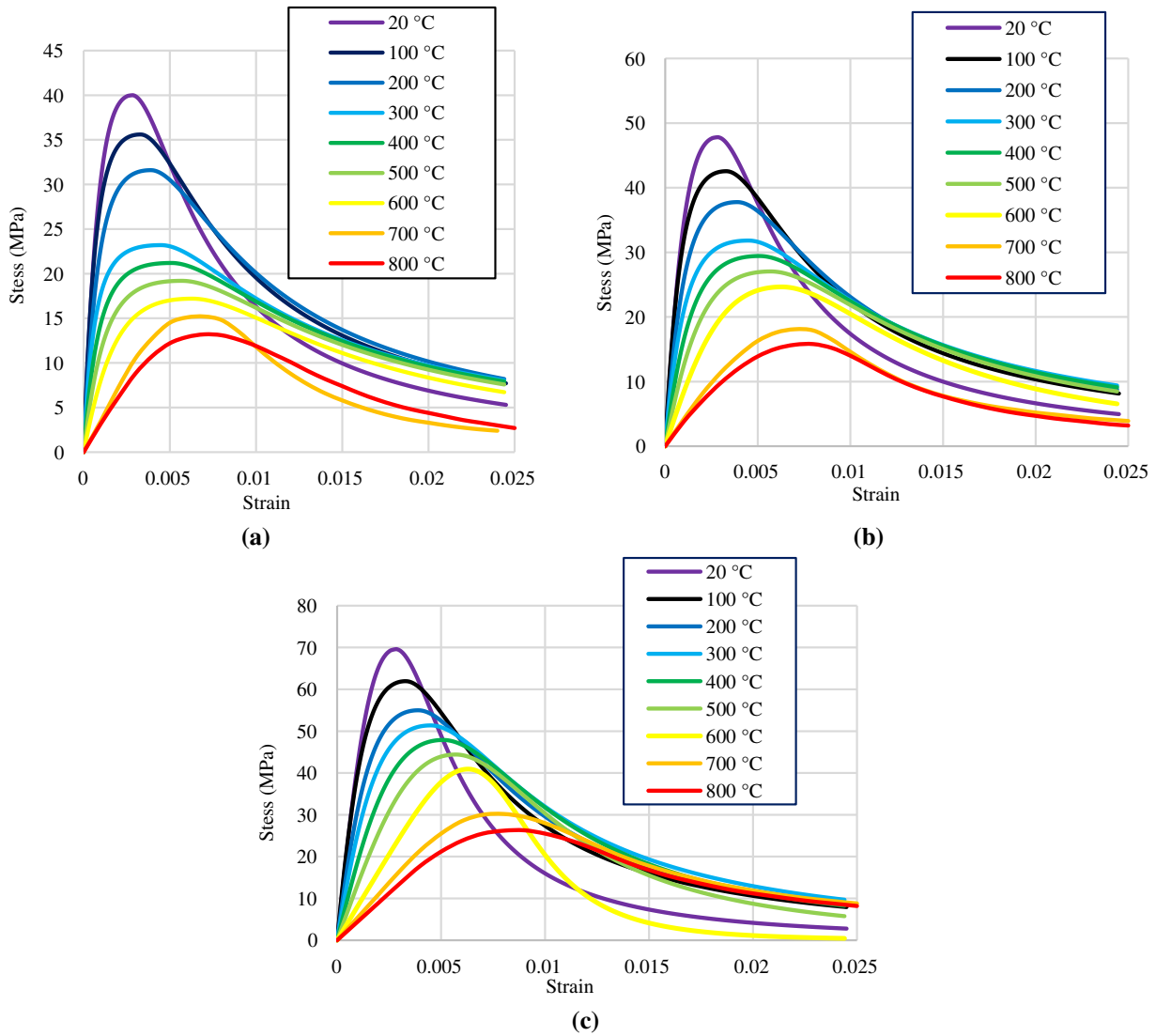


Figure 4: Stress-strain curves at different temperatures of (a) SCC, (b) HFSCC with 1% of VF of steel fibres, and (c) HFSCC with 2% of VF.

2.3.1 Test by Dwaikat and Kodur [21]

The beam designated B1, tested by Dwaikat and Kodur [21], was made of normal-strength concrete (NSC) with a compressive strength of 52.2 MPa. It had a cross-sectional dimension of 406 mm $\times$ 254 mm and a total length of 3969 mm. The beam was reinforced with three ϕ 19 mm bars as tensile reinforcement and two ϕ 13 mm bars as compression reinforcement, both having a specified yield strength of 420 MPa. Additionally, ϕ 6 mm stirrups with a spacing of 150 mm were provided along the beam length, with a specified yield strength of 280 MPa.

The fire resistance test was conducted by placing beam B1 in a furnace and applying a mechanical load corresponding to 55% of its load-carrying capacity. This load was maintained until no further increase in deformation was observed. After 30 min of loading, the beam was exposed to fire in accordance with the ASTM E119 standard fire [53], on three longitudinal sides, while the mechanical load remained constant throughout the fire exposure.

The comparison between the predicted and measured temperature evolution at different locations within the cross-section of B1 is illustrated in Fig. 5a. It can be observed that the model accurately predicts the temperature distribution, closely matching the experimental results. Fig. 5b presents the comparison between predicted and measured mid-span deflection under fire exposure for B1. The results indicate that the predicted deflections are in good agreement with the experimental measurements.

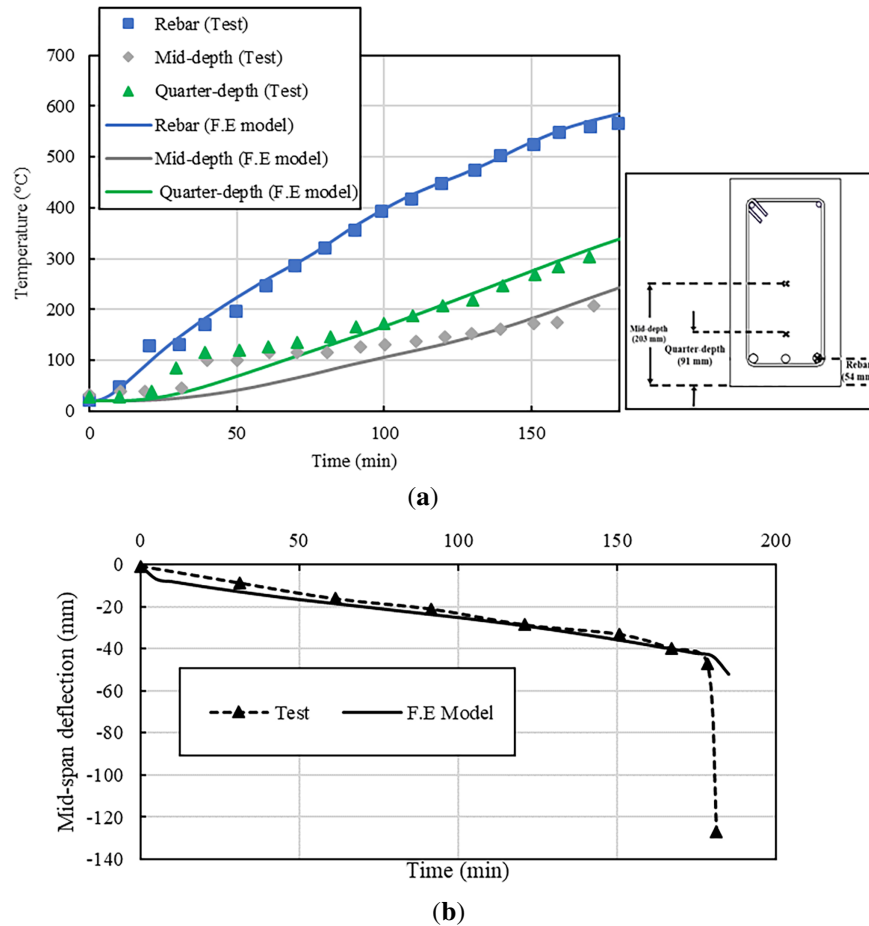


Figure 5: Comparison between predicted and measured test by Dwaikat and Kodur [21] results (a) thermal response and (b) structural response for B1.

2.3.2 Test by Hou et al. [52]

The beam designated RPCL-1, tested by Hou et al. [52], was made of reactive powder concrete (RPC) with a compressive strength of 127 MPa. The concrete contained 2% steel fibers and 0.2% polypropylene fibers by volume. The beam had a total length of 4900 mm and a span length of 4500 mm, with a cross-sectional dimension of 200 mm × 400 mm. It was reinforced with three $\phi 25$ mm bars as tensile reinforcement, having a yield strength of 463.3 MPa, and two $\phi 10$ mm bars as compression reinforcement. The shear reinforcement consisted of $\phi 8$ mm stirrups with a yield strength of 415.2 MPa.

The fire resistance test was conducted by subjecting the beam to combined structural loading and fire exposure. A static load corresponding to 30% of the load-carrying capacity was applied 30 min prior to fire exposure and maintained until the deformation stabilized. Subsequently, the beam was exposed to fire

on three longitudinal sides in accordance with the ISO 834 standard fire [54], while the mechanical load remained constant throughout the duration of the test.

Fig. 6a shows the comparison between the predicted and measured temperature evolution at different locations within the cross-section of RPCL-1. It can be observed that the predicted temperature distribution agrees reasonably well with the experimental results. Fig. 6b presents the comparison between the predicted and measured mid-span deflection under fire exposure. The results indicate that the predicted deflections are in good agreement with those measured during the fire tests.

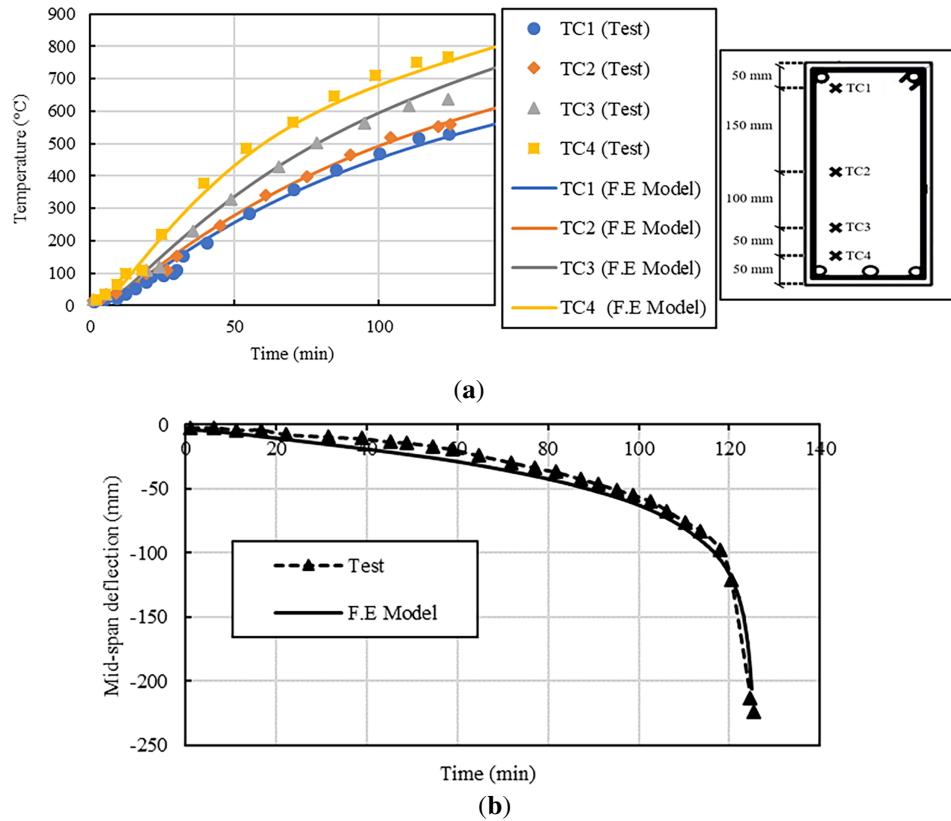


Figure 6: Comparison between FE model and Hou et al. [52] test results for (a) temperature evolution and (b) the mid-span deflection.

3 Results and Discussion

The following sub-sections present the numerical findings used to evaluate the mechanical performance of SCC and HFSCC beams exposed to elevated temperatures, with particular attention to their behaviour up to failure under load-bearing fire conditions

3.1 Load-Deflection Behaviour

The mechanical analysis of the beams was carried out at various high temperatures, and the load-deflection results are presented. Fig. 7 shows the evolution of the load as a function of the deflection of the studied beams at ambient and high temperatures of 400°C, 600°C, and 800°C. As illustrated in Fig. 7, the ultimate load capacity at room temperature (20°C) is 78 kN for B0, 92 kN for B1, and 102 kN for B2, and decreases with increasing temperature. The values of this capacity for B0, B1, and B2 are respectively 44, 58, and 76 kN at 400°C; 36, 49, and 66 kN at 600°C; and 27, 40, and 56 kN at 800°C. This is due to the

deterioration of strength and stiffness at high temperatures. The ultimate load capacity and deflection of HFSCC beams (B1 and B2) are greater than those of SCC beams without fibres (B0) at the same temperature. Hence, it can be said that adding fibres to SCC beams improves their ductility at room and high temperatures and allows a decrease in the rate of reduction of tensile strength and elastic modulus. These results are consistent with the findings of Antonius et al. [27], Jin et al. [34], Zitouni et al. [45], Khalighi et al. [55], and Lee et al. [56].

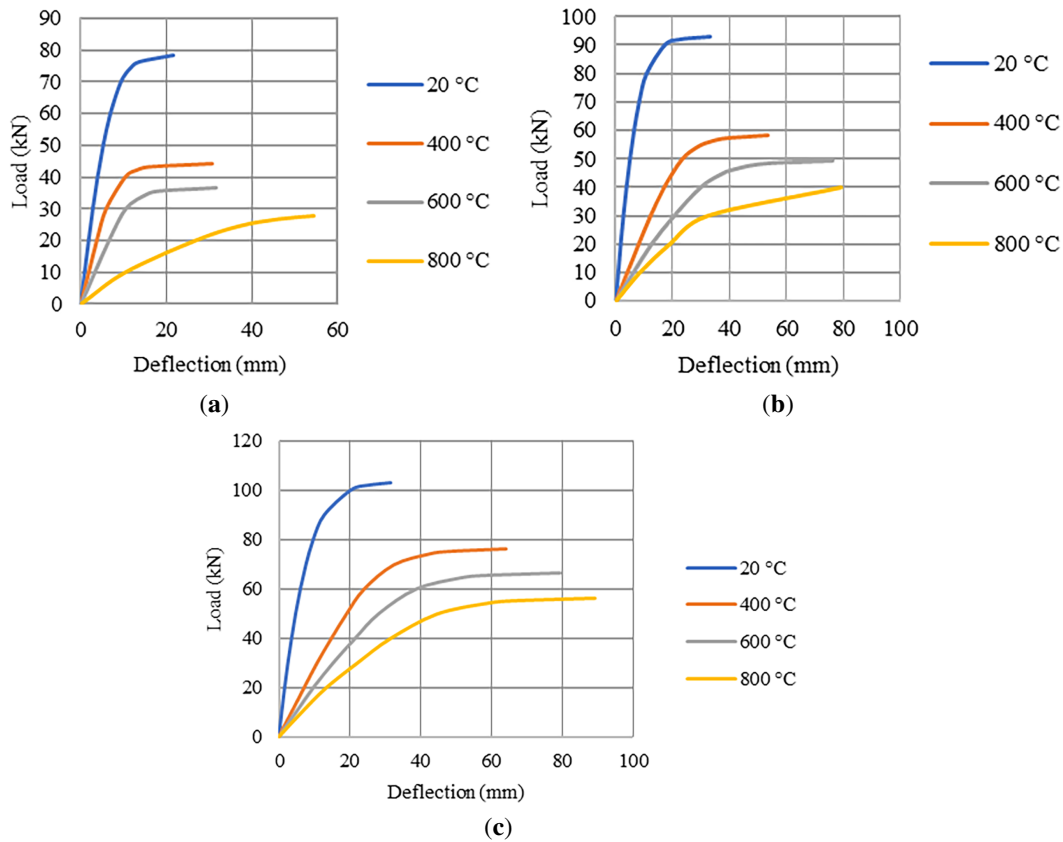


Figure 7: Load–deflection response of beams at different temperatures (a) B0, (b) B1, and (c) B2.

3.2 Reduction Rate of the Ultimate Load Capacity

To investigate the influence of incorporating hybrid fibres overall, with a specific focus on the impact of steel fibres in enhancing the behaviour of SCC beams, the reduction rates of ultimate load capacity of beams under different high temperatures are presented as bar graphs in Fig. 8. It can be noted that at an elevated temperature of 800 °C, the reduction rates of the ultimate load capacity reach 65%, 57%, and 45% for B0, B1, and B2 beams, respectively. This reduction rate for HFSCC beams is lower than for SCC beams, due to the combined effect of adding steel and hybrid polypropylene fibres to improve the ductility of the concrete. Additionally, it is interesting to note that the reduction rate for the HFSCC beam with a volume fraction (VF) of 2% steel fibres is lower than that of the beam with 1%. This is attributed to the effect of steel fibres significantly enhancing the tensile strength of the concrete, which is evident at various temperature levels. These results align with the findings of studies conducted by Ali Abdelrahim et al. [57], Abdulhaleem et al. [58], and Bezerra et al. [59].

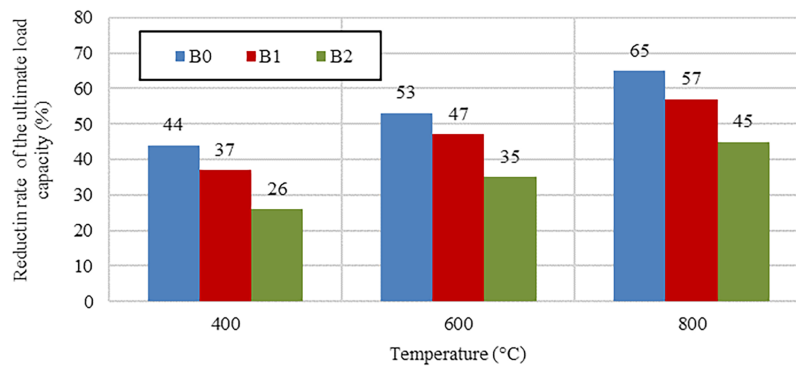


Figure 8: Reduction rate of the ultimate load capacity of the studied beams at different temperatures.

4 Conclusion

The numerical study conducted involved the development of finite element (FE) models to explore the impact of incorporating hybrid fibres into self-Compacting Concrete (SCC) beams. These hybrid fibres consisted of 0.1% polypropylene and 1% or 2% steel fibres, aimed at assessing the mechanical response of SCC beams under elevated temperatures caused by fire. Previous validated FE models were used to assess the ultimate load capacity of both SCC and hybrid fibre reinforced self-compacting concrete (HFSCC) beams across a range of temperatures. The key findings from the analysis are as follows:

- The addition of hybrid fibres significantly enhances the ultimate load capacity of SCC beams at different temperature levels (20°C, 400°C, 600°C, and 800°C), leading to increased deflection and ductility. At room temperature, incorporating 0.1% polypropylene fibres and 1% steel fibres boosts the ultimate load capacity from 78 to 92 kN in SCC beams.
- Increasing the volume fraction (VF) of steel fibres from 1% to 2% results in an ultimate load capacity of 102 kN. Similarly, at 800°C, introducing 0.1% polypropylene fibres and 1% steel fibres enhances the ultimate load capacity from 27 to 40 kN, with a further increase to 56 kN by raising the VF of steel fibres to 2%.
- The inclusion of hybrid fibres in SCC beams proves effective in mitigating the reduction rate in ultimate load capacity when subjected to high temperatures (400°C, 600°C, and 800°C). For example, at 800°C, utilizing 0.1% polypropylene fibres and 1% steel fibres reduces the reduction rate in ultimate load capacity from 65% to 57%, with a further decrease to 45% by increasing the VF of steel fibres from 1% to 2%.

The results of this study highlight the effectiveness of incorporating hybrid fibres in improving the structural performance of SCC beams under fire conditions. The findings provide useful insights into the role of steel and polypropylene fibres in enhancing load-bearing capacity and reducing performance degradation at elevated temperatures. Therefore, this study contributes to a better understanding of the fire behaviour of HFSCC structural elements and can support the development of more reliable design approaches for fire-resistant concrete structures.

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Author Contributions: The authors confirm contribution to the paper as follows: Conceptualization and study design: Belkacem Lamri, Abdelhak Kada; methodology: Mohamed Zitouni; software: Mohamed Zitouni, Belkacem Lamri, Mário Rui Arruda; validation: Mohamed Zitouni, Belkacem Lamri, Mário Rui Arruda; formal analysis: Mohamed Zitouni; investigation: Mohamed Zitouni, Belkacem Lamri, Abdelhak Kada, Mário Rui Arruda; writing—original draft preparation: Mohamed Zitouni; writing—review and editing: Mohamed Zitouni, Mário Rui Arruda, Belkacem Lamri, Abdelhak Kada; visualization: Mohamed Zitouni, Mário Rui Arruda; supervision: Belkacem Lamri, Abdelhak Kada, Mário Rui Arruda. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Not applicable.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Dedicated to: This work is dedicated to the memory of our esteemed co-author, Professor Lamri Belkacem, whose passing has deeply saddened us. He made remarkable contributions to civil engineering, with a focus on structural fire engineering and the thermomechanical behaviour of structures under extreme conditions. His expertise, dedication, and passion for research profoundly influenced this study and inspired all who had the privilege of working with him. His guidance and legacy will continue to inspire future advancements in fire-resistant structures.

Abbreviations

HFSCC	Hybrid fibre-reinforced self-compacting concrete
MISO	Multilinear isotropic hardening
NSC	Normal-strength concrete
PP	Polypropylene
RPC	Reactive powder concrete
SCC	Self-compacting concrete
TCF	Tensile crack factor
VF	Volume fraction

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