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ORIGINAL PAPER

Numerical simulation of ultra-high-performance fiber-reinforced concrete frame structure under fire action

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Abstract

The research activity in progress and the advancements in concrete technology are leading to an increased use of ultra-high-performance fiber-reinforced concrete (UHPFRC) in structural engineering. UHPFRC is characterized by steel fibers, cement, silica fume, fine sand, superplasticizer, and very low water–cement ratio. UHPFRC is defined as a new material, with unique properties (high ductility, low permeability, very high strength capacity in compression, higher toughness) in comparison with conventional concrete (Buttignol et al, Revista IBRACON de Estruturas e Materiais 10(4):957–971, 2017). This makes it possible to make slender constructions because a smaller cross section can transfer the same force as a larger cross section. However, in case of fire safety design a disadvantageous behavior of UHPC compared to normal-strength concrete is well known and documented. The high packing density of the cement matrix is the main reason for explosive spalling behavior when exposed to fire. In this paper, the numerical simulation using finite-element method has been used to evaluate the behavior of UHPFRC frame structure under fire action. According to results, the three-dimensional finite-element model can be used for calculating the mechanical localized of UHPFRC concrete frame structures subjected to nominal fire curves. The results of numerical analysis under fire action are also compared to the other materials for more understanding the fire resistance between UHPFRC material (with PP fiber, without PP fiber) and high-strength concrete.

Keywords Ultra-high-performance fiber-reinforced concrete (UHPFRC) · ISO 834 · Fire resistance · Polypropylene fiber (PP)

Introduction

Fire resistance of building elements is an important consideration in building design. Fire in buildings has the potential to cause substantial loss of serviceability that may lead to structural collapse. Ever since its earliest applications, reinforced concrete has been used as the main construction material worldwide. Being a non-combustible material, concrete performs exceptionally well in the event of fire by preventing the spread of fire to other compartments (Kahanji et al. 2016).

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a relatively new class of concretes which has been developed in the past several decades. UHPFRC have exceptional mechanical properties in comparison with normal-strength concrete (NSC) and high-strength concrete (HSC). Among them, highly enhanced strength, energy absorption capacity, unique strain hardening behavior with multiple micro-cracks, improving ductility and highly corrosion resistance are the basic characteristics of UHPFRC (Shin et al. 2018; Yoo and Banthia 2016). To achieve these characteristics, UHPFRC typically has low water-binder ratio and adequate packing of particles (both fine and coarse) to achieve a dense microstructure, which is crucial toward mechanical and durability properties (Arora et al. 2018; Hoang et al. 2016). Owing to the tiny particles of materials used in casting UHPFRC, the resulting solid material is of lower porosity with virtually no pores leading to the surface.

Despite the positive characteristics of these structures, they are still susceptible to fire. Fire exposure induces temperatures of up to 1000 °C, which could be detrimental to the structural integrity of UHPFRC. Water stored in the fine pores of the dense matrix evaporates under temperature

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extremities, and pressure builds up internally. When stresses cannot be withstood, explosion of concrete follows, a phenomenon known as spalling (Nazri et al. 2016).

A great deal of work has been done on the normal concrete and high-strength concrete under fire action (Ko et al. 2011; Sangluaia et al. 2018). However, due to relatively new nature of UHPFRC under fire action, the amount of research done is limited. The addition of 0.6% by mixture volume of PP fibers improved the fire-resistant properties (prevented spalling) of UHPC since melting of the PP fibers at high temperature creates space to release the buildup of pressure (Heinz and Ludwig 2004). However, 0.3–0.5-mm cracks were observed at the specimen's surface, and UHPC with 0.6% PP fibers by volume mixture achieved weight loss of less than 9% at 1000 °C. Quasi-static compression tests were conducted by Xiangwei Liang after the UHPFRC was first exposed to a high temperature, i.e., 200, 400, 600, 800 or 1000 °C and then cooled down to room temperature (Liang et al. 2019). Based on the tests on this UHPFRC, mechanical and physical characteristics under the combined effect were studied. Piotr Smarzewski carried out the flexural toughness test plain ultra-high-performance concrete (UHPC) and UHPC with different types of fibers (steel fiber and polypropylene PP fibers) exposed to elevated temperatures of 400, 600 and 800 °C. The observation results showed that the thermal damage of fiber-reinforced UHPC depends on the pore pressure effect and significant decrease in the load–deflection response, and toughness were observed for the polypropylene fiber-reinforced UHPC when temperature approached 800 °C (Smarzewski 2019). Ming-Xiang Xiong and J.Y. Richard Liew discovered the effective way to prevent spalling for the ultra-high-performance concrete and gauge its mechanical properties after it was subjected to fire. Test results showed that the compressive strength and elastic modulus of the ultra-high-performance concrete declined slowly than those of normal-strength concrete after elevated temperatures (Xiong and Richard Liew 2015). Ultra-high-performance fiber-reinforced cementitious composites (UHPFRCC) containing high-alumina cement (HAC) and ground granulated blast furnace slag (GGBS) in conjunction with hybrid fibers—a prospective fire-resistant UHPFRCC for structural members, were heated to 400, 700 and 1000 °C by Anwar Q. Sobia Mohd et al. Results showed that the use of hybrid fibers significantly improved the room-temperature mechanical strengths of UHPFRCC (Sobia et al. 2015).

Accurate modeling and simulation of UHPFRC structure subjected to fire action is a method for decreasing the big challenge involving costly experimental characterization of material properties. Additional investigations are needed to increase the knowledge on the effects of high temperatures on the performance of ultra-high-performance fiber-reinforced concrete. This paper contributes to the development of UHPFRC and its application in the field of fire resistance. The 3D UHPFRC frame structure with and without PP fiber is modeled under fire action in accordance standard ISO 834 fire curve. Thermal and structural responses were calculated using ABAQUS software. Parametric analyses are conducted for the fire scenario, and the output results are compared to high-strength concrete frame structure to determine the different behavior between high-strength concrete structure and UHPFRC with PP fiber and without PP fiber under fire action.

Material and method

Objective of the research

In this paper, a numerical model implemented to predict the structural behavior of 3D frame structure under fire action with other materials: UHPFRC with PP fiber, UHPFRC without PP fiber and high-strength concrete. Structural analysis is carried out in two steps. In the first step, mechanical load is applied. In the second step, the deformed structure with initial pre-stress condition resulting from mechanical actions is exposed to fire in 2 h. The main objective of the analysis is to assess the fire resistance of 3D frame structure, and based on the calculation model, the temperature propagation of elements in frame structure can be determined. Structural displacement, internal force and stresses in frame structural are also evaluated for more understanding the response of UHPFRC frame structure under fire action.

A three-story two-bay frame structure is subjected to standard ISO 834 fire. The thickness of floor is 15 cm under the uniform load of 2.4 kN/m^2. The fire sector is assumed to cover the entire second floor area. Beam and column cross sections are shown in Fig. 1a. The fire scenario is displayed in Fig. 1b.

Table 1 shows the composition of selected mixes. Figure 2 shows the ISO-834 standard fire curve and thermal conductivity of the materials. Other parameters such as density, Young's modulus, Poision's ratio, thermal expansion coefficient can refer to Fehling et al. (2014) and Kodur and Khaliq (2011).

Finite-element method in heat transfer analysis

Modeling assumptions

1. Fire spalling of used material was not considered in this research. The addition of 0.6% by mixture volume of PP fibers improved the fire-resistant properties (prevented spalling) of UHPFRC (Heinz and Ludwig 2004).
2. Perfect interaction (embedded interaction) between steel reinforcement and concrete is assumed, resulting in a node of an embedded element that lies within a host

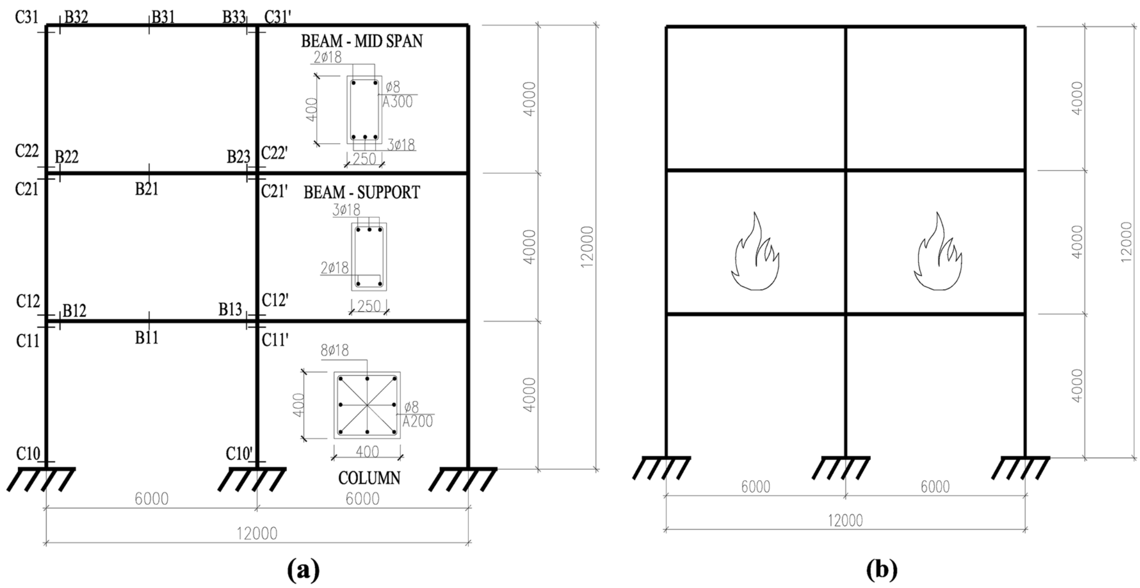


Fig. 1 Beam and column cross section (**a**) and fire scenario (**b**)

Table 1 Composition of selected UHPFRC and HSC material

Composition of selected mixes	Material	
	UHPFRC	HSC
Cement (kg/m^3)	775	560
Water (kg/m^3)	183	140
Silica fume (kg/m^3)	164	42
Super plasticizer dosage, % by mass	1.1	0.24
Quartz powder/fine aggregate (kg/m^3)	193	630
Quartz sand/course aggregate (kg/m^3)	946	1090
Microwire fibers, % by vol.	2.5	–
PP fiber (kg/m^3)	0.75	–

element, the translational degrees of freedom and pore pressure degree of freedom at the node are eliminated and the node becomes an embedded node (Dassault Systèmes Simulia Corp 2016).

Discretization and thermal model

The model was calculated in ABAQUS software using coupled temperature displacement analysis procedure, which requires two models with a same geometry to be developed: the first to be used in transient thermal analysis, to evaluate the thermal response of the structure, and the second to

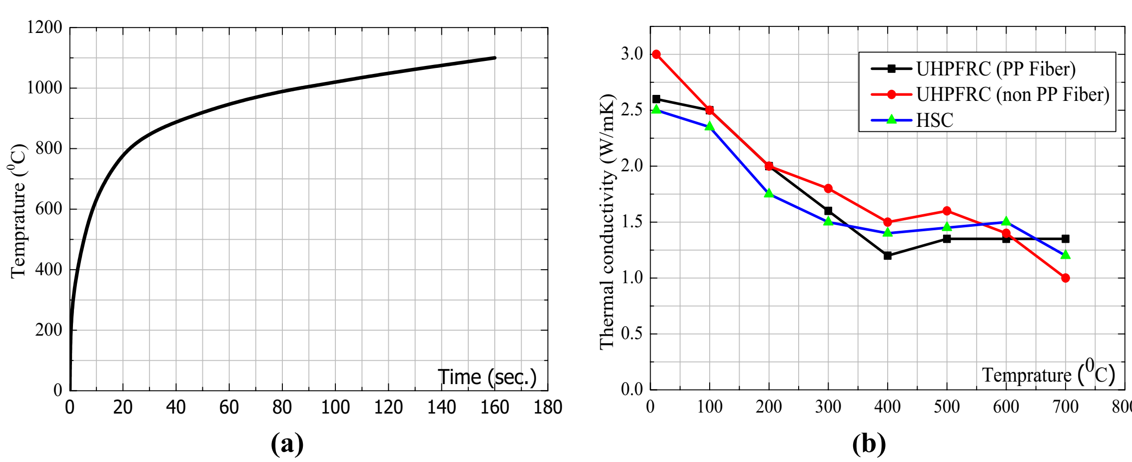


Fig. 2 The ISO-834 standard fire curve (**a**) and thermal conductivity of the material (**b**)

be used in a transient structural analysis, where mechanical and thermal loads are used to obtain the physical response of the structure.

In structural analysis, three-dimensional eight-node reduced integration (C3D8R) element type was adopted for column, beam and slab elements. C3D8R element has eight nodes with three degrees of freedom, namely three translations in x, y, and z directions. This element can be used for 3D modeling of solids with or without reinforcement, and it is capable of accounting for cracking of concrete in tension, crushing of concrete in compression, creep and large strains (Dassault Systèmes Simulia Corp 2016). The reinforcements in frame were meshed with the 2-node 3-D thermally coupled truss (T3D2T). T3D2 elements are used to model one-dimensional reinforcing bars or rods that are assumed to deform by axial stretching only. They are pin jointed at their nodes. Only translational displacements and the initial position vector at each node are used in the discretization. When the strains are large, the formulation is simplified by assuming that the trusses to be made of incompressible material. This approach has been used effectively to model reinforcement explicitly wherein nodes of reinforcement are coincident with corresponding nodes of concrete (Dassault Systèmes Simulia Corp 2016).

For the thermal model in 3D model, UHPC, concrete and reinforcement are discretized using DC3D8 element (8 noded linear, available in ABAQUS library), having nodal temperature (NT11) as the only active degree of freedom. The external surface areas of DC3D8 elements, which are exposed to fire, are used to simulate the surface effect of convection and radiation that occur from fire (ambient air) to the beam. According to EN 1991-1-2 (2002), the convective heat transfer coefficient is taken to be 25 W/m^2 C on fire-exposed surface. For the un-exposed surfaces, a convective coefficient of 9 W/m^2 C is used to account for the effects of heat transfer through radiation.

Due to heat transfer is dominant throughout the cross section and is practically constant along the element, to avoid using large time-steps or the appearance of space oscillations of the solution, in case of thermal shock (Bergheau and Fortunier 2010), mesh element size is adopted as 5 cm. This appropriate mesh density not only produces the proper results, but also reduces the number of elements and analysis time. Finite-element mesh model for the elements of the frame structure is presented in Fig. 3.

Results and discussion

Thermal response of the frame structure

Figures 4 and 5 show the temperature propagation of column in frame structure with other materials, where the cross section of column with three side exposed to fire and the cross section of corner column with two sides exposed to fire after 2 h, respectively.

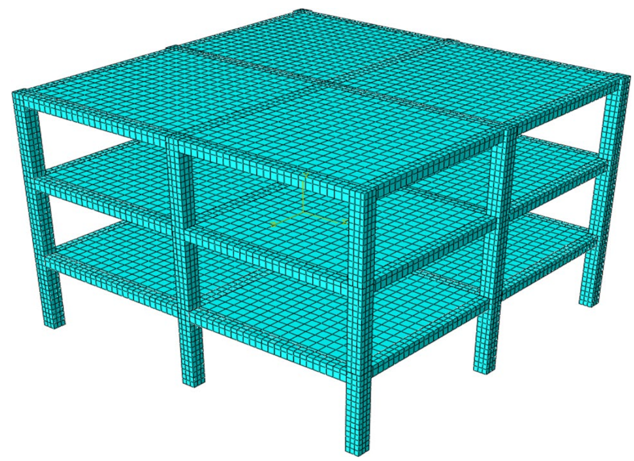


Fig. 3 3D finite-element mesh model of frame structure

Figure 6 presents the temperature propagation of beam element B21 in frame structure with other materials, where beam separates fire sector from the rest of the structure after 2 h.

As shown in Figs. 4, 5 and 6, after 2 h, there is a slight disparity in the thermal propagation in beam and column elements of UHPFRC with PP fibers and HSC material (characterized by the red area corresponding to the temperature of 1050 °C). However, there is a big difference in thermal propagation between UHPFRC with the PP fibers and UHPFRC without PP fibers. This can be explained by the fact that thermal conductivity of UHPFRC with the PP fibers is relatively low compared to UHPFRC without PP fibers, providing the better thermal insulation.

Structural displacement

Vertical displacement at mid-span of beam (B21 cross section) exposed to fire is presented in Fig. 7a. The maximum vertical displacement of UHPFRC beam with PP fiber is smaller than high-strength concrete beam. In contrast, the UHPFRC beam without PP fiber showed the maximum displacement of 31 mm. This value is 10.7% and 17.8% higher than UHPFRC with PP fiber and HSC beam, respectively. During the first 30 min (1800 s) after exposed to fire, there was no significant difference in vertical displacement with different material cases. However, after a period of 30 min, the vertical displacement of UHPFRC beam without PP fiber increased faster than other two cases.

Vertical displacement at the top of fire-exposed C21 columns is presented in Fig. 7b. The vertical displacement of HSC column is higher than UHPFRC with PP fiber column.

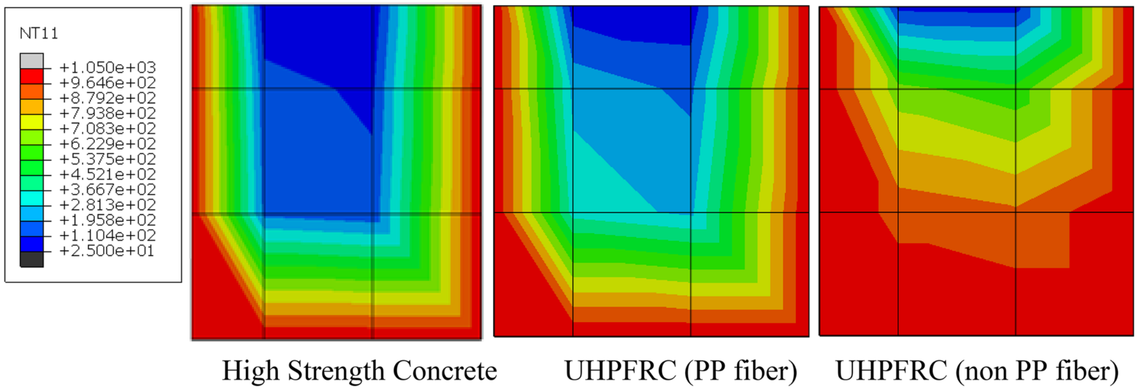


Fig. 4 Temperature propagation of column with three sides exposed to fire

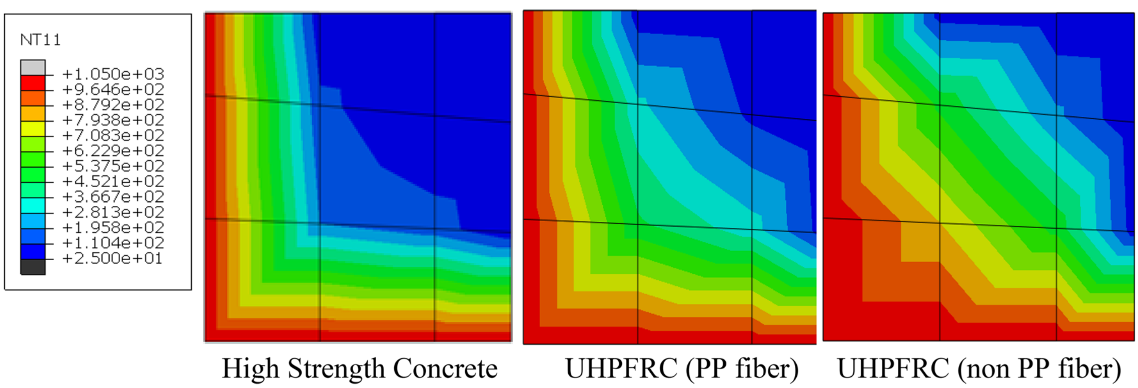


Fig. 5 Temperature propagation of corner column with two sides exposed to fire

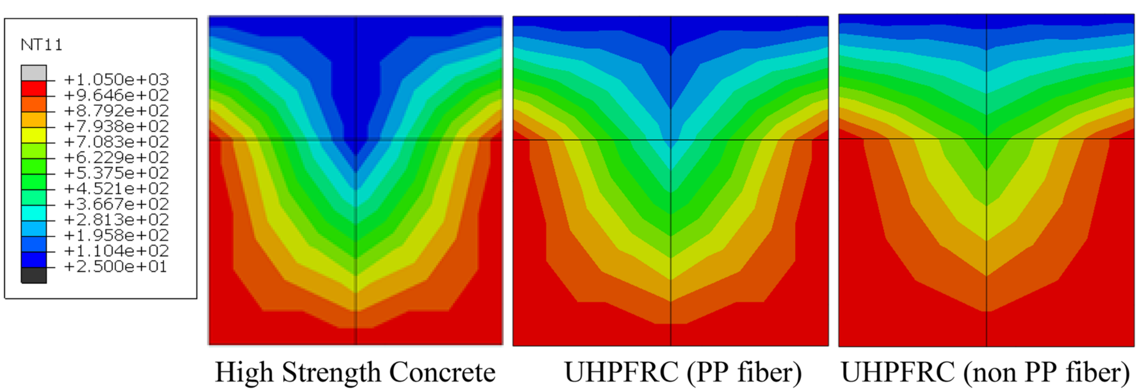


Fig. 6 Temperature propagation of beam (B21)

The UHPFRC without PP fiber column showed the maximum displacement of 25.1 mm after 90 min. This vertical displacement value is higher than UHPFRC with PP fiber column and HSC column 15.2% and 24.2%, respectively. Basically, at the first step of 30 min (1800 s) after exposed to fire, column with different material cases showed the same displacement. However, after 30 min, displacement of UHPFRC without PP fiber increased faster than the other two cases. Furthermore, after about 90 min, displacement of column tended to move downwards. This phenomenon related to the thermal expansion. After exposing to fire, due to thermal expansion, the columns extend upwards. But after about 90 min, since the strength and stiffness of column are reduced with higher temperatures, vertical thermal

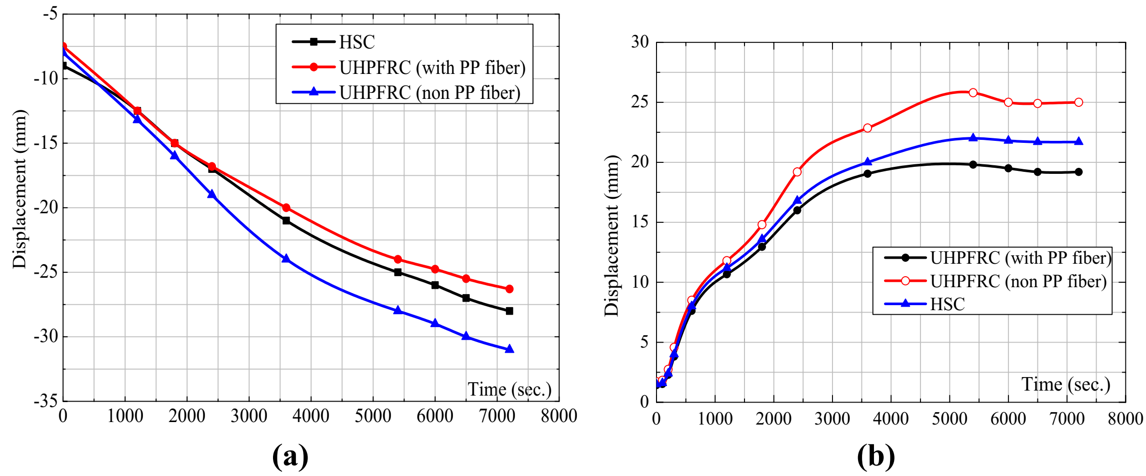


Fig. 7 Vertical displacement of beam B21 (**a**) and column C21 (**b**)

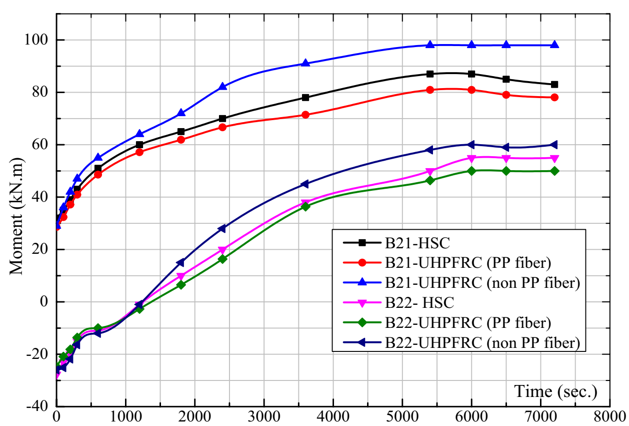


Fig. 8 Bending moment of beam elements (B21 and B22 cross section)

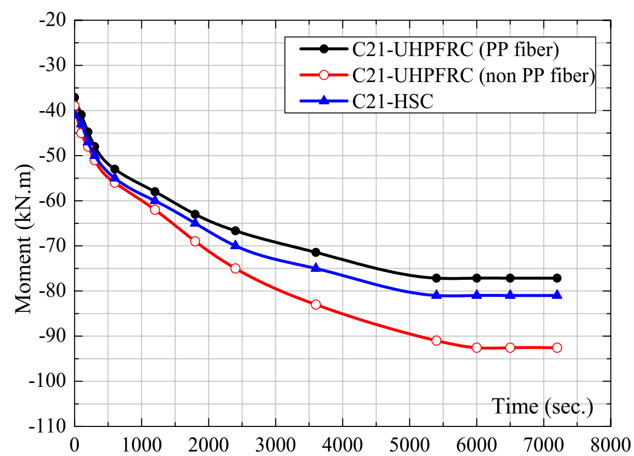


Fig. 9 Bending moment of column (C21 cross section)

expansion becomes smaller than the deformation from the applied external load. It resulted in the vertical displacement moving downwards.

Bending moment

Bending moment in beam elements (B21 and B22 cross section) exposed to fire are presented in Fig. 8. One see that maximum positive bending moment at the mid-span of UHPFRC without PP fiber is 98.8 kN m with B21 cross section and 60 kN m with B22 cross section. Maximum bending moment at these sections after 90 min of fire exposure and reached 3.4 times and 4 times higher values than before the fire. Both of B21 and B22 cross sections, during the time exposed to fire, beam of UHPFRC with PP fiber material showed lower bending moment than HS material. In contrast, beam of UHPFRC without PP fiber material showed the largest displacement compared to the rest. Since thermal expansion of the heated parts is partially restrained, compression is rising in concrete areas exposed to thermal action, resulting in shifting of bending moment diagrams in the direction of heat transfer. Negative bending moments of B22 cross section became all positive at 90 min of fire exposure. This is very meaningful in structural design under fire action because of shifting of negative bending moment might potentially lead to an early failure if the cross section bending capacity is exceeded.

Bending moment at the C21 cross section of column is presented in Fig. 9. During the first 30 min (1800 s) after exposed to fire, there was no significant disparity in moment with different materials. However, after the period of 30 min, bending moment of UHPFRC without PP fiber column increased faster than the rest. Absolute maximum bending moment of UHPFRC without PP fiber is 92.5 kN m after 90 min of fire exposure. This value is higher 3 times than before the fire. Similar to the case of bending moment in beam, bending moment of UHPFRC with PP fiber material in column is smaller than the other two materials.

Stress of steel reinforcement at B21 cross section beam is presented in Figs. 10 and 11. Stress in the steel reinforcement with the case of UHPFRC without PP fiber reached the maximum value of 415 MPa after 90 min (5400 s). After 90 min of exposure to fire, the temperature in reinforcement reached over 400 degrees. Load-bearing capacity of steel reinforcement begins to decrease and plastic strains started to develop. In contrast, the stress in steel reinforcement of UHPFRC beam with PP fiber is smaller than the other two cases. This proved that UHPFRC with PP fiber material is better at thermal insulation compared to UHPFRC without PP fiber and HSC material.

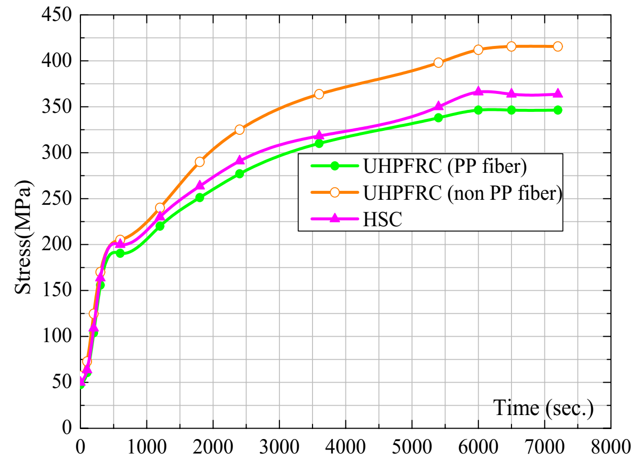


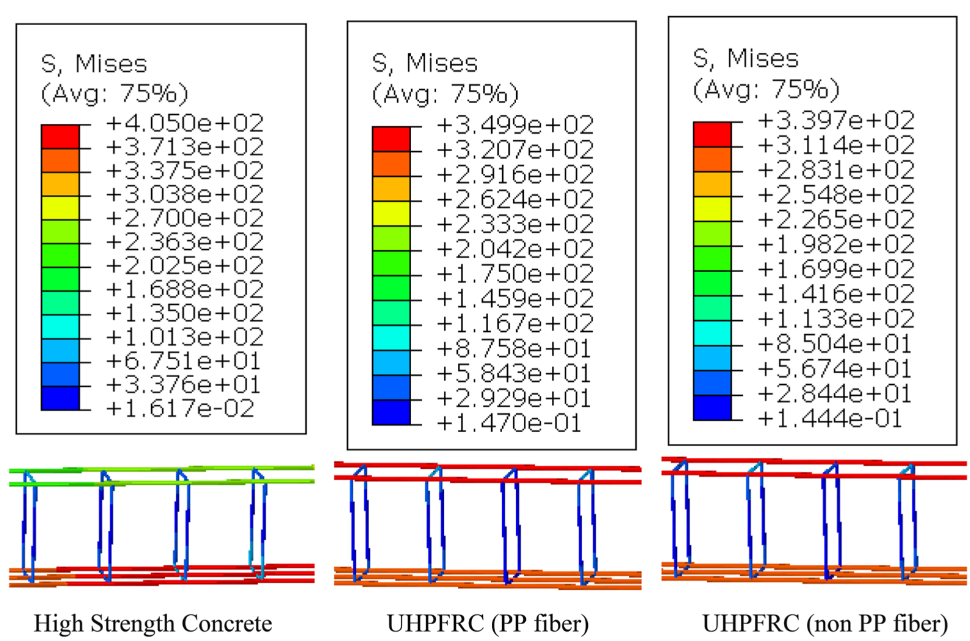
Fig. 11 Stress of steel reinforcement in beam (B21 cross section)

Conclusions

This research presented the numerical simulation of the 3D frame structure subjected to standard ISO 834 fire with three different material cases: UHPFRC with PP fiber, UHPFRC without PP fiber and high-strength concrete. From the results addressed in this research, the following conclusions are drawn:

1. At the first step of 30 min (1800 s) after exposure to fire, in terms of thermal propagation, displacement and internal force, there is a small disparity of beam and column elements in frame structure with different materials. However, after 30 min, these values of UHPFRC without PP fiber elements increased faster than the other two cases. UHPFRC elements without PP fiber showed the higher of thermal propagation, maximum displacement and internal force compared to the rest. This proved the low fire resistance of UHPFRC without PP fiber. On the contrary, UHPFRC material with PP fiber proved better fire resistant than other two materials in lower displacement, internal force and stresses in reinforcement. Clearly, the addition of PP fiber contents of 0.75 kg/m^3 provided a significant effect in the fire resistance design. This result is similar to the experiments that Smarzewski carried with UHPFRC material.
2. Negative bending moment of beam sections exposed to fire shifted during fire in the direction of heat transfer. This phenomenon resulted in reducing the cross section

Fig. 10 Stress of steel reinforcement in beam (B21 cross section) at moment of 5400 s (MPa)



moment capacity these elements. This should be carefully considered in the design of the structure under fire action.

3. After 90 min of fire exposure, deformation and bending moment of the elements in the frame structure increased significantly. This proved that fire considerably affected the loading capacity of the frame structure.
4. Although considered to be a flammable material as mentioned above, when adding the PP fiber content 0.75 kG/m^3 to the material matrix, fire resistance of UHPFRC with PP fiber material is not inferior to conventional concrete material.
5. ABAQUS software can be successfully utilized to simulate the response of frame under fire action, taking into account nonlinear thermal and mechanical temperature-dependent properties of other materials.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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