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Experimental and numerical study on post-fire behaviour of concentrically loaded reinforced reactive powder concrete columns

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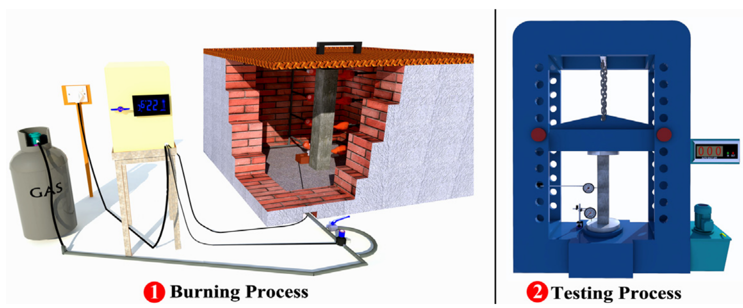
HIGHLIGHTS

- The behavior of RPC columns after exposure to fire at different sides are analyzed.
- The various parameters that influence the post-fire behavior are evaluated.
- Increasing concrete cover and introducing lateral ties are ineffective.
- The effect of fire exposure at 2 adjacent sides is more severe than 2 opposite sides.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an experimental and numerical work on the behaviour of concentrically loaded reinforced reactive powder concrete (RPC) columns after exposure to fire. The first part is an experimental work to ensure that the model developed is adequate while the second part is a three-dimensional finite element (FE) modelling of the RPC columns with the program ABAQUS using a sequentially coupled thermal displacement analysis. Fire-induced spalling is also presented based on pore pressure calculations in concrete. The test results indicated that RPC columns lost about (39–45%) of their bearing capacity after fire exposure at 600 °C and with 1 h fire duration. Increasing concrete cover and introducing lateral ties are shown to barely improve the post-fire behaviour of RPC columns. Moreover, the reduction in the residual bearing capacity increased significantly with increasing the number of sides of the exposure and fire duration.

1. Introduction

With growing of structural design requirements for higher strength materials in applications where member size is governing factor in design especially in construction of columns in high-rise buildings [1–5], reactive powder concrete (RPC) as a king of ultra-high performance concrete is catching more attention recently [2,6,7].

Nowadays, many fire accidents have been reported worldwide, and with the increase of utilization of new trends of concrete (recently RPC) in construction of the load-bearing members for high-rise buildings consisting of beams and columns, the fire safety design of these buildings has become essential. The reason for this is because, when other means to extinguish the fire fail, the fire resistance of these members for adequate time is the last line of defence [8]. Moreover, it is important to design safe buildings with a minimum level of risk to both people and property as possible [9,10]. However, previous research focused only on the performance of concrete columns during fire while it is very important to understand the performance of these columns after the cooling

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Nomenclature

Δ_u	ultimate axial displacement (mm)
ϵ	emissivity
ρ_L	density of liquid water
$\varepsilon^{\cdot}$	strain rate
$C.C$	concrete cover thickness (mm)
Cw	crack opening (mm)
$f'c$	concrete compressive strength (MPa)
$f_{(tf,d)}$	dynamic tensile strength (MPa)
$f_{(tf,s)}$	static tensile strength (MPa)
fy	yield stress of steel (MPa)
h	heat transfer coefficient
k	thermal conductivity
k_T	permeability of concrete at temperature T
M	molar mass of water
m_D	mass of liquid water due to dehydration
m_L	mass of liquid water
m_v	dynamic viscosity of water vapour
p_u	ultimate failure load (Kn)
pc	heat capacity
Q	heat source
q	heat flux
R	gas constant
T	temperature (°C)
t	time (min.)
v_v	volume of water vapour
$Vf\%$	volume fraction of fibres

phase because most concrete structures exposed to fire conditions did not collapse and can be reused by applying suitable repair methods [11]. However, the decision whether it is more economical to retrofit the fire exposed structures or it must be demolished and reconstructed is a challenging task. This decision requires a full understanding of the behaviour of these structures after being exposed to fire in order to decide whether the residual load bearing capacity for the load-bearing members is still adequate. Upon cooling from fire exposure, previous research has shown that steel reinforcements usually recover a majority of its material properties [12,13] whilst concrete continues to lose its strength after the fire. Such reductions in strength are attributed to the occurrence of a series of irreversible chemical and physical changes in cement paste and aggregate [12]. Moreover due to the low thermal conductivity and low thermal diffusivity, concrete acts like a heat sink [14]. In the cooling phase, even though the temperature is decreasing, the interior of the concrete member could still be increasing in temperature. Khoury [15] reported that spalling of concrete cover continues to take place even after cooling down or during extinguishing which assumed to be due to the developing of the thermal gradient between the inner and outer of the column.

Previous research reported that columns made of normal strength concrete (NSC) could provide the required fire resistance and it can be successfully repaired and reused [16–18]. However, RPC columns may not endure the fire with the same level of performance compared with NSC columns. Furthermore, RPC will be more vulnerable to fire-induced spalling due to its low permeability which causes a rapid loss of concrete cover during the fire [3,4,19,17,20], thereby increasing the fire temperatures in the inner layers of the column [21].

The positive effect of increasing the transverse reinforcement amount (reducing tie spacing) on improving the ultimate load of concrete columns at normal temperature has recently been the subject of many studies [2,14,22–27]. These researchers reported that by reducing the lateral tie spacing, there is a tangible increase in the ultimate load of these columns. The positive influence of reducing the tie spacing on the ultimate load at ambient temperature raises a question whether a similar impact would be noticed during the post-fire behaviour.

Another important factor affecting the fire behaviour of the concrete columns is the minimum thickness of concrete cover to the reinforcement [28]. Previous researchers reported that for most of the fire-damaged concrete structures, the main reason for the collapse is caused by the failure of the steel reinforcement [29,30]. The reason is because the position of the reinforcement is usually located near the surface of the concrete member. Therefore, the steel reinforcement is deteriorated firstly due to its higher rate of heat transfer in comparison to the concrete [30].

Formerly, the most common technique of satisfying the necessities of the fire safety of concrete structures was depended mainly on the minimum values of the column dimensions and concrete cover, which is derived from a regression of the test data [31]. These tests were carried out on concrete columns exposed to fire from four sides, as being the most critical situation. In real fire events, concrete columns may expose to fire from different sides depending on the architecture and structural layout of the building [32,33]. For example, a wall could work as a barrier to column exposing only one, two or three faces of the column to fire. On the other hand, a column could be located in the middle of a room thereby exposing all four sides of the column to fire.

The uncertainties in using tabulated values for fire design have raised the urgent requirement for better fire design method. Recently, a performance-based approach has been developed and used instead of depending only on the tabulated values. This approach provides flexible design and reduces the cost required [34–38]. This approach has encouraged the evolution of numerical simulation models with higher accuracy [39–41]. Many finite element models (FEM) have been developed to simulate the behaviour of the concrete columns after fire exposure [12,18,38,42–44]. The only available model proposed to simulate the effect of fire exposure from different sides was developed by Raut and Kodur [32].The governing equations used in this research incorporated with the equations proposed by Kodur and Dwaikat [42] and Ali et al. [45] for heat transfer and pore pressure calculations, were employed in this investigation after validations were performed.

However, the research on the post-fire behaviour of concrete columns needs to be conducted further because the relevant research is insufficient. In this work, a numerical and experimental study on the post-fire behaviour of RPC columns after being exposed to fire at two adjacent sides and for 1 h was presented with evaluating the effect of some testing parameters including fire temperature levels, lateral ties, and concrete cover thickness. The other parameters including different directions of fire exposure (1-, 2-opposite, 3-, and 4-sides) for each fire duration (1 and 2 h) were investigated in the parametric study using the FE model developed in this paper after validations were done with good agreement.

2. Experimental investigation

The experimental program consists of three groups according to the fire temperature levels. Each group consists of four reinforced reactive powder concrete columns as shown in Table 1. Each RPC column is identified by two symbols. The first symbol is a number refers to the concrete cover (C.C); (1) and (2) for 15 and 30 mm concrete cover respectively. The second symbol is a number that