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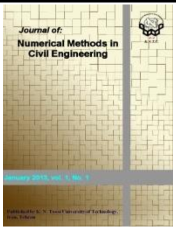

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Numerical investigation of the behavior of HSC columns in fire

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Abstract:

This paper numerically investigates the fire resistance of HSC columns under the ISO-834 standard fire curve. Due to its complexity, concrete behavior is mainly evaluated using experimental testing. Because of the limitations of experimental studies, this study uses the finite element method to model concrete behavior under fire conditions. The effects of various parameters such as concrete cover, loading rate, concrete strength, aggregate type, and axial load on the behavior of concrete columns, including temperature and displacements, are investigated. The results showed that concretes with high cover, low preloading, siliceous aggregates, and lower compressive strength exhibit a higher fire resistance than other types.

1. Introduction

One of the advantages of reinforced concrete is its high resistance in fire conditions, but it does not mean that concrete is a fireproof material. There have been many concrete constructions where fire has caused irreparable damage to structures. The collapse of the WTC Twin Towers due to high temperature on September 11 put a spotlight on the importance of resistance of different construction materials during fire [1].

Despite the relative advantages of concrete structures over steel structures in fire conditions, they could be extremely vulnerable. In this regard, high-strength concrete is more susceptible than the conventional one. At high temperatures, change in the characteristics of concrete and reinforcement materials, including their modulus of elasticity, failure strength, and a phenomenon called spalling, associated with a reduction in cross-section of concrete members, cause the displacements to increase. The increased displacements ultimately lead to a complete fracture of the structure.

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Stresses induced in concrete members during a fire are mainly due to their expansion and pressure of entrapped evaporated water.

Investigating the performance of structures against fire is a necessary approach in the design of buildings in structural engineering. In general, the behavior of individual elements such as beams and columns under fire conditions is investigated with the prescribed approaches of regulations or with standard fire tests [2].

Most building materials, including steel and concrete, are highly vulnerable to heat build-up. In concrete members, in addition to reducing the strength, it also leads to the scaling phenomenon. With increasing temperature, the physical, chemical, thermal and mechanical properties of concrete and steel change significantly, different strains are created in concrete and steel materials, and the stress-strain behavior of materials changes depending on the temperature and time of heat increase [3]

High-strength concrete, with a strength of more than 60 MPa, was introduced in the 1980s, and several studies have since been performed on its behavior against fire. Some characteristics of this type of concrete, such as its low permeability, make it very susceptible to fire hazards. However, the focus of previous studies on the properties of concrete in high temperatures made these studies pay less attention to structural factors such as loading conditions and supports. Identifying this weakness led to valuable papers concerning the structural behavior of conventional and high-strength concrete [4, 1].

Results from several studies have shown well-defined differences in the properties of high-strength concrete (HSC) and normal strength concrete (NSC) at high temperatures. Furthermore, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire. This potential risk of explosive spalling was found to occur primarily in structural members made of HSC and ultra-high performance concrete (UHPC). The various investigations have generally identified two main differences in the behavior of HSC at high temperatures from that of NSC, namely, more pronounced loss of strength in HSC at elevated temperatures and the susceptibility of HSC to explosive spalling even at temperatures below 400C [5, 6]. With the exception of these two points, it is commonly suggested that HSC can be treated as conventional NSC in fire engineering design [7, 8].

In terms of concrete properties, Abrams found that the compressive strength of concrete decreases with increasing temperature, but the rate of resistance decline depends on the type of aggregates used in concrete mixing [1]. In 1982, Malhotra also concluded that concrete loses compressive strength in temperatures above 600° C. As the temperature rises to the range of 300° C, cracks form in the concrete, which reduces the strength of the concrete by 30% [4, 9]. In 2002, Chandra investigated the effect of fire on concrete with lightweight aggregates. The results showed that in reinforced concrete structures with the possibility of fire, the use of lightweight concrete in the members can prevent the phenomenon of thermal bursting and ultimately maintain the strength of the members [3] [10].

In 2004, Georgali showed that by observing physical changes such as the color of concrete changing from gray to pink, the quality of concrete surface, fine cracks as well as changes in the quality of aggregates, the impact of fire on concrete can be assessed [11]. In 2008, Hodhod conducted several experiments on protective coatings as thermal insulation in concrete structures [12].

Spalling of concrete at high temperatures is the most important factor in decreasing its strength in fire conditions. Spalling often occurs in the presence of thermal stress and high pressure in pores. The collapse of concrete components due to explosion leads to a noticeable reduction of the cross-section of structural members, which results in a catastrophic failure. The pore pressure spalling mechanism is mainly associated with the hygro-thermal process inside the heated concrete. Pore pressure builds up gradually in the micro-pores due to heat transfer and moisture migration. When the tensile stress induced by pore pressure is greater than the tensile strength of concrete, spalling occurs [13, 14, 15]. The duration of fire is one of the most important factors in scaling. Observations by Harmathy [16] indicated that spalling of concrete tended to occur within 10-25 min in the case of the ASTM E119 fire. Mindeguia et al. [17] observed that thermal spalling occurred in unrestrained and unloaded concrete slabs between 10 and 20 min of the ISO-834 (similar to the ASTM E119) fire test. Ko et al. [18] observed that spalling occurred in unrestrained and unloaded concrete slabs within 10 min of the ISO-834 fire test. These problems motivated researchers to conduct more studies on the behavior of concrete structures against fire, most of which were carried out as experimental and numerical modeling. In most of these researches, a single type of fire, introduced by standards such as ISO-834 [19], called the “standard fire,” was used for convenience.

Nadjaei and Kodur et al. [1, 20] studied the behavior of concrete in a furnace. Their results showed that adding the fibers was very effective in reducing explosive spalling. The average degree of spalling for the six columns considered was less than 1% compared with 22% without using the fibers.

There are several problems in testing high-strength concrete in furnaces, such as high costs, time-consuming processes, and limitations related to the type of furnace used. Therefore, it is convenient to use finite element (FE) software and precisely model the structure and the fire conditions. Accordingly, to evaluate the effects of different parameters on the behavior of high-strength concrete columns, an experimental test performed by Kodur et al. [20] was modeled using Abaqus software in this study.

This paper aims to report the numerical study on the effect of loading, aggregate type, concrete cover, and strength on explosive spalling of 17 models of high-strength concrete columns in fire. It includes results regarding temperatures and axial displacements of high-strength concrete columns. Abaqus software was used to consider the finite element models of the concrete columns. The concrete columns, including the embedded reinforcements, were modeled to conduct a nonlinear transient structural analysis.

2. Numerical modeling

2.1 Models

In this study, the effect of various parameters on the performance of reinforced concrete columns under fire was explored numerically. Models with different parameters of compressive strength, concrete cover, and axial load were analyzed. The following table lists the specifications of the various models considered. It is assumed that the column height, cross-section, and area of reinforcements are constant in all the models.

Table. 1: Specifications of the numerical models.

Models	Concrete strength (MPa)	Cover (mm)	Aggregate type	Axial load (KN)
C-80-4-S-2000	80	40	siliceous	2000
C-80-6-S-2000	80	60	siliceous	2000
C-80-2-S-2000	80	20	siliceous	2000
C-80-4-C-2000	80	40	carbonate	2000
C-80-6-S-1600	40	60	siliceous	1600
C-60-6-S-1600	60	60	siliceous	1600
C-80-6-S-1600	80	60	siliceous	1600
C-80-4-S-1600	80	40	siliceous	1600
C-80-4-S-2000	80	40	siliceous	2000
C-80-4-S-2400	80	40	siliceous	2400
C-80-4-S-2800	80	40	siliceous	2800

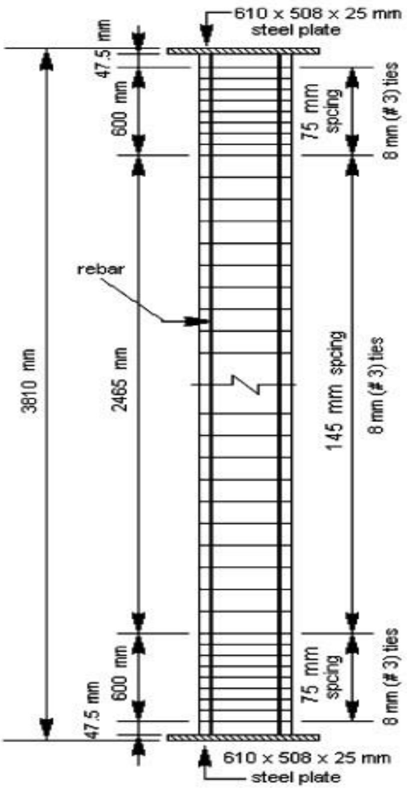

Fig. 1: Schematic view of the test performed by Kodur and Mcgrath [7].

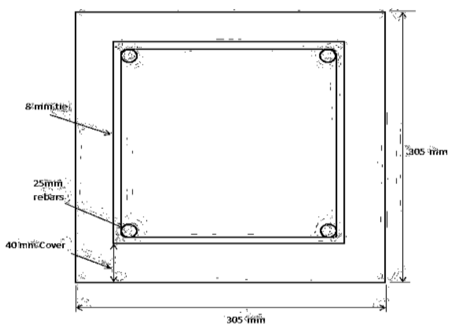

Fig. 2: Cross-section of the concrete columns in the test performed by Kodur and Mcgrath [7].

2.2 Modeling assumptions

1) The column is fixed at one end and guided at the other.
2) The slip between concrete and rebar is trivial.
3) Temperature of the column surface is considered to be equal to furnace temperature.
4) Temperature of the rebar is considered to be equal to surrounding concrete due to its high conductivity and small cross-section.

2.3 Elements

Solid elements were used to model concrete and rebars. The 8-node cubic mesh geometry with coupled temperature-displacement analysis capability was used. The reduced integration was selected for the analysis, and therefore, the type of elements for both steel and concrete was C3D8RT. Degrees of freedom included three displacement degrees of freedom Ux, Uy, and Uz, and one temperature degree of freedom NT [22].
The interaction between the concrete and steel rebars was of the "embedded" type, making the displacement degrees of freedom Ux, Uy, and Uz tied together.

2.4 Geometry of the FE models

The size of the concrete columns was assumed to be 0.305×0.305×3.81 m. In pursuance of reducing time and increasing accuracy, the rebars were modeled with a square equal to a real circle cross-section so that all meshes were of the "structured" type.

2.5 Materials properties

2.5.1 Concrete

Materials used in the modeling process included concrete, rebar steel, and stirrup steel. Concrete properties taken from references [23, 24] were used in the modeling process. In addition, the stress-strain relation of high-strength concrete was considered in accordance with relations given by Kodur in the appendix of reference [25]. Table 2 shows the properties of high-strength concrete (with a compressive strength equal to 99.6 Mpa) at high temperatures. The concrete density in all temperatures was considered equal to 2400 Kg/m^3.

Table. 2: Properties of high-strength concrete (99.6 MPa) at high temperatures.

Temperature (C^o)	Compressive strength (MPa)	Modulus of elasticity (MPa)	Conductivity (W/mC^o)
20	99.6	40000	1.67
100	74.7	36000	1.5
200	74.7	32000	1.33
400	74.7	24000	0.83
700	31.4	12000	0.67
900	2.5	4000	0.67

2.5.2 Longutinal rebars

Table 3 shows the properties of rebar steel used. This table is calculated based on the formula given in Eurocode 3 [26] for steel properties at high temperatures. According to Eurocode 3, the modulus of the elasticity and yielding strength of steel at high temperatures can be calculated by multiplying reduction factors by the modulus of elasticity and yielding strength of steel in normal temperatures [21]

Table. 3: Properties of steel with 420 MPa yielding stress at high temperatures [21].

Temperature (°C)	Yielding strength of steel (MPa)	Modulus of elasticity (MPa)	Density (kg/m^3)
20	420	210000	7850
100	420	210000	7850
200	420	189000	7850
400	420	147000	7850
700	96.6	27300	7850
900	25.2	14070	7850

2.5.3 Stirrup rebars

Properties of steel with yielding stress of 280 MPa at high temperatures according to the relations given in EN1993 are as follows [21]:

Table. 4: Properties of steel with 280 MPa yielding stress at high temperatures [21][9].

Temperature (°C)	Yielding strength of steel (MPa)	Modulus of elasticity (MPa)	Density (kg/m^3)
20	280	210000	7850
100	280	210000	7850
200	280	189000	7850
400	280	147000	7850
700	64.4	27300	7850
900	16.8	14070	7850

2.6 Verification

For verification purposes, the THC4 specimen with a 28-day strength of 60.6 MPa and 100-day strength of 99.6 MPa was used. At the beginning of the test, a load of 2000 kN was applied to this specimen. This load was applied about 45 minutes before the commencement of the test, and after the longitudinal displacement became constant and the column reached a fixed position, the fire test started. Furnace temperatures were according to the ASTM E119 standard [21] (Fig. 3).

In 2003, Kodur et al. [20] performed an experimental test with different loading conditions on conventional and high-strength concrete columns. They used concrete columns with a cross-section of 305×305 mm^2 and a length of 3.8 m which encased four rebars with a cross-section of 25 mm^2 and yielding strength of 420 MPa in the corners and #8 stirrups with the spacing of 145 mm in mid-height and 75 mm at the two ends with yielding strength of 280 MPa. [20]. Figures 1 and 2 show the details of the experiment.

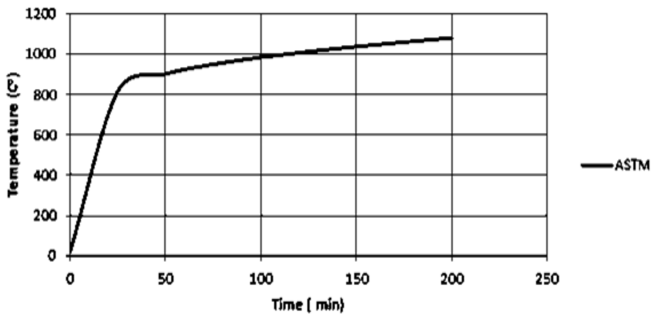

Fig. 3: Time-temperature curve of the furnace according to ASTM E119 standard.

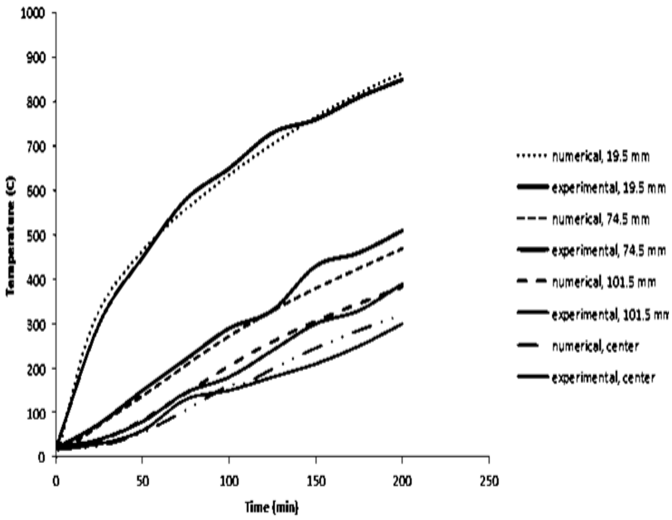

Fig. 4: Comparison between experimental and numerical values obtained for the temperature of the C-80-4-S-2000 model at various distances from the surface of the column.

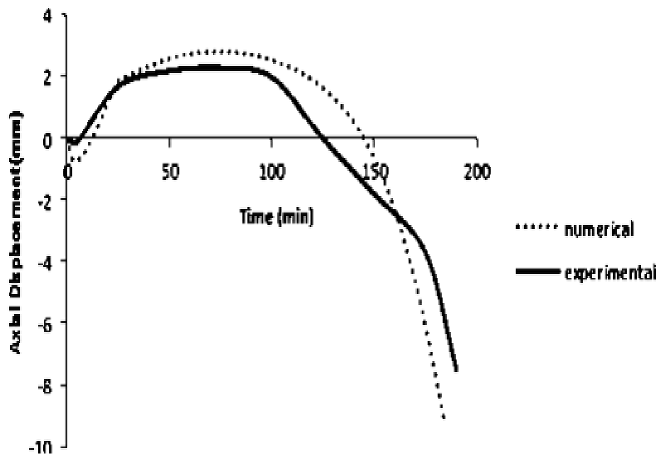

Fig. 5: Comparison between axial displacement values from the experimental testing and numerical analysis of the C-80-4-S-2000 model.

Results of the analysis are given using time-temperature and time-displacement graphs. According to Fig. 5, the FE results were compared with the laboratory results using the same materials and boundary conditions parameters as the FE model. Both graphs show that the FE results had a high modeling accuracy.

According to ASTM [10], the concrete failure criterion at high temperature is introduced as the time in which concrete cannot withstand the applied axial load. Moreover, the fire standard ISO-834 [27] recommends any one of the following criteria:
1) The axial displacement of the column reaching h/100 (h: height of the column).
2 The axial displacement ratio of the column reaching 3h/1000 (mm).
In this research, we used the first criteria.

3. Results and discussions

After verifying the numerical model, the behavior of high-strength concrete columns against fire and the effects of different parameters of concrete cover, aggregate type, concrete strength, and loading rate were investigated.

3.1 The effects of concrete cover

To study the effects of concrete cover, three high-strength concrete columns with a cross-section of 300×300 mm^2 and a height of 3.8 m, subjected to 2000 kN axial load with different covers of 20, 40, and 60 mm were assumed. Each of the three columns had a 28-day strength of 80 MPa. Reinforcement details were similar to those mentioned previously in the experimental test. Figures 6 and 7 demonstrate the analysis results of these three columns under the ISO-834 standard fire conditions.

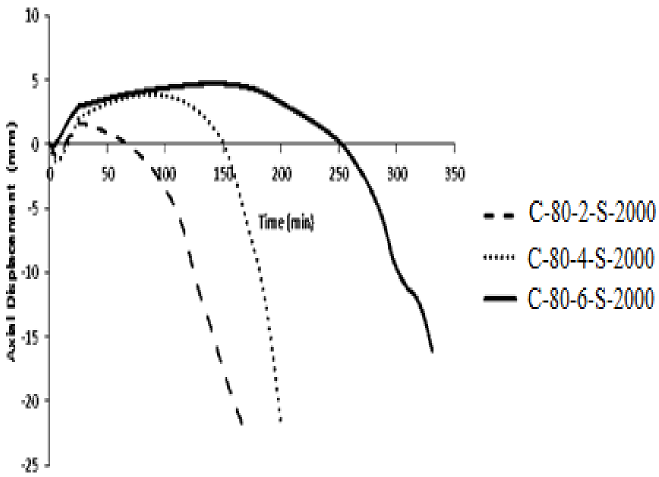

Fig. 6: Effect of concrete cover on axial displacement.

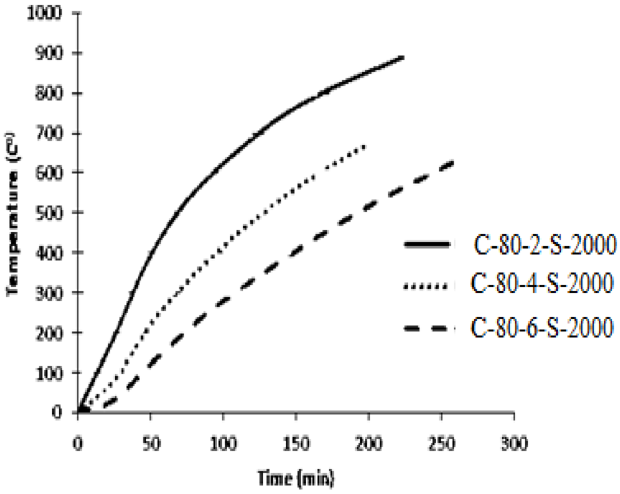

Fig. 7: Effect of concrete cover on the variation of reinforcement temperature.

Steel's mechanical properties do not change up to a temperature of 400 °C [21][9]. However, at temperatures higher than 400 °C, the mechanical properties greatly degrade, and consequently, the reinforcement steel also tends to lose its resistance. Figure 6 shows that the columns with 20, 40, 60 mm covers lost their strength at 150, 200, and 340 °C, respectively.

3.2 The effects of aggregate type

Two columns with equal strengths of about 80 MPa, one with silica and the other carbonate aggregates and an equal cross-section of 300×300 mm^2 and height of 3.8 m, were studied. A 2000 kN axial load was applied to each of these columns. These columns' cross-section, height, and reinforcement were similar to those considered in the previous section.
Figures 8 and 9 show the behavior of these columns under the ISO-834 standard fire conditions.

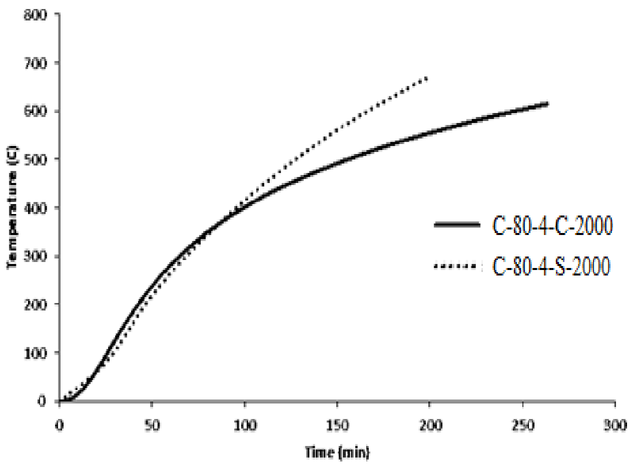

Fig. 8: Effect of aggregate type on the temperature of reinforcement.

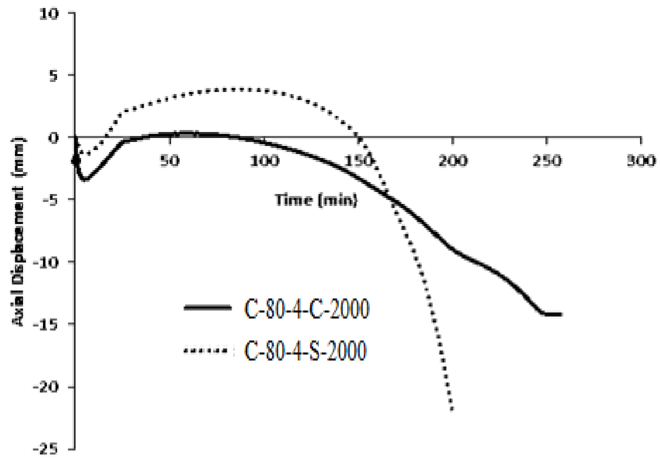

Fig. 9: Effect of aggregate type on the axial displacement.

As seen in Figs. 8 and 9, the concrete column with carbonate aggregates demonstrated a higher strength under fire conditions. Also, as shown in Figs. 8 and 9, in siliceous and carbonate concrete, when the temperature in reinforcement reaches 400 °C, failure begins to occur.

3.3 The effect of concrete strength

To study the effect of concrete strength, three different concrete columns with strengths of 40, 60, and 80 MPa were studied. The axial load level for all three columns was equal to 25% of their loading capacity. The axial load of the columns with 40, 60, and 80 MPa strengths were equal to 2000, 1550, and 1100 kN, respectively. All three models had silica aggregates, and their reinforcing details were kept the same as in previous sections.

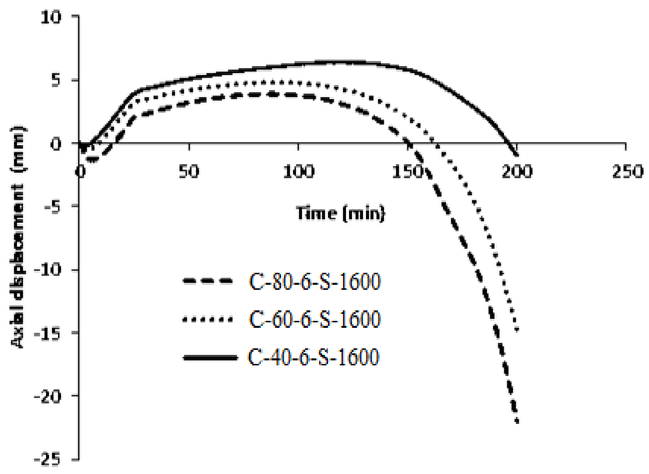

Fig. 10: the effect of compressive strength on axial displacement.

As can be seen in Fig. 10, the concrete with 40 MPa compressive strength had a higher resistance in the fire. That is because of the lower axial strains of concretes with lower compressive strength.

3.4 The effect of axial load

To study the loading rate's effect on the behavior of concrete columns, four different axial loads of 1600, 2000, 2400, and 2800 kN are applied at high temperatures. All four columns had a strength of 80 MPa, a cross-section of 300×300 mm^2, and a height of 3.8 m with siliceous aggregates. All the other details were the same as those in the previous section.

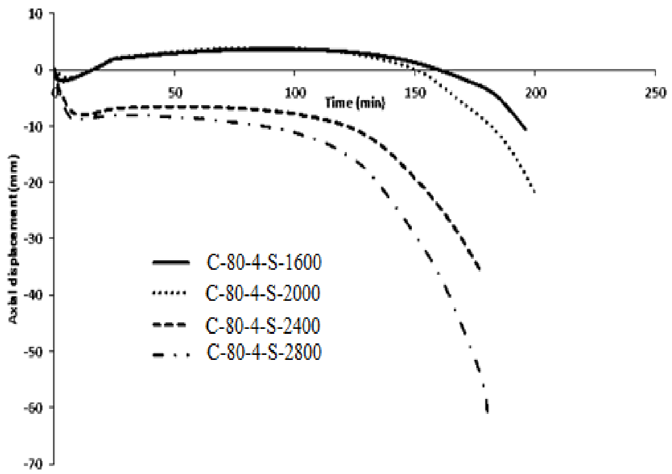

Fig. 11: Comparison of time-related axial displacement for four columns with different loads.

It can be seen from Fig. 11 that a higher axial load decreases the resistance time of a given column under fire conditions.

4. Conclusions

A finite element-based numerical method was developed in this study to determine the behavior of high-strength concrete columns under fire conditions. Change of material properties with time and expansion of concrete at high temperatures was considered to conduct the study. Concrete and reinforcements were modeled rigorously. The following conclusions are derived from this investigation:

•Thicker concrete cover improves the behavior of concrete columns at high temperatures resulting in the lower temperature of reinforcement and better performance of the concrete column.

•Columns with carbonate aggregates show better performance under fire conditions due to the lower thermal conductivity.

•At similar load levels, concrete columns with lower compressive strength exhibited a better performance under fire conditions. This is because of the lower nonlinear strains and weaker effect of the spalling phenomenon in concrete specimens with lower strength.

•Lower preloading of concrete columns leads to better strength in a fire condition, so columns with higher initial load showed more brittle behavior under fire conditions.

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