The Axial Loading Capacity of Reinforced Concrete Columns Exposed to High Temperature

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ABSTRACT: Reinforced concrete structures are traditionally designed to carry service loads and lateral forces caused by seismic events. However, recent incidents such as Grenfell Tower fire in London highlighted the fact that fire and high-temperature should be also taken into account as hazardous phenomena that can significantly affect the safety of the reinforced concrete structures. High-temperature exposure can considerably affect the structural performance and load carrying capacity of reinforced concrete members, and therefore lead to a partial or total collapse. To address this issue, this study aims to investigate the axial load bearing capacity of reinforced concrete columns exposed to high temperature. A custom made high-temperature electric furnace was used to test reinforced concrete columns under simultaneous effects of axial load and high temperature. In addition, thanks to its twin unit design, the furnace allows investigating the effects of both water-cooling and air-cooling on the axial loading capacity of the columns after high temperature exposure. Also, an advanced computer control system was designed using Arduino micro-controller to apply any kind of heating curves to the test specimens. In this study, ISO-834 standard fire curve was used for the experimental tests. The main parameters considered within the study are heating duration, and cooling scenario. Dimensions of the column specimens were chosen as 250 × 250 × 1200 mm. The specimens were subjected to a predefined constant axial load during heating and cooling process. Subsequently, in order to obtain the post-fire residual capacity of the reinforced concrete columns using different heating durations and cooling scenarios, loading was continued up till the failure. The results of this study, can be used to develop more efficient methods to design reinforced concrete columns exposed to high temperature.

1 INTRODUCTION

Investigation of the behaviour of reinforced concrete structural elements under fire is one of the important subjects of experimental structural mechanics. The results of such studies generally aim to evaluate experimentally the behaviour of main structural components (e.g. reinforced concrete columns) under the effect of service loads during and after fire. Several research studies have been conducted on fire or high temperature behaviour of concrete and reinforced concrete structures. In the following, some of the relevant experimental studies about fire or high temperature exposed reinforced concrete columns are summarised.

Kodur (1999) compared fire performance of high-strength and normal-strength concrete structural members. The study showed that members with high-strength concrete exhibited worse fire performance than the members with normal-strength concrete. Plus, spalling under fire was indicated the major problem within the high-strength concrete due to its low water/cement ratio.

Franssen and Dotreppe (2003) raised an issue that all previous works on fire resistance of concrete columns have been based on square or rectangular cross-sections, for which corner spalling was observed very often, while circular sections are nowadays becoming more popular. Therefore, they conducted an experimental study to examine the effects of the circular shape on the behaviour of concrete columns under fire conditions. In another relevant study, Wu et al. (2007) showed that cross-section dimensions, axial load ratio, eccentricity ratio are all effective parameters on fire behaviour of both high-strength and normal-strength concrete under both axial or eccentric loading. In addition, it was also observed that there is no significant effect of reinforcement ratio on fire resistance of axially loaded columns with normal and high strength concrete, while explosive spalling is generally highly effective on fire resistance of high-strength concrete.

Jacintho et al. (2012) presented experimental results for short composite steel and concrete columns subjected to high temperature in ovens with or without an axial load. The load bearing capacities of the composite columns were reduced when they were subjected to high temperature. This effect was observed for only the specimens which were heated for 60 minutes. In another study, Tan and Nguyen (2013) performed an experimental research to investigate the effects of equal biaxial bending, restraint ratio and concrete strength on the structural behaviour of reinforced concrete columns at elevated temperatures. The study showed that the plane strain assumption is reasonably and reliable for biaxially-loaded columns and simplified criterion of Eurocode-2 is capable to predict the failure load of columns under equal biaxial bending at room temperature.

Bamonte and Monte (2015) performed an analytical study to simulate the performance of reinforced concrete columns exposed to fire. A Fortran subroutine was developed which could provide analytical results consistent with the reference experimental test. It was also highlighted that transient and creep strains should be taken into account in analyses of the reinforced concrete columns exposed to fire. More recently, Shah and Sharma (2017) proposed an empirical model to obtain the behaviour of reinforced concrete elements subjected to high temperature. Within the suggested model, some important parameters such as concrete strength, lateral confinement, longitudinal reinforcement and load ratio of the columns are taken into account.

In the current study an innovative experimental setup has been designed, in which the concrete columns can be tested simultaneously under the effects of high temperature and axial loading. The results are then presented and discussed to provide useful information for the performance assessment of reinforced concrete structures exposed to high temperature.

2 EXPERIMENTAL STUDY

2.1 Specimen Details and Test Setup

The main objective of this study is to investigate the axial load bearing capacity of reinforced concrete columns exposed to high temperature. Within this purpose, five reinforced concrete column specimens were produced and tested in the Structures Laboratory at Karadeniz Technical University. Mean cube (150 mm) compressive strength was obtained as 48.6 MPa. Cross-section dimensions and height of the columns were chosen as 250 x 250 mm and 1200 mm, respectively. Longitudinal reinforcement of the specimens was chosen as 4 number of 14 mm diameter bars which is equal to 1.0% reinforcement ratio. Spacing of transverse rebars was chosen as 200 mm. Thickness of the clear concrete cover from ties to concrete surface was 20 mm. In order to prevent undesired damages at the end zones of the specimens, transverse rebar spacing was decreased at those zones. The specimen dimensions and reinforcement details are shown in Figure 1. Mechanical properties of reinforcement steel are also given in Table 1.

As a part of this project, a custom high-temperature furnace which allows to apply axial load and heating simultaneously was designed and produced. The furnace consists of two identical electric furnace halves which can slide on the rails and are integrated to a loading frame with 6000 kN axial loading capacity. The constant axial load level was chosen as 40% of axial load bearing capacity of the reference column, which is the maximum axial load level for reinforced concrete columns in the Turkish seismic code, TBEC-18 (2018). In order to determine axial load capacity of the columns, the reference column was tested under room temperature.

All reinforced concrete columns were produced using ready-mix concrete. All columns were cured for nearly 90 days at the test day. The column specimens and their concrete cubes were kept under wet condition in the first 15 days and left in a dry condition in the lab until the tests. The ambient temperature was measured as 16±2 °C in the laboratory during the tests.

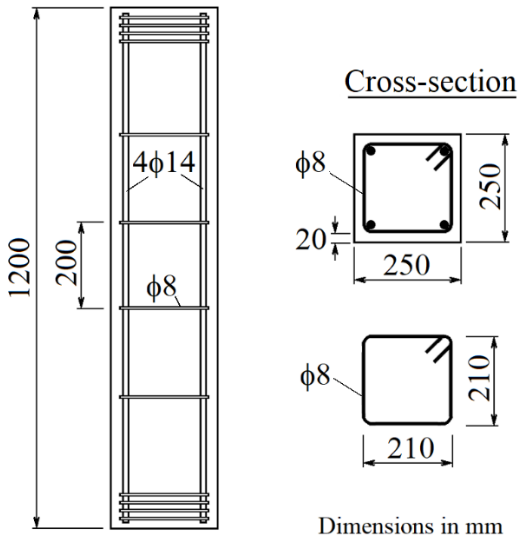

Figure 1. Dimensions and details of the column specimens.

Table 1. Mechanical properties of rebars

Diameter (ø), mm	Yield strength (R_e), N/mm^2	Tensile strength, (R_m), N/mm^2	R_m/R_e	Elongation at rupture, %
8	487	640	1.31	28.2
14	493	602	1.22	22.4

Due to the special design of the electric furnace, it can be locked onto the specimen for heating or move away from the specimen for cooling, while the axial load being kept constant. A computer control unit was designed for the electric furnace to provide the desired heating curve. Also, a custom software was developed using MATLAB to control the furnace. The software communicates the K-type thermocouple using Arduino micro-controller connected to USB port. It can also communicate to the Solid-State Relay (SSR) to turn on or off the furnace. The real temperature inside the furnace is measured and the desired temperature is calculated by the software for a certain time. According to the relationship obtained between desired and the real temperature, software decides to turn on or off the furnace. Thus, temperature inside the furnace can make follow a predefined heating curve. Operating frequency of the computer control system is about 1.0 Hz. Test setup is given in Figure 2 schematically. Loading frame is shown partially to better demonstrate the details of the furnace.

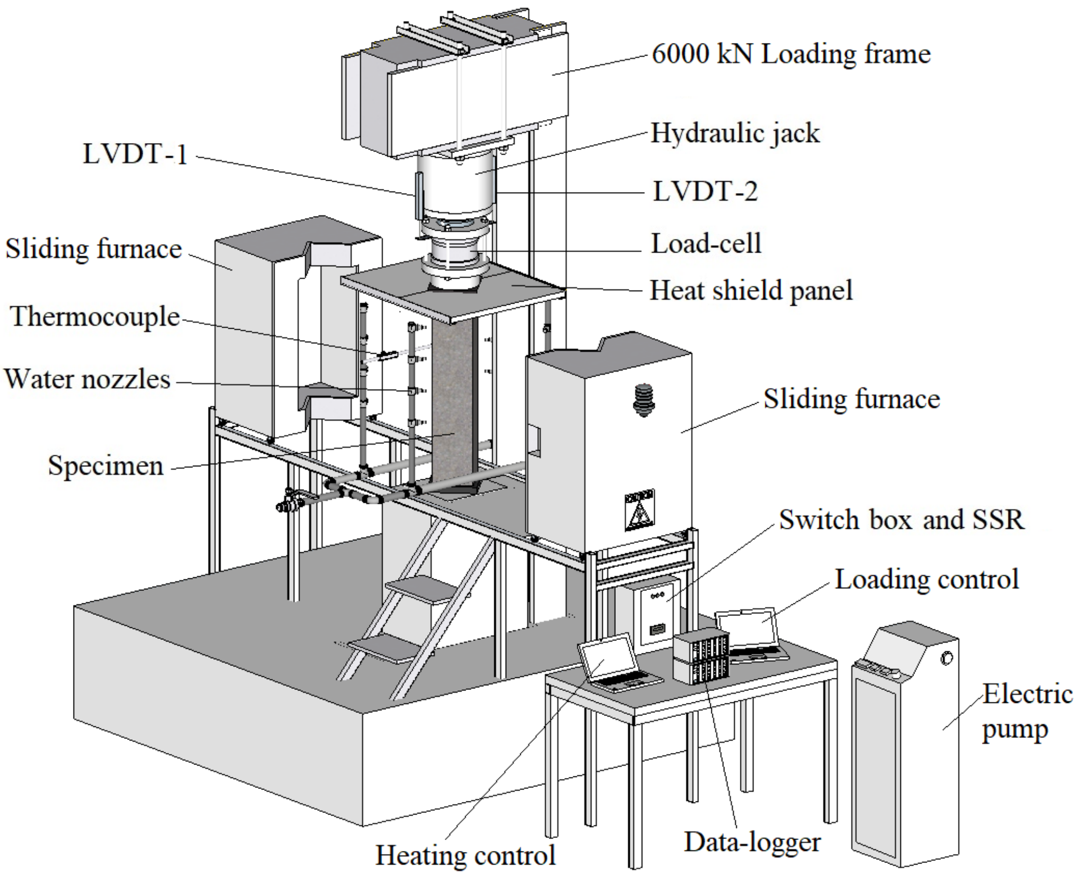

Figure 2. Test setup.

2.2 Test Details

As mentioned before, five reinforced concrete column specimens were tested under monotonic axial loads as a part of this study. One of the columns was the reference specimen, which was not subjected to the heating, while the others were exposed to high temperature tests. Test details of the heating and cooling scenarios are given in Table 2. During the tests, specimens were subjected to predefined axial load and the load level was kept constant using continuous-feed electric pump and pressure relief valve. A continuous-feed pump was used to prevent the pressure drop inside the hydraulic system, while the relief valve prevented the pressure to exceed the pre-set value. By using this arrangement, the pressure inside the hydraulic system can be kept stable, and consequently, the load applied by hydraulic cylinder would be kept constant. In all heating scenarios, the specimens were exposed to ISO-834 standard cellulosic fire curve as shown in Figure 3.

Table 2. Test program

Columns	Axial load level (during heating and cooling)	Heating duration (min)	Cooling method
CN-REF	Cold test	-	-
CN-60-A	0.40 $f_{CN\text{-}Ref}$	60	Air
CN-60-W	0.40 $f_{CN\text{-}Ref}$	60	Water
CN-120-A	0.40 $f_{CN\text{-}Ref}$	120	Air
CN-120-W	0.40 $f_{CN\text{-}Ref}$	120	Water

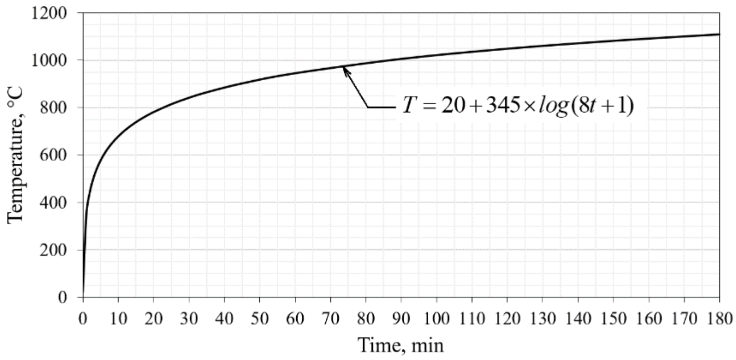

Figure 3. Applied ISO-834 heating curve.

After finishing the heating phase, the halves of the furnace were moved away from the specimen and the cooling phase was started. Some views from the heating phase and just after it are given in Figure 4(a, b). Two different ways of cooling method (air-cooling and water-cooling) were utilised. In air-cooling method, the specimens cooled gradually in the laboratory conditions. For water-cooling, a steel pipeline with nozzles was installed to the system, and the water at approximately room temperature from water supply was used. The cooling was carried out by spraying water onto all surfaces of the columns by means of sixteen nozzles. The water-cooling process is shown in Figure 4(c).

Figure 4. Views from tests: a) Heating b) Just after heating c) Water-cooling.

2.3 Test Results

Load – displacement curves obtained from tests are given in Figure 5. Although they were kept for 90 days to release the moisture inside, spalling explosions were occurred in all of the specimens during the heating process. Spalling in the specimens were observed when the furnace temperature reached between 250 °C and 600 °C. After the heating process, furnace was moved away and cooling process was started and continued until a certain level of specimen's core temperature. In order to measure the core temperature, specimens were drilled with the same diameter of thermocouple probe at the middle section for placing the thermocouple. Observations related to heating and cooling duration and core temperatures are given in Table 3.

During experimental tests, it is observed that the failure mechanism of the specimens is similar. All specimens were failed due to concrete crushing leading to longitudinal bar buckling, while there was no stirrup failure. In addition, no damage was observed at the end zones of the specimens. The column specimens after the tests are shown in Figure 6.

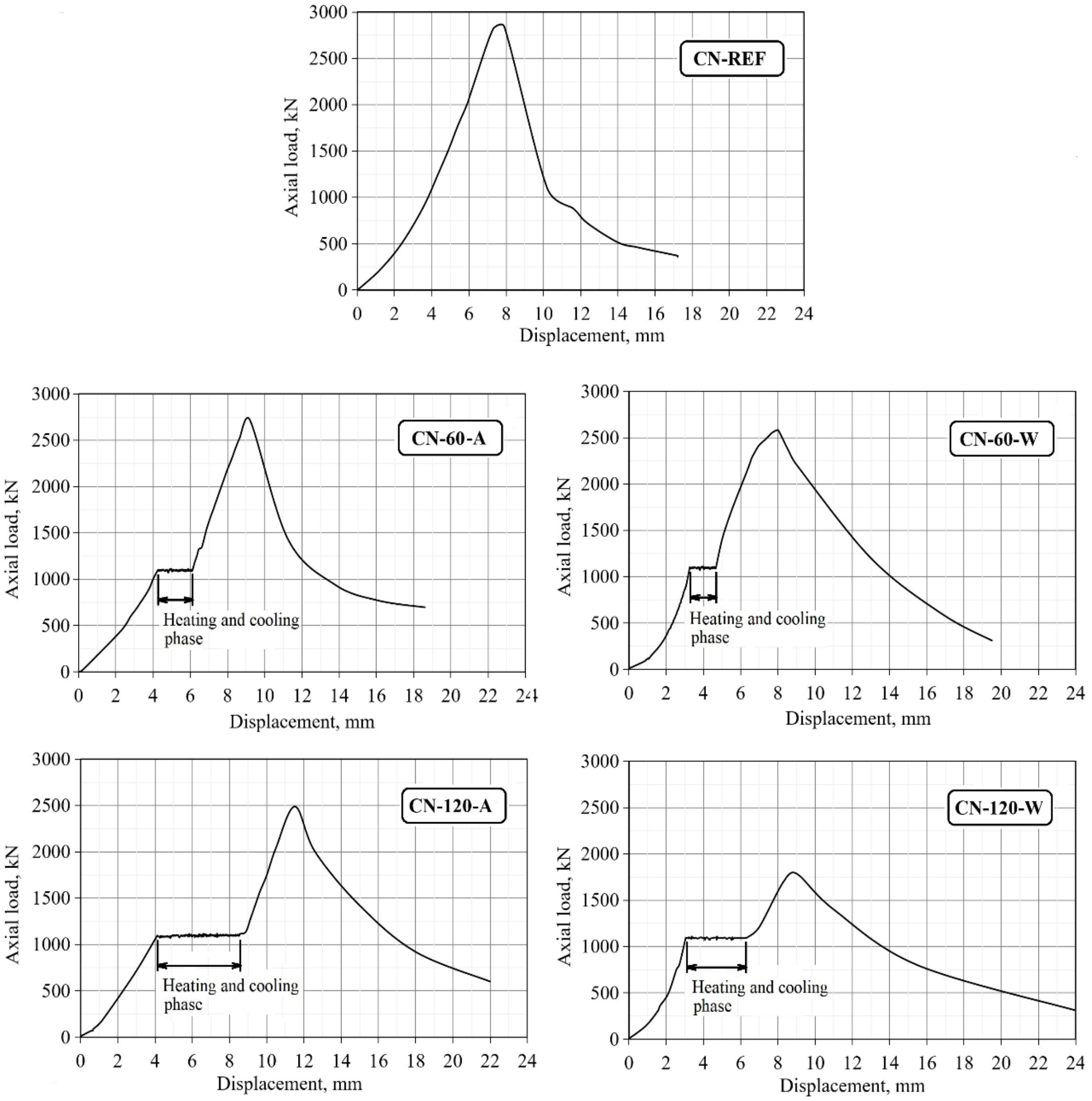

Figure 5. Load - displacement behaviour of the columns during high-temperature test.

Table 3. Heating and cooling durations and core temperatures after cooling

Columns	Heating duration (min)	Cooling method	Cooling duration (min) (approx.)	Core temperature after cooling (°C) (approx.)
CN-60-A	60	Air	300	100
CN-60-W	60	Water	30	100
CN-120-A	120	Air	420	150
CN-120-W	120	Water	30	150

Figure 6. Views from tested columns.

3 CONCLUSIONS

This study summarized the results of axial loading capacity of reinforced concrete columns exposed to high temperature using an innovative experimental test set-up. Based on the test results obtained in this study, the following conclusions can be drawn:

- For the specimens exposed to ISO-834 standard fire curve for 120 minutes, significant differences on both load bearing capacity and post-peak behaviour were obtained before and after fire exposure.
- It is clearly shown that both heating duration and cooling type can influence the load bearing capacity of the axially loaded reinforced concrete columns. According to test results, it can be inferred that cooling type is more effective than heating duration. For the specimens exposed to high temperature for 60 minutes, air-cooled specimens lost their load bearing capacities by 4%, while this reduction was 10% for water-cooled specimens. For the specimens exposed to high temperature for 120 minutes, air-cooled and water-cooled specimens lost their load bearing capacities by 13% and 37%, respectively.
- A quick and explicit spalling and erosion (which spread inward) was observed especially in case of water-cooling. This can due to the thermal shock caused by sudden temperature drop while spraying water onto the hot surface of the columns.

- In terms of the slope of the post-peak descending branches, it is observed that air-cooled specimens exhibited like reference specimens. However, in case of water-cooling, slopes of the descending branch were decreased. In addition, closest behaviour to reference specimens was observed in the specimen which was exposed to high temperature for 60 minutes and air-cooled while the farthest behaviour was captured in the specimen which was exposed to high temperature for 120 minutes and water-cooled. This implies that both heating duration and cooling method affect the softening behaviour of the reinforced concrete columns.
- It is shown that there is a relationship between drop of the load bearing capacity and slope of the post-peak descending branch. Slope of the post-peak descending branch increases while load bearing capacity decreases. This can be explained as high temperature exposure and cooling method can affect both the crushing and fracture energy of the concrete material. As the slopes of the post-peak descending branch of the water-cooled specimens are lower than others, it can also be inferred that water-cooling might decrease the crushing energy of concrete while increasing the fracture energy.

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