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ORIGINAL ARTICLE

Behavior of reinforced concrete short columns exposed to fire

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Abstract Fire could dramatically reduce strength of reinforced concrete columns. The objective of this work is to study columns exposed to fire under axial load and to evaluate reduction in column compressive capacity after fire. The first part of this research is experimental investigation of fifteen-column specimens (15 × 15 × 100) cm exposed except one specimen to (600 °C) fire. The second part is a theoretical analysis performed using three-dimensional nonlinear finite element program. The main studied parameters were concrete strength, fire duration, level of applied loads, longitudinal reinforcement yield strength, percentage of longitudinal reinforcement, and bar diameters.

Comparison between experimental results and theoretical analysis indicated that for columns not exposed to fire, the first crack appeared at 80% of column failure load while the first crack occurred at 50% of column failure load for columns exposed to fire. Columns with the same reinforcement percentage but with smaller bar diameters gained less lateral strain and smaller vertical displacement than columns with bigger bar diameters. Using high-grade steel as main reinforcement showed failure load higher by 55% than that of column reinforced by mild steel. Cooling column by jet water resulted in 17% reduction in failure load than columns cooling gradually in room temperature.

1. Introduction

Reinforced concrete is the common material used in structural system in Egypt and all-over the world. Thus, the behavior of these structures and their failure modes are extensively studied. The degradation of concrete strength due to short-term exposure to elevated temperature (fire) has attracted attention in the last decades. The behavior of concrete exposed to fire depends on its mix composition and determined by complex interactions during heating process. The modes of concrete failure under fire exposure vary according to the nature of fire, loading system, and types of structure. Moreover, the failure could happen due to different reasons such as a reduction of

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bending or tensile strength, loss of shear or torsional strength, loss of compressive strength, and more.

In the past decade, several experimental and theoretical studies have been carried out on the degradation of column concrete strength due to the short term exposure to fire [1–7]. These studies of columns exposed to fire have indicated the following observations:

i. Surface cracking in concrete occurs at nearly 300 °C with a deeper cracking at 540 °C. Spalling occurs followed by breaking off thin concrete cover at corner and edges.
ii. Concrete begins to lose about 30% of its compressive strength when heated up to 300 °C and loses about 70% of its compressive strength when heated up to 600 °C.
iii. Concrete modulus of elasticity reaches 60% of its original value at 300 °C and reaches 15% of its original value at 600 °C.
iv. Concrete stiffness decreases with the increase in temperature and the reduction in stiffness is accompanied with a reduction in the concrete strength with the increase in the concrete strains.
v. Vertical cracks clearly appear and then crushing of concrete accompanied by crackle sound with a local buckling of the longitudinal reinforcement occurs.
vi. Columns with large longitudinal bars diameters lead to fire resistance appreciably smaller than columns with smaller bar diameters and the increase in concrete cover has a positive effect on the columns fire resistance.

Studies showed that there is an excellent correlation between column models and prototype (similar modes of failure and cracking patterns), which means that there is no need to study true effect on a full-scale model, and time scale factor for models and prototype can be used [3,4].

Design building codes require some provisions for structural fire-resistance to ensure building integrity for a certain period under fire conditions. Such provisions allow safe evacuation of occupants and access for firefighters. Egyptian design building code ECCS-2007 [8], recommend minimum column dimension not less than 25 cm. The minimum thickness of the concrete covers varied between 25 and 35 mm according to both ECCS-2007 [8] and ACI building code [9] for fire resistance periods (1.0–3.0) hours to protect the main longitudinal reinforcement. However, the behavior of buildings after fire, whether it is worthy to repair it or not, is another point of interest that needs more investigation.

This research is aimed at investigating the effect of fire on the behavior of axially loaded reinforced concrete columns subjected to fire and to estimate the percentage loss of column compressive strength under the effect of the following parameters:

1. Concrete characteristic strength.
2. Fire duration.
3. Applied loads on columns during fire.
4. Diameters of the main steel reinforcement.
5. Percentage of the main steel reinforcement.
6. Cooling manner of column after exposed to fire.
7. Grade of the longitudinal steel reinforcement.

To achieve these objectives, mathematical models in conjunction with laboratory experiments are used to simulate the behavior of columns exposed to fire. Analysis was performed to examine the influence of these different parameters on the column strength. The results of these analyses are presented and discussed hereinafter.

2. Experimental investigation

The experimental program consisted of fifteen reinforced concrete column specimens (C_1 to C_{15}) having ($15 \times 15 \times 100$) cm in cross section [representing one third scale model] with 0.6% percentage of stirrups (∅6 mm @ 10 cm). All specimens except the reference column C_1 were subjected to 600 °C constant temperature fire and were divided into seven groups as follows:

Group 1: consisted of four specimens (C_3, C_4, C_5, C_{14}), to study the effect of concrete characteristic strength.
Group 2: consisted of four specimens (C_1, C_{10}, C_{12}, C_{13}), the aim of this group is to study the effect of fire period.
Group 3: consisted of three specimens (C_{11}, C_{13}, C_{15}), to study the effect of the applied load on column during fire.
Group 4: consisted of two specimens (C_7, C_8), to study the effect of different grade of the main longitudinal reinforcement.
Group 5: consisted of two specimens (C_2, C_9), to study the effect of the diameters of the main longitudinal reinforcement.
Group 6: consisted of two specimens (C_{13}, C_6), to study the effect of column cooling manner after exposed to fire.
Group 7: consisted of three specimens (C_7, C_9, C_{I4}), to study the effect of the percentage of the main longitudinal reinforcement.

Table 1 summarizes the tested specimens for different groups.

2.1. Concrete mix design

Four mix designs for one-meter cube of concrete representing four series were used in this study to classify a various concrete characteristic strengths and the mixes were used in manufacturing of column specimens. For each mix, six cubes were cast and tested under compression to evaluate the target strength of the mix. The average strength values for each mix and corresponding concrete strength are as shown in Table 2.

2.2. Testing procedures

All column specimens, except the reference one, were exposed to fire first, and then tested under compression until failure. The furnace is a steel structure made of metals and consist of three main parts, loading frame, firing cage, and isolation caps as shown in Fig. 1, the column placed in the furnace manually by using a lever crane.

Columns were exposed to a 600 °C constant fire temperature at Building Research Center laboratory. After exposed to fire, columns were tested using a hydraulic loading machine of 500-ton capacity and 0.5-ton accuracy at Concrete research laboratory – Cairo University. The load was

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