Decays in strength, ductility, stiffness, and toughness of RC corbels due to fire exposure

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Abstract. This paper presents an experimental study to explain the effect of high fire flame temperatures on the behavior of reinforced concrete corbels. Five reinforced concrete corbels were made using the same concrete grade. All specimens were comparable in geometry and reinforcement details. The key parameter of this study was the temperature of the fire. Therefore, four corbels were exposed to 300, 500, 700, and 900 ºC fire flame, respectively, while the fifth was the reference sample kept without burning. All specimens were posteriorly tested by applying gradual three-point loading till collapse. The results revealed that the exposure to fire flame resulted in a significant deterioration in the strength, ductility, stiffness, and toughness of burned corbels touched 17.7%-47.3%, 39.25%-47.08%, 5.62%-22.5%, and 20.19%-70.8%, respectively.

1. Introduction
In the industrial constructions, corbels are often built to transfer the loads being vertical or horizontal to the supporting reinforced concrete (RC) elements like walls, beams, or columns. The probability of fire accidents in the industrial building is high [1]. Usually, concrete weakens as the reinforced concrete elements are subjected to extreme temperature, and thus, the concrete strength greatly declines, resulting in spalling. Therefore, the load-carrying capacities of the RC members exposed to direct fire could be dropped considerably, leading in turn to a catastrophic failure [2,3].

Previously, the negative influence of the exposure to fire on RC members has been comprehensively inspected. Li et al.[4] disclosed that the concrete is hugely temperature-sensitive material due to altering its mechanical properties as a consequence of microstructural variations resulting from raised temperatures. In general, There are a number of influences that determine the level of damage in concrete exposed to high temperatures, including characteristics of reinforcing steel bars and used concrete, restraint degree, and the fire scenario [5]. These conditions accordingly make the evaluation of the residual strength of the exposed RC element more tedious because they are interdependent and change in various procedures [6]. However, several standards have been existing recently to evaluate the residual strength after exposure to fire, inclusive Eurocode 2 part 1-2 [7], ACI 216.1 [8], BS 8110 -2 [9], and AS 3600 [10]. It is worth mentioning that the calculation procedures of these standards vary from simple to very detailed [11]. Besides, these codes yield conservative estimations and limitedly define the influence of some factors affecting the fire-resistance of RC elements such as loading level, support settings, and the response of concrete beyond cracking [12,13]. Hence, more tests on burned RC members are still required, particularly for element susceptible to brittle failure, as short columns, deep beams, and corbels.

Regarding RC columns, many studies have been conducted [14–19]. Based on their observations, the load-carrying capacities of columns were found to be remarkably plummeted owing to fire.
exposure; the reported reduction in strength reached 51% when columns were two hours heated to 600 °C constantly. Other researchers [19] pronounced that high-temperatures impact high-strength columns more than columns constructed using normal-strength concrete. On the topic of beams, sufficient studies [20–24] have also been introduced. Also, these investigations revealed the strength of beams to be high declines in case of subjecting to fire accidents or elevated temperatures.

On the other hand, the RC corbels under fire are seldom investigated. Excluding the study presented by Abdulhaleem et al.[1]. The authors did not find further studies conducted on corbels published in reputable sources. However, the authors’ consideration were directed on the enhancement in the strength of fire-damaged corbels as a result of adding steel fibers. They used different percentages of fibers up to 1% and heated the corbels till 750 °C. Outcomes referred to a positive effect for fibers on the ultimate strength and ductility of corbels before and after heating. Thus, this study was carried out to get more understanding about the influence of direct exposure to fire flame on the structural properties of corbels. Herein, five corbels were manufactured using the same concrete strength and burned under the fire flame at different temperatures, and beyond cooling, they were tested by subjecting a three-point loading until collapse.

2. Test Specimens
In this paper, five RC corbels, having the details shown in figure 1, were created to evaluate the impact of fire temperature on their structural responses. Each one involved two corbels projecting from the central column. The corbel shape is trapezoidal with a width of 150 mm and a total length of 250 mm, while the larger depth was 250 mm at the column face and set to 125 mm at the free end. The columns' dimensions were 200 mm × 150 mm in the cross-section and 450 mm as the entire length. As seen in Figure 1, the corbels had main, secondary, and framing reinforcements consisted of 3Ø12, 2Ø12, and 2Ø6, respectively, whereas the columns were reinforced longitudinally with 4Ø12 and stirrups of 6 mm, distributed at a spacing of 130 mm center-to-center. The characteristics of these bars are described in Table 1. The reinforcement cages comprising the forementioned bars were positioned inside the specimens with a concrete cover of 20 mm from all sides. One concrete batch was adopted to cast all specimens in order to evade the differences in the concrete grades. The raw materials of the concrete mixture were ordinary Portland cement (Tasluja type, agrees with Iraqi specifications [25]), crushed coarse aggregate with a grading size of (5-12 mm), and sand with the largest size of 4.75 mm; the water to cement ratio was fixed to 0.45; these materials were mixed in the weight proportion of 1 (cement): 1.72 (fine aggregates): 2.24 (coarse aggregate). For each specimen, three 150 mm cubes were fabricated according to the British standards [26]. The five corbel samples and the control cubes were kept damp for 28 days after casting to get the necessary treatment. Based on the results of ten poured cubes, the average concrete strength of five corbels was 32 MPa at 28 days.

3. Burning Processes and Test Setup
As stated, this article aimed at studying the impact of fire temperature on the reinforced concrete corbels. Therefore, four specimens were exposed to direct fire flame with different temperatures, starting from 300 °C to 900 °C, at an interval of 200 °C for one hour. A diesel furnace, stated in figure 2, was employed for this purpose; the internal space of this furnace was 1100×770×450 mm. the remaining one corbel was the reference left without exposure to fire for a comparison destination. After realizing the planned fire scenarios, the furnace was turned off, and specimens were remained inside the stove to cool down slowly. Then, the corbels were taken out; and their external surfaces were inspected accurately. In general, hair cracks were found to be distributed randomly on these surfaces, as demonstrated in figure 3. These cracks became much more evident and deepest as the fire temperature was elevated, chiefly above 500 °C.

Finally, the burned and reference corbels were tested through applying a three-point loading, with a shear span of 100 mm, by a hydraulic jack shown in Figure 4. Loads were applied regularly until the occurrence of failure. The applied loads were monitored by a load cell inserted between the upper face of columns and the piston rod of jack, whilst one LVDT was utilized to observe the vertical
displacement, located at the center of each corbel below the column, as clarified in figure 4. At each load level, the initiation and expansion of cracks on specimens’ faces were also surveyed.

It is worth declaring that the specimens were acknowledged by a letter C tailed by a burning temperature, as summarized in table 2.

Table 1. Mechanical characteristics of the used steel bars.

| Nominal diameter (mm) | Actual area (mm²) | Yield strength (MPa) | Ultimate strength (MPa) | Elongation % |
|-----------------------|-------------------|----------------------|-------------------------|--------------|
| 6                     | 28                | 271                  | 413                     | 21.64        |
| 12                    | 112               | 520                  | 672                     | 18.7         |

Figure 1. Dimension and reinforcement details of RC-corbels.

Figure 2. Burning and cooling process of the tested specimens.

Figure 3. Surface cracking after subjected to high temperatures.
4. Test Results

4.1 Cracking patterns and failure modes

As listed in Table 2, the first cracks appeared on the tested specimens at the connection lower points between the corbels and columns at loads of 48, 40, 20, 10, and 10 kN for samples C-25, C-300, C-500, C-700, and C-900, respectively. These observations could be justified as the concrete exposed to fire, its strength dropped as well, and therefore, the first cracks occurred prematurely.

The cracking behaviors of specimens C-25, C-300, and C-500, were relatively similar. In these samples, by increasing the loads, more cracks were initiated associated with the former's expansion. Then, diagonal cracks developed near the supporting points. The latter was seen to propagate toward the loaded face of columns. Once these cracks reached the upper connection points between columns and projected corbels, the specimens collapsed catastrophically due to shear failure, as shown in Figure 5.

The further two corbels, C-700 and C-900, which were exposed to significant temperatures of 700 ºC and 900 ºC, experienced completely different failure modes; this mode was direct shear, as seen in Figure 5. The main reason for the collapse of these specimens was developing one straight-up crack at the supporting beams' interior edge. This crack was seen to extend vertically throughout the corbels' depth. This crack configuration may be explained by high temperatures of more than 500 ºC, a sizeable amount of concrete cover spalled off. Accordingly, the external surfaces of corbels got coarse, mainly at the supporting zones, and hence, tremendous friction loads produced between these zones and the face of supporting beams. As a result, the vertical cracks causing the collapse of specimens C-700 and C-900 were detected owing to these immense horizontal friction loads.

| Specimens | Failure load (KN) | Residual Strength % | Failure mode |
|-----------|------------------|---------------------|--------------|
| C-25      | 148.88           | -----               | Diagonal shear |
| C-300     | 122.52           | 82.3                | Diagonal shear |
| C-500     | 94.68            | 63.6                | Diagonal shear |
| C-700     | 81.12            | 54.5                | Direct shear  |
| C-900     | 78.42            | 52.7                | Direct shear  |
4.2 Load-Deflection Response and residual strength.
At each load step, the vertical displacement was documented by LVDT mounted below the column stub at the center of corbel samples, as demonstrated in Figure 4. These consecutive readings are plotted parallel to the corresponding load level in Figure 6 for all corbels. As noted, the load-deflection curve of unburned corbel C-25 seems to be separated into two parts; the first one was approximately linear up to 90 kN, while the second was more soften where the increase in deflection was notable versus insignificant raise in the applied load. The last phase continued until failure. On the other hand, these two apparent phases were not perceived in the load-deflection curves of fire-exposed corbels; the curves were shown to consist of one phase without a sensible change in their stiffness with varying the applied load.

Compared with the reference corbel, the burned specimens had a less stiff load-deflection response from the beginning of tests due to experiencing fire hair cracks before experiments, as pronounced beforehand. These cracks led to remarkable decay in the stiffness of burned specimens. However, the samples burned at a temperature of higher than 500 °C indicated nearly matching responses. This similarity in behaviors could be imputed to losing the reinforcing bars and the significant concrete values of their strength beyond 500 °C, as stated in earlier studies [27–29].

Concerning the residual strength, the exposure to direct fire flame caused essential falls in the strength of corbels, as reported in table 2. These reductions resulted from deteriorations in the strength of principal components of corbels, steel bars, and concrete. As well, the bond strength between reinforcing bars and concrete dropped by higher temperature, reflecting the disability of reinforcing bars to develop sufficient strength. These reasons collected made the load-carrying capacities of fire-exposed specimens much lesser than that of the unburned specimen. Nevertheless, no distinguished alteration in the residual strength was informed after the temperature of 500 °C. Broadly, as listed in table 2, the residual strength of specimens exposed to temperatures of 300 °C, 500 °C, 700 °C, and 900 °C were about 82.3%, 63.6%, 54.5%, and 52.7% of the reference specimen strength, correspondingly.

Figure 5. Crack pattern of tested specimens at failure.
4.3 Ductility

The ductility index is a pointer recounting reinforced concrete members' adequacy to sustain essential plastic deformations without a vital reduction in their peak strength [30–32]. There are many procedures available to determine this indicator, and most of them depend on the yielding of steel reinforcement. However, in specimens exposed to high temperatures of fire flame, the use of strain gauges on steel bars was not potential. Therefore, this measure was determine based on the method presented by Spadea et al. [33]. In this manner, the ductility represents the total area ratio under the load-deflection curve to a partial area extended up to the service loads. The service loads for specimens were supposed 75% of their peak loads according to recommendations of prior studies [34–38]. Table 3 logs the ductility values of six considered corbels. As observed, the corbels’ ductility was reduced when burning specimens due to the reasons mentioned in the previous section. The decline in the ductility was in a range of 39.25% to 47.08%, compared to the reference corbel.

4.4 Secant Stiffness

The stiffness of reinforced concrete members can be assessed using several procedures. Herein, the secant stiffness was considered to explore the impact of fire flame on the stiffness of corbels. The secant stiffness was measured as the slope of a line linking the origin point of the load-deflection response with the point of ultimate loads [3]. Although this manner does not reflect the reinforced concrete corbels' real stiffness, it gives a clear indicator to discuss the descent in the stiffness due to fire flame, as instructed in table 3. It is clear that the corbels stiffness was damaged as a result of the burning processes. The damage level increased as the flame temperatures were augmented. The stiffness waning could be related to the creation of hair cracks during the burning operations. Besides, concrete porosity raises with high temperatures due to losing moisture. Therefore, the total stiffness of concrete was reduced [14]. These two reasons interpret the drop in the stiffness of burned samples. In general, the stiffness of burned specimens C-300, C-500, C-700, and C-900 were 5.6%, 13.5%, 16.9%, and 22.5% below the stiffness of unexposed corbel, respectively.

4.5 Flexural Toughness

Toughness defines the efficiency of concrete members to absorb energy without displaying a substantial reduction in their strength [39–41]. This mensuration is equivalent to the total area under the load-deflection response. The calculated values of flexural toughness for five corbels are addressed in table 3. This table discloses that enormous deteriorations were registered for burned corbels relative to the reference corbel without fire exposure. In the deep reinforced concrete members with short spans, their ability to resist cracking and crushing relies chiefly on the concrete strength. The latter
was found to be highly reduced because of fire flame, and as a result, the capacity of exposed corbels to disperse energy dropped. Due to subjecting the corbels to temperatures from 300 ºC to 900 ºC, the toughness of these corbels decays about 20.2% to 70.1%, respectively.

Table 3. Ductility factor, service stiffness and flexural toughness of the tested specimens.

| Specimens | Ductility factor (D.F) | secant stiffness (kN/mm) | Flexural toughness (kN.mm) | % Decrease In Ductility factor | % Decrease In secant stiffness | % Decrease In Flexural toughness |
|-----------|------------------------|--------------------------|---------------------------|------------------------------|-------------------------------|-------------------------------|
| C-25      | 2.93                   | 89                       | 257.75                    | 39.25                        | 5.62                          | 20.19                         |
| C-300     | 1.78                   | 84                       | 205.70                    | 43.34                        | 13.48                         | 48.47                         |
| C-500     | 1.67                   | 77                       | 132.81                    | 47.10                        | 16.85                         | 60.88                         |
| C-700     | 1.55                   | 74                       | 100.83                    | 47.08                        | 22.47                         | 70.08                         |
| C-900     | 1.58                   | 69                       | 77.13                     |                              |                               |                               |

5. Conclusions
The fundamental discoveries of the current investigation are described as follows;
- After burning, tiny fire cracks appeared on corbels' external faces; these cracks became more intense as the fire temperature increased. Moreover, two failure modes were observed; diagonal shear and direct shear when the exposure temperature exceeded 700 ºC.
- The burned specimens showed different load-deflection responses from the unexposed reference one. At the same force, the burned corbels gave more significant deflections than the unexposed one did. Moreover, the first cracking was seen prematurely in specimens subjected to fire flame.
- Compared to the reference corbel, the strength of 300 ºC to 900 ºC exposed specimens dropped around 17.7% to 47.6%, respectively.
- The exposure to 300 ºC to 900 ºC fire flame resulted in decays in corbels' mechanical properties, including ductility, stiffness, and toughness. The deteriorations in these characteristics arrived at 39.3%-47.08%, 5.6%-22.5%, and 20.2%-70.1%, respectively.

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