Behavior of eccentrically loaded normal weight concrete encased steel columns at elevated temperature

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Abstract. This paper presents an experimental investigation on the behavior of normal weight concrete encased steel (CES) columns eccentrically loaded and exposed to different elevated temperature using an electrical furnace. Four CES columns were tested with cross section dimensions of 150 ×150 mm (width× depth) and 1250mm total length and encased a steel section with dimensions of 70×60× 4×4 mm (total height× flange width× flange thickness)× web thickness. The top and bottom ends of the columns were designed as corbels to prevent the premature local bearing failure at the concrete due to axial load. The corbels had a cross section dimensions equal to 240mm ×150mm (width × depth) with a distance between them equal to750mm. The experimental results have revealed that all CES columns have failed by flexural buckling failure mode with concrete crushing at the middle third of the compression side column accompanied with local buckling of the steel section flange. Analysis of the test results has also indicated that when the exposed temperature increases, the failure load considerably decreases. Where, the failure load of the CES columns has decreased by 53.6%, 61.2%, and 63.6% compared to the control CES column when they exposed to temperature of 400°C, 500°C, 600°C, respectively.

1. Introduction
Due to the high thermal conductivity of the structural steel, its stiffness and yield strength reduce significantly under the high temperature levels. Therefore, thermal insulation is always required. On the other hand, the concrete has higher fire resistance compared to the steel due to the lower heat conductivity and the higher density AISC 360-16 [1], Jansson [2], Al-Thairy and Al-Jasmi [3], and Al-Thairy and Al-hasnawi [4]. So, one possible approach to provide the fire protection for the steel section, it can be encased inside the concrete. Many research studies such as Mao and Kodur [5], Mao et al. [6], and Wang et al. [7] have found that the concrete used in the composite columns enhance their load bearing capacity. So the different standards and codes start to take the concrete into account when designing composite members such as AISC 360-16 and EC4 part1-2 [1] and [8].When the load bearing members such as the columns are designed, great attention should be taken into the high temperature effect on the residual load bearing capacity. The EC4 part1-2 [8] have an attempt to take the effect of elevated temperatures into account in the design procedures of the composite columns subjected to elevated temperatures. However, it was found that most of the suggested procedures and equation still lack accuracy after comparing them to the results of the experimental tests at high temperature levels.
Therefore, the research on the failure modes of concrete encased I-section steel columns (CES) under high temperature levels are rare due to that the current study was made. Haung et al. [9] have carried out an experimental tests to study the effect of axial restraint on the fire resistance of concrete encased steel (CES) columns. Results have shown that the axial restraint decreases the fire resistance of the columns and all columns failed by crushing of concrete and the bending in the I-section steel. Haung et al. [10] have conducted an experimental and numerical study on fire resistance of concrete encased steel composite columns. The results of both studies have shown that lateral displacement of the column with least cross section is the largest one. In addition, it has been shown from FEA that increasing the load level results linear decreasing in concrete resistance to fire. Ellobody and Young [11] have proposed a numerical study to examine the performance of concrete encased steel columns under the high temperature levels. The results showed two failure modes which are concrete compressive failure in the specimens with small load and slenderness ratios and flexural buckling failure in all other columns with high slenderness ratio or high load ratio or both. The results have also revealed that the fire resistance of the composite columns increases by decreasing slenderness ratio and the load ratio. Further, it was noticed that the fire resistance decreased in columns with high steel ratio when small concrete cover and high load and slenderness ratios are used. Elllobody and Young [12] have conducted numerical study to investigate the influence of axial restraint on the behavior of composite columns at high temperatures. The fire resistance calculated using the finite element analysis was compared to the fire resistance predicted by the EC4 part 1-2 [8]. The results of the comparison showed that the EC4 [8] was conservative for the axially restrained composite columns except the columns with higher load and slenderness ratio.

Mao and Kodur [5] have made an experimental study to check the influence of heating from 3 sides and 4sides on the failure modes and performance of composite columns. The results have indicated that in the case of 3-sides heating exposure, the steel section temperature was lower than 4-sides heating exposure. Also, it was noticed that the high eccentricity and load ratio could lead to lower fire resistance of CES columns. Correia and Rodrigues [13] had made an experimental study to investigate the behavior of partially encased steel columns with axial and rotational restraint subjected to fire. All the columns had global flexural failure and no one of them had local buckling in the flange and this could be attributed to the partial encasement by the concrete.

The ultimate aim of this study is to experimentally investigate the behavior of normal weight concrete encased steel (CES) columns under eccentrically loaded and exposed to different elevated temperature. Four CES columns were designed according to AISC 360-16 [1] with cross section dimensions of 150 ×150 mm (width× depth) and 1250 mm total length. The top and bottom ends of the columns were designed as corbels to prevent the premature local bearing failure at the concrete due to axial load. The corbels had a cross section dimensions equal to 240mm ×150mm (width × depth) with a distance between them equal to 750mm. The CES columns specimens were firstly exposed to different elevated temperatures of 400°C, 500°C, and 600°C and then subjected to eccentric axial load with eccentricity ratio (e/h) equal to 0.5 where h is the depth of the column section.

2. Experimental program and test setup
2.1 Ingredient and proportions of concrete mixture
The ordinary Portland cement type (I) was used in this study which has been brought from the local market and conform to the Iraqi specification NO.5/1984. The fine aggregate used was natural sand. The results showed that the sand having grading which complied with the requests of the Iraqi standard specification (I.Q.S. No. 45 /1984) - zone 2. The coarse aggregate used was gravel with maximum size of (14 mm). The used water/cement ratio was 0.41 for the mixture. Depending on the used water/cement ratio, the concrete mix proportion was selected depending on ACI 211.1 [14]. The mix proportion was (1:1.6:2.6) (cement: sand: gravel) by weight. The resulted mixture gave 25 MPa compressive strength depending on the results of compressive strength test of the cylinders. The used reinforcing bars of diameters equal to 6,8,10,12, and 16mm gave yield strengths equal to 320, 325, 460, and 520.
2.2 The reinforcement and the geometric details

2.2.1.1 Steel section. A build up (I-section) composed from steel plates with yield strength equal to 160 MPa was used. The thickness of the plate used is 4mm for both web and flanges with flanges width of 60 mm and total depth of 70mm as shown in Figure 1.

![Figure 1](image)

**Figure 1.** The steel section used in the experimental study

2.2. CES column specimens.

Four concrete encased steel columns with dimensions of 150mm× 150 mm (depth× width) for the cross section and total length of 1250 mm were considered in the experimental tests. All concrete encased steel columns were designed to fail under the same axial concentric load at room temperature which was equal to 548kN. The columns were heated under different high temperature values and stayed inside the furnace for half an hour, then, they were cooled down to the room temperature (i.e. 20℃) naturally. Finally, the column specimens were subjected to eccentric axial load using eccentricity ratio (e/h) equal to 0.5 to case bending about the major axis of the I section. Minimum longitudinal bars reinforcement was used in the columns according to the design requirement of the AISC 360-16 [1].

The reinforcing and geometrical details of concrete encased steel columns are shown in Table 1 and Figure 2. Where the first number refers to the eccentricity ratio while the second letter (T) refers to the temperature and the followed number refers to the high temperature value used in the test

| Symbol | Dimensions (mm) | Eccentricity ratio (e/h) | Steel section (web length× Flange width× flange thickness × web thickness) mm | Longitudinal reinforcement | Temp.  |
|--------|-----------------|-------------------------|--------------------------------------------------------------------------------|---------------------------|-------|
| 0.5T20 | 150×150×1250    | 0.5                     | 68×60×4×4                                                                       | 4Ø8                       | 20℃   |
| 0.5T400| 150×150×1250    | 0.5                     | 68×60×4×4                                                                       | 4Ø8                       | 400℃  |
| 0.5T500| 150×150×1250    | 0.5                     | 68×60×4×4                                                                       | 4Ø8                       | 500℃  |
| 0.5T600| 150×150×1250    | 0.5                     | 68×60×4×4                                                                       | 4Ø8                       | 600℃  |

2.3 Casting and curing

2.3.1 CES column specimens. Four normal weight encased steel columns were casted and cured. All columns had the same dimensions. Before casting the specimens, the interior surface of the molds was cleaned. During casting process of the concrete electrical vibrator used to ensure the sufficient compaction for the specimens. After that the surface of the specimens was smoothly finished by using hand trowel. The columns were demoded after 24 hours from casting and treated using wet burlap for 28 days. The casting and curing of the column specimens are shown in Figure 3.

2.3.2 Concrete cubes and cylinders. Twenty-four cylinders with dimension of (100 x 200) mm and sixteen cubes with dimension of (150x150x150) mm were used to determine splitting tensile strength, modulus of elasticity, and compressive strength respectively. It should be noted that four temperature levels were tested in this study and that lead to divide the cubes and cylinders into four groups corresponding to these temperatures. Each group consist of four cubes and six cylinders. After finishing
the surface of the specimens using hand trowel, all of them were demoded after 24 hours from casting them and then they were immersed in the curing water in steel tanks for 28 days under ambient temperature. The steel tank was covered by a nylon sheet to ensure keeping the temperature within the limits of temperature required for curing. The casting and curing of the specimens are shown in the Figure 4.
3. Testing of concrete encased steel columns

3.1 Heating tests

In the heating tests, four CES columns were tested under different high temperatures values, namely: 400°C, 500°C, and 600°C using similar heating rate. After reaching the required temperature value, the temperature was fixed for half an hour inside the furnace for each one of the four columns. An electric furnace was designed, fabricated and examined for this study and used for heating the CES columns as shown in Figure 5. When the required temperature value is reached, the CES columns were cooled off to room temperature naturally. Thermocouples of type-K were used to record the values of temperature with the time at the column’s surface and at the surface of the encased steel section as shown in Figure 6.

Figure 4. Casting and curing of concrete cubes and cylinders.

Figure 5. Longitudinal section in electric furnace.
Figure 6. Positions of the thermocouple; (a) Thermocouple used for steel section; (b) Thermocouple used for concrete; (c) Thermocouple at the web of the steel section; (d) Thermocouple attached to the concrete surface.

3.2 Structural tests
In the structural tests, the control columns and the heated CES column were tested under an increased axial eccentric load at the bottom face of the column till the failure using Universal Testing Machine at the College of Engineering/ Al-Qadisyah University/Iraq (as shown in Figure 8). The Testing machine is able to apply load up to 2000 KN. Two bearing plates of dimensions 180 ×150 ×20 mm (width × length ×thickness) were used to prevent the local failure due to concentration of the stresses under the axial load. The boundary conditions of the column ends were arranged to replicate the simply support condition using 8 mm rode by allowing the ends to rotate freely about the line perpendicular to the column axis and to move in axial direction at the bottom end. In addition, to achieve the required eccentricity ratio (e/h=0.5), the location of the bearing plates at the ends of the column were selected such that the location of resultant applied the load distributed over the plated is equal to the required eccentricity value (i.e. e=75mm)as shown in Figure 7.

Figure 7. Location of the bearing plate.
3.3 Measurements devices

The axial and the mid height lateral displacements corresponding to every increment in the load during structural tests were monitored and recorded using mechanical dial gauges of 0.01 mm accuracy (Figure 9). The values of the displacements and load at each increment in the load were used to draw the load-axial displacement and the load –lateral displacement curves of the CES columns under different temperature values.

4. Results

4.1 Temperature- time relationships

The normal weight CES columns were exposed to different temperature values at first using specially manufactured electrical furnace. The furnace was designed for heating the CES columns before loading them. The relationship between the temperature and the time at concrete surface, inside the electrical furnace and at the steel section surface were recorded for all the heated specimens using thermocouples of type-K. Figure 4 describe the temperature – time relationships for all the heated CES columns under different temperature values. The heating process can be described as slow increment in temperature were the temperature of the furnace was raised 50 ℃ every twenty minute which gave heating rate equal to 2.5 ℃/min. A natural cooling method was used for all the columns. It can be noticed that the steel section get a small temperature value and that can be attributed to effect of the protecting cover of concrete which decrease the temperature transferred to the steel section. The temperature difference between the concrete and the steel section surfaces in the tested CES columns for the three high temperature values tested in this study is shown in Figure 10. It can be noticed that, the difference in temperature values between the concrete and the steel section surfaces is large even at the high temperature values which conform the low temperature transmitted between concrete and the steel section.
4.2 Load-displacement behavior, failure mode and crack patterns
The structural performance of the CES columns exposed to different elevate temperature values and tested under axial eccentric load are shown in Figures 12 and 13. It can be noticed from these two Figures that by increasing load, each column shows three response phases which are: elastic response, inelastic response, and failure response respectively. Flexural transverse cracks were originated at the mid span of the tension zone and propagate toward the compression zone. In addition, spalling of concrete cover, buckling of longitudinal reinforcement, and local buckling of the flange of the steel section took place at the compression zone as shown in Figure 14. Figures 12 and 13 shows that the maximum load bearing capacity of the heated NWC under different temperature of 400°C, 500°C, 600°C has reduced by 53.6%, 61.2%, and 63.6% when it compared to the unheated column. Table 2 shows the exposed temperature, maximum load bearing capacity and failure modes for all the tested CES columns.
Table 2. Summary of the test results.

| Column      | Failure Load (kN) | Failure Mode                                                                 |
|-------------|-------------------|------------------------------------------------------------------------------|
| 0.5T20      | 272.65            | Flexural buckling accompanied with steel local buckling and concrete spalling at the compression zone |
| 0.5T400     | 126.45            | Flexural buckling accompanied with steel local buckling and concrete spalling at the compression zone |
| 0.5N500     | 105.56            | Flexural buckling accompanied with steel local buckling and concrete spalling at the compression zone |
| 0.5N600     | 99                | Flexural buckling accompanied with steel local buckling and concrete spalling at the compression zone |

Figure 12. Load-lateral displacement behavior of normal weight CES columns under different temperature values.

Figure 13. Load-axial displacement behavior of normal weight CES columns under different temperature values.
5. Conclusions
The experimental results that study the behavior and failure modes of normal weight concrete encased steel columns that are exposed to different temperature values was described here. Four normal weight CES columns have been tested, three of them were exposed to different temperature values of (400°C, 500°C, and 600 °C). These temperature values were kept fixed for 30 minutes for each tested temperature. Afterward, all the CES columns were tested under eccentric axial loading until failure. The performance of CES columns which include failure load, load-lateral displacement, load–axial displacement, and failure modes have all been disused in this study. Some conclusions can be drawn.
from the current experimental test results which may help to suggest and give more accurate equations regarding the design of CES columns under elevated temperatures. The conclusions can be summarized as follows:

1. All the CES columns showed buckling failure mode with concrete crushing at the middle third of the column at the compression zone accompanied with inelastic local buckling of the steel flange and the main reinforcement.

2. The load bearing capacity is considerably decreased, when the applied high temperature is increased. Where, the load bearing capacity of CES columns has decreased by 53.6%, 61.2%, and 63.6% compared to the control CES column after exposing them to different temperature of 400℃, 500℃, 600℃, respectively.

3. All the tested CES columns under different elevated temperatures showed similar behavior when it comes to the difference between the temperature of the concrete surface and the steel surface where the difference between the two temperatures start to decrease after the concrete reaching temperature close to 400℃.

References

[1] “AISC 360-16, Specification for Structural Steel Buildings,” Chicago AISC, 2016.
[2] R. Jansson, “Fire spalling of concrete: theoretical and experimental studies.” KTH Royal Institute of Technology, 2013.
[3] H. Al-Thaier and S. K. Al-Jasmi, “Behavior of light weight reinforced concrete beam under elevated temperature,” MS&E, vol. 737, no. 1, p. 12020, 2020.
[4] H. Al-Thaier and N. H. Al-hasnawi, “Behavior and Failure Mode of GFRP bars RC Beams under Elevated Temperature,” in IOP Conference Series: Materials Science and Engineering, 2020, vol. 888, no. 1, p. 12012.
[5] X. Mao and V. K. R. Kodur, “Fire resistance of concrete encased steel columns under 3-and 4-side standard heating,” J. Constr. steel Res., vol. 67, no. 3, pp. 270–280, 2011.
[6] X. Y. Mao, W. H. Guo, and L. L. Li, “Experimental Investigation on Fire Resistance of CES Columns Subjected to 3-Side Heating,” in Advanced Materials Research, 2011, vol. 250, pp. 1657–1666.
[7] Y. Wang, Z. Liu, G. Li, J. Jiang, Y. Gao, and C. Fu, “Factors Influencing Bond Properties in Concrete Encased Steel Columns at High Temperatures,” Int. J. Steel Struct., pp. 1–12, 2020.
[8] E. C. Eurocode, “4: Design of Composite Steel and Concrete Structures Part 1-2: General Rules–Structural Fire Design,” Br. Stand. Institution, BS EN, pp. 1–2, 1994.
[9] Z.-F. Huang, K.-H. Tan, and G.-H. Phng, “Axial restraint effects on the fire resistance of composite columns encasing I-section steel,” J. Constr. Steel Res., vol. 63, no. 4, pp. 437–447, 2007.
[10] Z.-F. Huang, K.-H. Tan, W.-S. Toh, and G.-H. Phng, “Fire resistance of composite columns with embedded I-section steel—Effects of section size and load level,” J. Constr. Steel Res., vol. 64, no. 3, pp. 312–325, 2008.
[11] E. Ellobody and B. Young, “Investigation of concrete encased steel composite columns at elevated temperatures,” Thin-Walled Struct., vol. 48, no. 8, pp. 597–608, 2010.
[12] B. Young and E. Ellobody, “Performance of axially restrained concrete encased steel composite columns at elevated temperatures,” Eng. Struct., vol. 33, no. 1, pp. 245–254, 2011.
[13] A. J. P. M. Correia and J. P. C. Rodrigues, “Fire resistance of partially encased steel columns with restrained thermal elongation,” J. Constr. Steel Res., vol. 67, no. 4, pp. 593–601, 2011.
[14] A. C. I. C. 211, “Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete:(ACI 211.1-91),” 1991.
Acknowledgement
The authors express their gratitude to the technical staff and the administrative of the Collage of Engineering/Al-Qadisiyah University for their help and support and their permission to use the facilities, the testing machines, and other testing devices at the structural laboratory to finish the experimental tests as a part of the MSc study of the first author.