Behavior of Encased Composite Concrete Columns under Fire Exposure

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Abstract: **Composite column systems have become popular in tall building construction due to combining the rigidity and formability of reinforced concrete with the strength, ductility, and speed of construction of structural steel to produce an economic structure. This paper presents an experimental study to get more knowledge about the characteristics and the fire resistance of encased composite concrete columns. Three-scale three reinforced composite concrete columns were constructed and tested up to failure under direct fire at 500°C for two hours. The experimental program Consists of three specimens with 150 mm in diameter and 1500 mm in height, the first specimen (CIG 500 °c) reinforced by steel bars and built-up section have 7 gaps with a diameter of 5cm at the section web, the second specimen (CIB 500 °c) reinforced by steel bars and built-up section have 56 bolts and finally, the third specimen (CIP 500 °c) reinforced by steel bars and built-up section has 14 welded metal plate. The performance of the tested composite columns specimens is evaluated based on the crack pattern, first crack, failure load, ductility. Moreover, the experimental results are shown a proportional relationship between the degree of temperature and residual strength, causing the residual strength to decrease by 18.29 %. The result shows that the failure load for the encased composite column by plates (CIP 500 °c column) was much greater than the load-carrying capacity of other composite columns, this is due to the high capacity of steel material which is found inside the column. After exposure to a degree of fire 500 ° C, the encased composite column by plates steel shows that the failure load is higher than the failure load for the encased composite column by gaps and bolts by 29.7% and 8.17% respectively.**

Keywords: **encased composite; concrete columns; fire exposure; civil engineering.**

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1. INTRODUCTION

Composite structures represent an ideal alternative to typical engineering materials, this is due to the high demand for using more modern construction materials by using lightweight and high-strength structures. Composite column systems have become popular in tall building construction due to combining the rigidity and formability of reinforced concrete with the strength, ductility, and speed of construction of structural steel to produce an economic structure. Further axial compression of the structure leads directly to the phenomenon of loss of stability (buckling) [1]. Generally, failure is interpreted as the loss of the effective cross-sectional area of a structure due to micro-cracks [2-3]. The advantages of composite columns are increased stiffness, leading to reduced slenderness and increased buckling resistance, good fire resistance, corrosion protection in encased columns, significant economic advantages over either pure structural steel or reinforced concrete alternatives, and erection of high rise building in an extremely efficient manner The failure process requires the simultaneous use of several independent test methods, allowing for a thorough analysis of the limit states, directly accompanying the failure of the composite material [4-5]. For Myoung-Ho Oh (2006) [6], study the structural performance of steel-concrete composite columns subjected to axial and flexural loading.

The experimental results show that the steel-concrete composite column showed the failure pattern of the concrete crushing that occurred for the strong-axis direction, resulting in the reaching of the maximum load, and the tensile failure of the concrete that occurred for the weak-axis direction, resulting in the maximum load and the flexural strength in the weak-axis direction was significantly lower by about 50% than that for the strong-axis direction. Due to the thermal mass of concrete, composite columns always possess a higher fire resistance than corresponding steel columns. (It may be recalled that composite columns were developed for their inherent high fire resistance). Some of them had applied high-strength steel bars to ordinary steel concrete structures and found that high-strength steel bars can significantly improve the bearing capacity and ductility of reinforced concrete columns. Compared with high-strength steel bars, high-strength steel tubes can better restrain concrete [7].

Compared with the normal reinforced concrete columns, steel-reinforced concrete (SRC) columns have better structural performance, which can effectively reduce the cross-sectional size of structural columns and obtain larger building space. Compared with concrete-filled steel tubular columns, SRC columns can make full use of the compressive performances of high-strength steel, and poured concrete outside the steel can also avoid steel corrosion and improve the fire resistance of components [8]. Compared with plain concrete columns, permanent formwork composite columns can better control the development of cracks and improve the crack development mode under compression [9]. Composite columns are usually designed in the normal or ‘cool’ state and then checked under fire conditions. The fire resistance of composite columns with fully concrete-encased steel sections may be treated in the same way as reinforced concrete columns. The steel is insulated by an appropriate concrete cover and light reinforcement is also required to maintain the integrity of the concrete cover. In such cases, two-hour fire resistance can usually be achieved with the minimum concrete cover of 40 mm. For Margot F. Pereira (2016) [10], study the Structural behavior of partially encased composite columns under axial loads.

To evaluate the effective influence of the reinforcement type on the behavior and load capacity of the partially encased column and result, the effect of the type of reinforcement on the load capacity, stiffness, and post-peak behavior was not significant and the welded wire mesh can be used to replace the conventional steel bars simplifying the fabrication procedure. The structural response of the composite columns under concentric loading was affected only when the concrete strength was increased to 80 MPa, which suggests a change in the failure mode. Shan-Shan Huang (2013) [11], studied experimental investigation of the robustness at elevated temperatures of steel connections to two types of H-section column: reverse-channel connections to unfilled steel and flush endplate and reverse-channel connections to partially encased H-section columns. The ultimate strength and rotational capacity of these connections are many parameters studied. Result of the test: increase in temperature led to the capacities decreased rapidly and at temperature 650℃, the connections had little residual resistance.

2. RESEARCH OBJECTIVE

In this research the degree of fire is (500◦C for two hours) as it is high enough or present a fire event, also the concrete has a lower coefficient of thermal conductivity so the movement of heat through it is slow and thus the reinforcement inside it is protected, this rate ensures reaching this temperature to the core of concrete and the internal reinforcement and built-up section. The main purposes of this research are:

- Studying experimentally the effect of encased composite columns with confinement methods for I-beam by gaps, bolts, and plates.
- Studying the effect of composite columns under fire exposure(500 ◦C for two hours) on the crack pattern, displacement, failure mode, and ductility.

During this research, the results may provide primary information about the performance of encased composite columns by using gaps, bolts, and plates for built-up internal sections and be able to predict their response under fire exposure.

3. EXPERIMENTAL WORK

3.1 Materials

Experimental concrete mixes were prepared to yield a design compressive strength (f_{cu}) of 47.0MPa after 28 days. Concrete was produced by adjusting the size of thin and rough aggregates and increasing the quantity of cement paste to achieve high workability and reduce the risk of separation during the placing of concrete. After many attempts of producing the concrete mixes, the final ratios of the contents used for the mixing concrete are as shown in Table 1. The components were mixed using a cylinder tilting rotary mixer. The coarse aggregates, fine aggregates, and cement were dry mixed. Subsequently, water was added at regular intervals into the concrete blend after measuring the amount of cement, and the cement–water ratio was 0.5. The concrete mix was blended for two more minutes, resulting in a homogeneous concrete mixture. From the concrete mixture, ten cubes measuring 150 mm × 150 mm × 150 mm were cast to determine the compressive strength and eight cylinders 150 mm × 300 mm to measure the tensile strength. The components were mixed thoroughly using a 0.2 m3 tilting rotating drum concrete mixer. The concrete mixture was mixed for two more minutes, resulting in a homogeneous concrete mixture. The curing and casting processes were carried out according to the procedure stipulated in the ECP standard specification [12].

Main reinforcement steel bars of 10 mm diameter, while spiral steel 6 mm diameter was used as stirrups in all columns. Six bars were used in the reinforcement of the tested specimens. One I-steel beam was used in the reinforcement pattern, this was confinement with the different methods as bolts, plates, and gaps. To evaluate the axial tensile strength, at least three samples of bar 10 mm diameter were tested. Electrical strain gauges were bonded at the middle of the bar to measure the strain in the bars during the test. As shown in Fig. 1, the test was performed using a Shimadzu machine at the strength of the materials laboratory at Helwan University. The stress-strain curves of the tested bars are shown in Fig. 2.

Table 1: Proportions of Components in Concrete Mixture

Compressive Strength fcu (MPa)	Cement Content (kg/m^3)	Fine Aggregates (kg/m^3)	Coarse Aggregates (kg/m^3)	Water–Cement Ratio
47.0	350	785	1200	0.5

Fig.1. Shimadzu machine

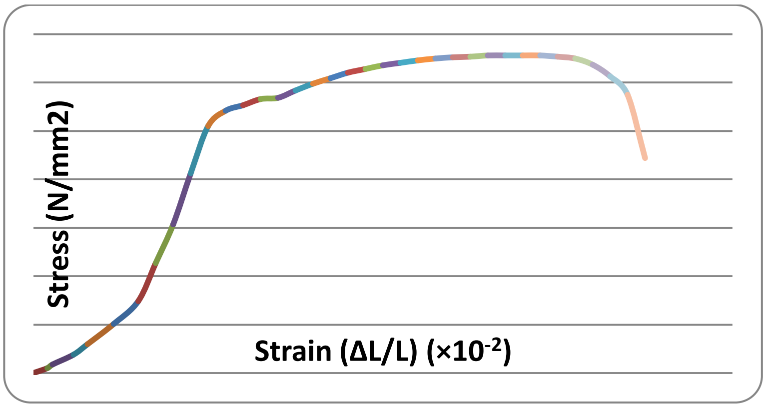

Fig.2. Stress-StrainCurveforSteelBar

Table 2: Details of Composite Columns Prepared in This Study

Sample name	Degree of fire	Fire duration	Type of Additional Bonding	Specimen Height (mm)	Specimen Diameter (mm)
CIG 500	500◦c	2 hours	I-Steel with bolts	1500	150
CIB 500			I-Steel with gaps		
CIP 500			I-Steel with plates		

3.2. Preparation of test specimens

Three reinforced concrete composite columns were tested in this study and tested up to failure under direct fire at 500 ◦C for two hours. All composite columns had 25 mm concrete cover, exposed to fire for two hours, and specimens are shown in Table 2. The details of the reinforcement and the cross-section of the tested columns are illustrated in Fig. 3. Wooden formworks were applied to make the FRP tubes fixed inside it, to be sure the vertical position for the columns and no lateral sway happen during casting for the columns. FRP tubes having an inner diameter of 150 mm and wall thick 4.7 mm were used as formwork. FRP tube transported to the laboratory in 6.00-meter length and then cut by a band saw to 1500 mm lengths. Tubes were organized above flat steel plates to ensure flatness and perpendicularity, as shown in Fig.4. All columns' specimens were cured regularly by a sprinkling of water and covered by sackcloth to prevent moisture release from the concrete surface until the date of testing. Cubes were cured by immersing them in water.

Fig.3. Details of Composite Steel Beams

Fig.4. Details of Composite Beams Inside the FRP Tubes

Fig.5. Columns subjected to fire

3.3. Fire exposure system

The furnace was heated to the required temperature, i.e. (500◦C), and then kept at this temperature for two hours. The columns subjected to direct fire are shown in Fig.5. The used regime for cooling the fire columns was air.

3.4. Experimental setup and testing

All the columns were tested using the Hydraulic Jack testing machine as shown in Fig.6 and Fig.7. To transfer loading from the machine to the columns uniformly, each column was leveled by high-strength plaster at both the top and bottom surfaces. Then the load was applied gradually by the loading machine. The displacement (LVDT) was measured using two dial gauges located on right and left of tested columns. The digital load cell of capacity 550kN was adopted to measure the applied load, the load increments, and the displacements were read directly from the data recorder. The crack growth of the specimens during loading and at the time of failure was observed.

Fig.6. Load Cell, Data Logger and Reader

Fig.7. Experimental Test Setup

4. RESULTS AND DISCUSSION

4.1. Crack pattern and failure mode

Table 3 shows the results of all tested composite columns, including the cracking load and its corresponding displacement (P_{cr} and Δ_{cr}) as well as the ultimate load and its corresponding displacement (P_f and Δ_f). Furthermore, the failure patterns of the Composite columns were observed, the spalling of concrete increases with increasing the temperature degree. This appearance was shown for columns which confinement with gaps and bolts more than columns confinement with plates. The cracks formed and grew randomly. With increasing load, the concrete cover spalls in some places near the specimens' corners. The spalling happened during the exposure to high temperature in wide areas, the effect of damaging in the specimens CIG 500℃ and CIB 500℃ more than the specimen CIP 500℃. Most of the cracks were observed in the middle third of columns and spalling happened in this place. The fire composite column confinement with steel plates for steel beam has a decrease in the number of cracks that extended at the ends of the column compared with the other fire composite columns, this is maybe due to the confinement method by steel plates having slightly affected by the degree of fire. As clearly, the failure mode depends on the degree of temperature and amount of steel materials inside the columns. Fig. 9 shows the crack development and failure type for all tested composite columns.

Table 3: Summarized Results for Composite Columns at 500°C

Specimen Name	First Crack Stage		Failure Stage		Mode of Failure
	P_{cr} (kN)	Δ_{cr} (mm)	P_f (kN)	Δ_f (mm)	
CIG 500	432.35	3.2	582.7	6.56	Buckling Failure
CIB 500	607.08	4.37	756.4	10.23	Buckling Failure
CIP 500	617.0	5.72	823.32	12.98	Compression Failure

Fig.8. Crack pattern and Failure Mode of Tested Composite Columns

4.2. Load-displacement curves

The relationship between the applied load and the axial displacement for the studied composite columns at 500°c is shown in Fig. 9. CIB 500°C column, and CIP 500°C column showed an increase in failure load, while the CIG 500°C column give a little lower failure load, this may be due to the increase in the volume for steel beam by confinement methods by steel plates, leading to an increase in the strength of column [12]. The use of confinement for steel beam enhanced the ultimate strength of the composite column but after exposure to the fire reduced the ultimate strength, this may be due to the fact the steel reinforcement was affected by high temperature (above 450°c) and this agrees with Shan-Shan Huang [10].

It was found that the CIG 500°c has the failure load smaller than the failure load for CIP 500°c column by 30.0 % and was found that the CIB 500°c has the failure load smaller than the failure load for CIP 500°c column by 19.13 %.

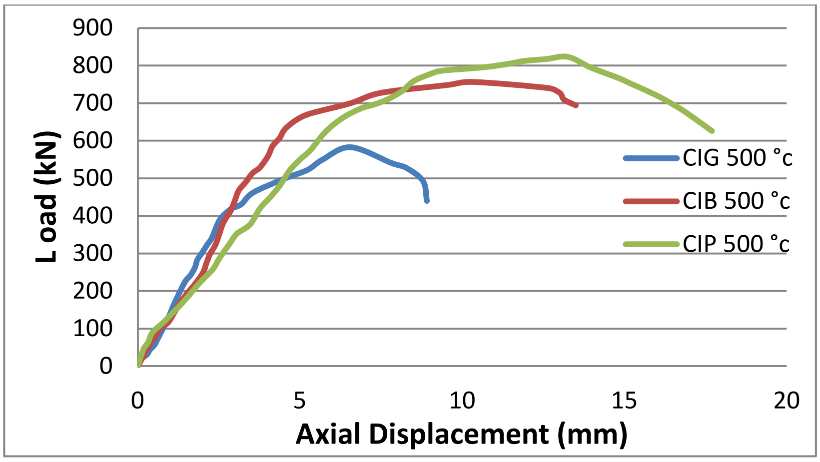

Fig.9. Load-Axial Displacement Curve for Tested Fire Composite Columns at Temperature 500°C

4.3. Ductility

Ductility is a measure of a material's ability to undergo significant plastic deformation before rupture or breaking. The ductility index is defined as μ = Ap / Au where Ap is the area under the load-displacement curve at peak load and Au is the area under load-displacement curve before the load drops to 25 % of the peak load. Should be observed that CIP 500° c column achieved the ductility higher than CIB 500℃ and CIG 500°c by 64.5 % and 36.16 %. Fig.10. shows the ductility index for all columns.

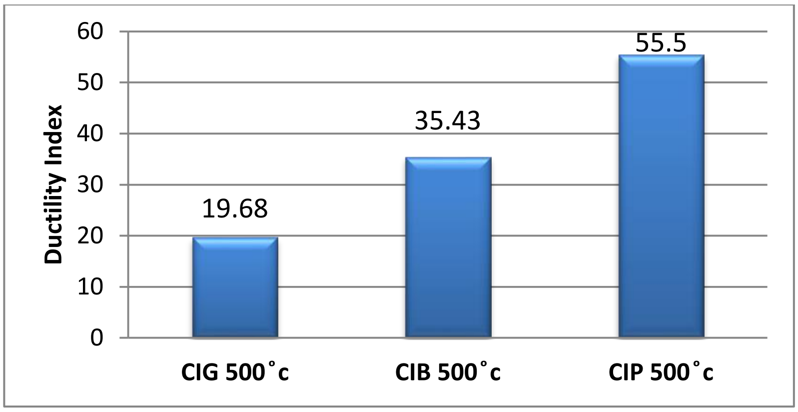

Fig.10. Ductility Index for Composite Columns at Temperature 500°C

5. CONCLUSIONS

The conclusions of this study are as follows:

- At exposure to the degree of fire, spalling of concrete increases with increasing the temperature degree. Thus, Exposure to a fire caused more damage to the concrete columns.
- At columns were exposed to the degree of fire, the relation between temperature degree and residual strength is an Inverse relationship. Also, the effect of temperature is increased when it reached 500°C, causing the residual strength to decrease by 18.29 %.
- An encased composite column with plates has a smaller number of cracks compared with the other encased composite columns with gaps and bolts. The weak deformation for encased composite columns with the plates compared to high deformation for encased composite columns with gaps.
- At exposure, the composite columns for the degree of fire at temperature 500℃, the failure load in the case of CIP 500℃ column, higher than failure load for CIB 500℃ and CIG 500℃ columns and that is a rate by 8.17 % and 29.70 % respectively.
- Encased composite column by plates (CIP) achieved the best results under the influence of fire.

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