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Experimental Study on the Effects of Fire on the Axial Strength of Hollow RC Columns

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Keywords:
Axial strength; Fire exposure; Hollow columns; Temperature effects; Reinforced concrete columns.

Highlights:

- *Assessing the performance of reinforced concrete hollow columns under fire flame.*
- *Two main parameters were considered: hollow diameter and burning temperature.*
- *Increasing the hollow size or burning temperature could deteriorate the column carrying capacity.*

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Abstract: Understanding the performance of the concrete members during fires is crucial for safety and risk assessment**.** The present study investigates the performance of reinforced concrete hollow columns when exposed to fire flame. Sixteen hollow columns, each with a uniform height of 1000 mm and a cross-section of 150 mm × 150 mm, were subjected to axial compression load until failure. The main parameters considered were the hollow diameter and flame temperature. The hollow diameter ranged from 25.4 mm to 76.2 mm, while the flame temperature varied from 300 °C to 700 °C in 200 °C intervals over a one-hour duration. The results indicated that the axial load capacity of columns has dropped as the fire flame temperature increased for the same hollow size. The reduction in axial load capacity ranged from 20.10% to 68.42% for temperatures between 300 °C and 700 °C. In addition, under identical burning conditions, the specimen with a bigger hollow diameter exhibited a higher load capacity reduction. Finally, beyond a hollow diameter of 25.4 mm or a fire flame temperature of 300 °C, the axial stiffness of columns was significantly reduced.

دراسة مختبرية لتأثير الحريق على مقاومة الأعمدة المجوفة الخرسانية المسلحة للحمل المحوري

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الخلاصة
ان فهم تصرف الاعمدة الخرسانية المسلحة خلال تعرضها للحريق هو امر في غاية الاهمية بالنسبة لسلامة المنشأ وتقييم المخاطر. تهدف الدراسة الحالية إلى التحقيق في أداء الأعمدة المجوفة الخرسانية المسلحة عند تعرضها الى لهيب النار. تم تعريض ستة عشر عموداً مجوفاً، بطول موحد يبلغ ١٠٠٠ مم ومقطع عرضي ١٥٠ مم × ١٥٠ مم، لحمل ضغط محوري حتى الفشل. تمثلت المتغيرات الرئيسية في قطر الفراغ ودرجة حرارة اللهب. وتراوح قطر الفراغ بين ٢٥,٤ مم و ٧٦,٢ مم، بينما تراوحت درجة حرارة اللهب بين ٣٠٠ درجة مئوية و ٧٠٠ درجة مئوية على فترات زمنية قدرها ٢٠٠ درجة مئوية لمدة ساعة واحدة. أظهرت النتائج انخفاض قدرة التحمل المحورية للأعمدة مع زيادة درجة حرارة اللهب لنفس حجم الفراغ. تراوح انخفاض القدرة التحميلية المحورية بين ٢٠,١٠٪ و ٦٨,٤٢٪ لدرجات حرارة بين ٣٠٠ درجة مئوية و ٧٠٠ درجة مئوية. بالإضافة إلى ذلك، وفي ظل ظروف الاحتراق نفسها، أظهرت العينة ذات القطر الأكبر للفراغ انخفاضاً أكبر في القدرة التحميلية. وأخيرًا، بعد تجاوز قطر الفراغ ٢٥,٤ مم أو درجة حرارة اللهب ٣٠٠ درجة مئوية، انخفضت قوة التحمل المحورية للأعمدة بشكل كبير.

الكلمات الدالة: قوة التحمل المحورية، التعرض للنار، الاعمدة المجوفة، تاثيرات الحرارة، الاعمدة الخرسانية المسلحة.

1.INTRODUCTION

The adoption of hollow sections in the design of columns for high-rise buildings has gained prominence, particularly in seismic-prone regions. The strategic reduction in concrete mass not only minimizes self-weight contributions but also enhances seismic response. Moreover, hollow columns alleviate foundation loads, leading to cost-effective construction practices [1–4]. Khamees et al. [5] studied the effect of the hollow ratio and column shape on the performance of the columns. It is reported that increasing the hollow ratio decreases the load-carrying capacity, ductility, and stiffness. Furthermore, the hollow circle column has a better performance than the hollow square columns. Jumah [6] investigated the performance of short hollow circular columns made of high-strength concrete. It is indicated that increasing the hole size could negatively affect the column strength. However, increasing the reinforcement ratio could notably enhance its strength. Azzawi and Abolmaail [7] experimentally studied the behavior of the steel fiber reinforced hollow columns under eccentric load. The results proved that adding fiber to hollow columns could delay the first cracking load, allowing the columns to absorb more load before failure. In the context of structural safety, fire resistance remains a critical criterion for building design. Ensuring satisfactory load transfer during fire incidents without endangering occupants or neighboring structures is paramount. Among structural elements, columns play a pivotal role, as the failure of even one column can result in severe damage to the entire structure [8–14]. Studies have explored the impact of fire on the behavior of reinforced concrete columns. Kodur et al. [15] explored the post-fire performance of externally confined reinforced concrete columns using fiber-reinforced polymer (FRP) wraps. Their study considered circular and square cross-sectional shapes, revealing superior structural behavior in circular columns reinforced with FRP wraps. Similarly, Izzat [16] examined twelve reinforced concrete columns with self-compacting concrete, subjecting them to varying temperatures (300 °C to 700 °C). The results highlighted significant reductions in axial load capacity due to elevated temperatures. Furthermore, sudden cooling (via water spraying) intensified the decline in ultimate load compared to gradual cooling. Bikhiet et al. [17] conducted experimental and theoretical investigations on reinforced concrete columns exposed to fire temperatures up to 600 °C. Their study emphasized parameters, such as compressive strength, fire duration, yield strength, and longitudinal reinforcement percentage. The findings demonstrated load capacity reductions of 20-40% for fire-exposed specimens. Concrete-filled steel tube (CFST) columns have also been scrutinized under fire conditions [17–24]. Romerot et al. [18] explored the behavior of circular CFST columns filled with normal and high-strength concrete (30 and 80 MPa). Despite variations in fire exposure, slender columns with high compressive strength concrete exhibited distinct behavior compared to shorter columns. Surprisingly, fire resistance did not improve significantly when using steel fiber-reinforced concrete as filling material, consistent with prior studies [25–27]. The primary objective of this study is to investigate the behavior of hollow concrete columns when exposed to fire flames. Despite the widespread utilization of hollow reinforced concrete columns, there exists a noticeable gap in experimental studies that comprehensively examine their fire performance. Specifically, this research aims to explore how varying hollow sizes impact the response of these columns under fire conditions.

2.EXPERIMENTAL PROGRAM

2.1.Geometry and Materials Properties

The experimental program featured 16 column specimens categorized into four groups. Each group comprised a solid RC concrete column and three hollow columns with a varying hole diameter (25.4, 54.8 mm, and 76.2 mm). The hollow core was made by inserting a PVC pipe in the center of the column. The first group was conditioned at the room temperature of 25 °C, while the remaining groups were exposed to three different temperatures (300, 500, and 700 °C), with each group exposed to a single temperature. The columns had a cross-section of 150 mm × 150mm and a height of 1000 mm. Each column was reinforced with 4 ∅ 12 mm as longitudinal reinforcement and 6 mm transversal ties spaced at 120 mm center to center. Figure 1 illustrates the geometrical dimensions and the reinforcement arrangement of the columns. The yielding strength of the longitudinal reinforcement was 444 MPa, while the yielding strength of the transversal reinforcement was 385 MPa. Concrete mix composition consisted of ordinary cement as a binder material. The coarse aggregate had a maximum particle size of 20 mm, while the fine aggregate had a maximum size of 4.75 mm. The water/cement ratio was maintained throughout the study at 0.45. The compressive strength of the concrete was assessed using standard cubes with a side length of 150 mm. The average compressive strength was determined to be 32 MPa. To facilitate the distinction between the specimens, they were named following a distinctive code system consisting of two parts. The prefix C in the first part denoted the hollow core, while the number after the prefix referred to the diameter of the central hollow core. The number in the second part indicated the burning temperature. Table 1 illustrates the specimens of each group.

Table 1 Details of Reinforced Concrete Column Specimens.

Group	Specimens	Hollow size (mm)	Burning Temperature (°C)
1	C0-25	0	25
	C25.4-25	25.4	
	C50.8-25	50.8	
	C76.2-25	76.2	
2	C0-300	0	300
	C25.4-300	25.4	
	C50.8-300	50.8	
	C76.2-300	76.2	
3	C0-500	0	500
	C25.4-500	25.4	
	C50.8-500	50.8	
	C76.2-500	76.2	
4	C0-700	0	700
	C25.4-700	25.4	
	C50.8-700	50.8	
	C76.2-700	76.2	

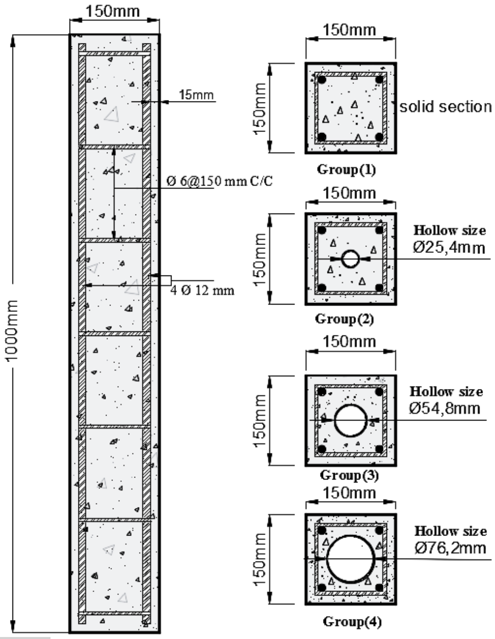

Fig. 1 Details of Reinforced Concrete Column Specimens.

2.2.Fire Burning Procedure and Test Setup

After 28 days of curing, the column specimens were exposed to a controlled temperature from a fire flame using a diesel furnace with internal dimensions 1100×770×450 mm. The specimens of each group were simultaneously exposed to a specific temperature of 300 °C, 500 °C, and 700 °C for one hour. These specific burning temperatures were selected based on the findings of Bamonte and Felicetti [28], who reported a peak temperature of approximately 500 °C for closed parking lots during real fire accidents. Therefore, to accurately simulate real-world conditions and gather meaningful data, a burning temperature of 500 °C was chosen in the present study. Furthermore, to gain a comprehensive understanding of the behavior of the hollow columns under various fire conditions, temperatures both lower and higher than the peak temperature were explored by subtracting and adding 200 °C, respectively, to the peak temperature (500 °C). Following the fire exposure, the test specimens were allowed to cool naturally without any external intervention. During the cooling phase, the surfaces of the burnt samples were carefully observed. It was revealed that the severity of cracks increased with the flame temperature of the fire. Subsequently, the column specimens were axially loaded using a universal testing machine with a capacity of 1000 kN. Figure 2 illustrates the test setup of the columns. The load was incrementally increased at a rate of 1 kN/s until failure. Throughout the testing process, axial deformation was recorded using a dial gauge with an accuracy of 0.01 mm. Figure 3 illustrates the surface cracking of concrete specimens after fire exposure.

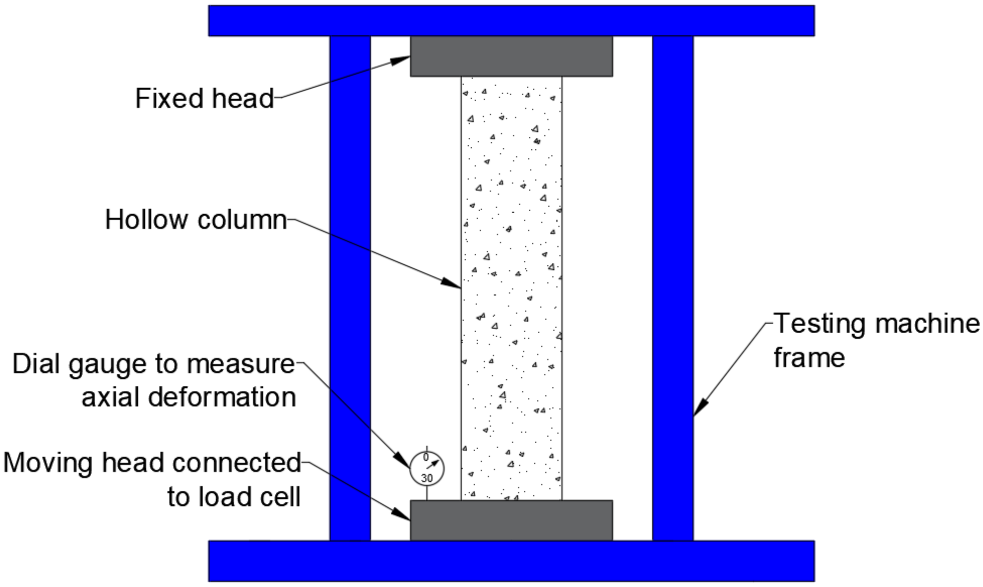

Fig. 2 Axial Load Test Setup.

Fig. 3 Cracking After Subjecting to High Temperatures.

3.TEST RESULTS

3.1.Modes of Failure

The results revealed that the control specimens, those not exposed to fire, exhibited smaller crack widths than the specimens exposed to fire. The first crack was recorded close to the middle of the specimens at loads of 102.3, 88.2, 63.5, and 44.5 kN for specimens C0-25, C25.4-25, C50.8-25, and C76.2-25, respectively. As the load increased, several new cracks were developed. In addition, the previously formed cracks were propagated vertically toward the ends of the columns, and their width increased. It was noted that the cracks continued to propagate longitudinally to the end of the columns before inclining toward the corners as the load value increased. Eventually, the specimens failed by crashing concrete at their end due to the high stresses. It is important to mention that specimen C76.2-25 was separated longitudinally at failure, as shown in Figure 4. Regarding the behavior of the burned specimens, it was difficult to specify the first cracking load due to the development of cracks during the burning processes, as illustrated in Figure 3. Nevertheless, the concrete cover of the burned specimens was easily flaked at early loading stages, especially for specimens exposed to a temperature of 700 °C. Like the control specimens, the burned specimens failed by crashing the concrete at the ends of the columns. However, unlike the control specimens, no longitudinal separation was observed in the burned specimens.

3.2.Load Capacity of Columns

Figure 5 illustrates the axial load capacity of the four groups. The load capacity of the specimens conditioned at room temperature (25 °C) continuously decreased as the diameter of the hollow core increased. Particularly, it is decreased from 260 kN for a solid specimen to 194, 133, and 98 kN for specimens with a hole diameter of 25.4, 50.8, and 76.2 mm, respectively, indicating a decreasing percentage of 25%, 49%, and 62%, respectively. This behavior was also noted for the specimens exposed to a temperature of 300 °C, where the load capacity of specimens decreased form 202 kN for the reference specimen to 155, 95, and 76 kN for the specimen with hole diameter of 25.4, 50.8, and 76.2 mm, respectively, indicating a decrement ratio of 23%, 53%, and 62%, respectively. The specimens of group three (exposed to 500 °C) revealed a similar behavior, where the load capacity decreased from 167 kN for reference specimen to 114, 67, and 52 kN for the specimens with hole sizes of 25.4, 50.8, and 76.2 mm, respectively, indicating a decrement ratio of 32%, 60%, and 69%, respectively. The decrease in the load capacity was also recorded for the specimens of group four where it is decreased from 114 kN for the reference specimen to 82, 42, and 33 kN for the specimens with a hole diameter of 25.4, 50.8, and 76.2 mm, respectively, representing a reduction percentage of 28%, 63%, and 71%, respectively. Figure 5 also demonstrates the effect of the various burning temperatures on the load capacity of the different groups. The load capacity of the solid specimens has progressively decreased as the burning temperature increased to 300, 500, and 700 °C, where the percentage of decrement was 22.3%, 36%, and 56%, respectively, as reported in Table 2. The load capacity of the specimens with a hole diameter of 25.4 mm continuously decreased as the burning temperature increased, where the ratios of decrement were 20%, 41%, and 58% at temperatures of 300, 500, and 700 °C, respectively. Specimens with a hole diameter of 50.8 also demonstrated a similar performance, where the load capacity decreased by 29%, 50%, and 68% as the temperature progressively increased to 300, 500, and 700 °C, respectively. Finally, the load capacity of the specimens with a hole diameter of 76.2 mm decreased with temperature increase, where the ratios of decrement were 23%, 47%, and 66% at temperatures of 300, 500, and 700 °C, respectively. It is implied from the results that increasing the hole diameter or burning temperature can notably reduce the load capacity. However, as the burning temperature increased, the percentage of decrement in the load capacity of hollow core specimens in comparison to the solid specimen was insignificantly affected.

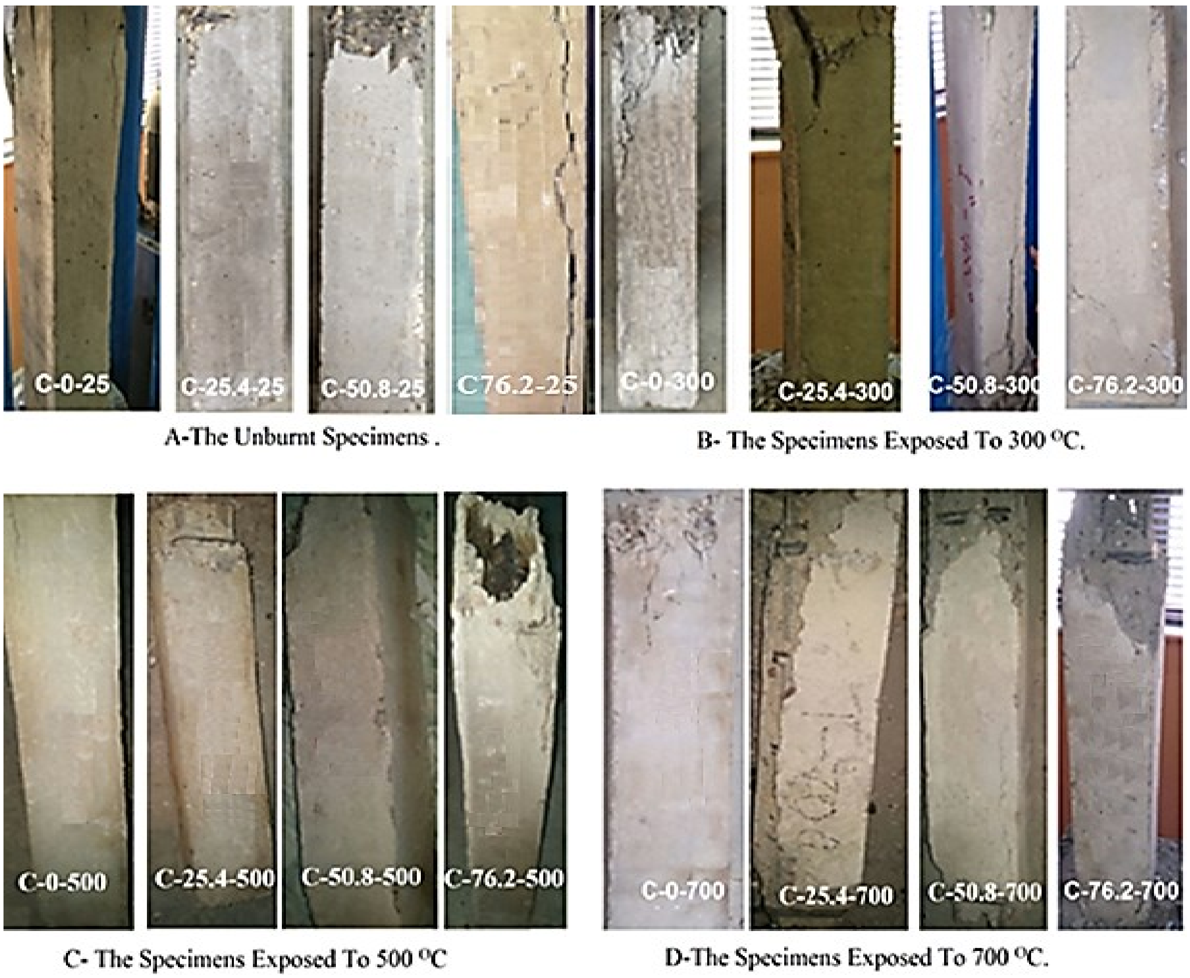

Fig. 4 Crack Patterns of Column Specimens at Failure.

Table 2 Ultimate Axial Loads of Tested Columns.

Group	Specimens	Temperature (°C)	Axial Load Failure (kN)	Decrease in load capacity in relation to reference specimens (%)
1	C0-25	25	260	Reference
	C25.4-25		194	
	C50.8-25		133	
	C76.2-25		98	
2	C0-300	300	202	22
	C25.4-300		155	20
	C50.8-300		95	29
	C76.2-300		76	23
3	C0-500	500	167	36
	C25.4-500		114	41
	C50.8-500		67	50
	C76.2-500		52	47
4	C0-700	700	114	56
	C25.4-700		82	58
	C50.8-700		42	68
	C76.2-700		33	66

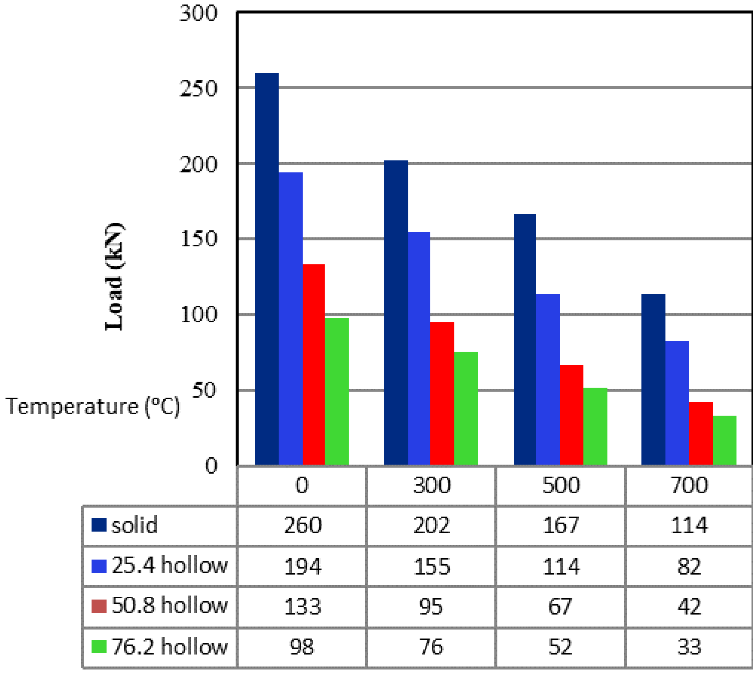

Fig. 5 Axial load Against Flame Temperature.

3.3.Load-deflection relationship

Figures 6-9 illustrate the relationship between the axial deflection and the axial load for RC columns having hole diameters of 25.4, 50.8, and 76.2 mm, respectively. The curves demonstrate that the axial deflection increased with the burning temperature. This behavior is ascribed to the decrease in axial stiffness due to the reduction in the effective cross-sectional area and formation of cracks and spalling of the concrete cover during the burning process. Moreover, the modulus of elasticity was significantly deteriorated with the rise of fire flame temperature [29]. The columns exposed to a burning temperature of 300 °C exhibited axial deflection comparable to their non-burning counterparts, up to a loading level of 170, 100, 50, and 55 kN for the specimens C0-25, C25.4-25, C50.8-25, and C76.2-25, respectively. Nevertheless, beyond these loading levels, it is obvious that the structural elements were severely damaged because of the elevated temperature, leading to a substantial deterioration in the mechanical properties of concrete and steel reinforcement [25]. Figures 10-13 present the load-deflection responses of specimens with different hole diameters at various temperatures. At the room temperature (Fig. 10), the reference specimen (C0-25) exhibited the highest load capacity and stiffness. Nevertheless, introducing a hole of 25.4 mm, as for specimen C25.4-25, decreased the load capacity and stiffness. The load capacity and stiffness continued decreasing as the hole diameter increased for the remaining specimen of this group. Figure 11 illustrates the load-deflection response of the specimens having various hole diameters at a temperature of 300 °C. The response of the specimens in this group was insignificantly changed from the response of the previous group of specimens. Figures 12 and 13 demonstrate the load-deflection response of the specimens having different hole diameters exposed to temperatures of 500 °C and 700 °C, respectively. The result denoted that the solid specimens, which had no holes, in addition to having the highest load capacity, also had the highest axial deflection, implying good ductile behavior. However, the load capacity and axial deflection reduced gradually as the hole diameter increased.

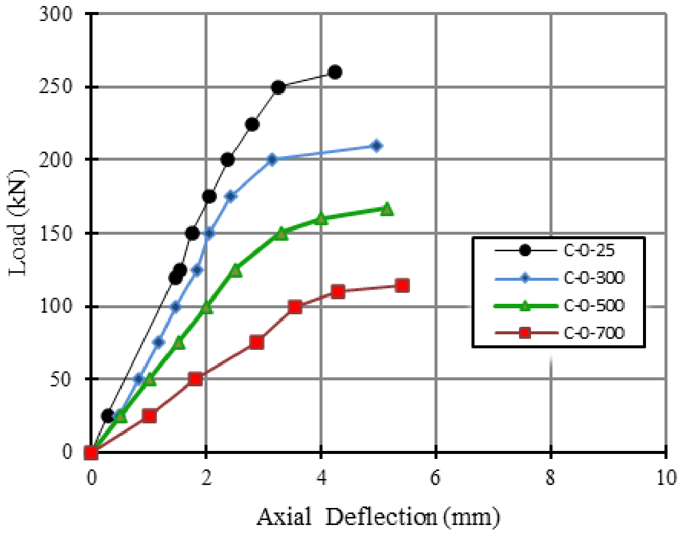

Fig. 6 Load-Axial Deflection for Solid Specimens.

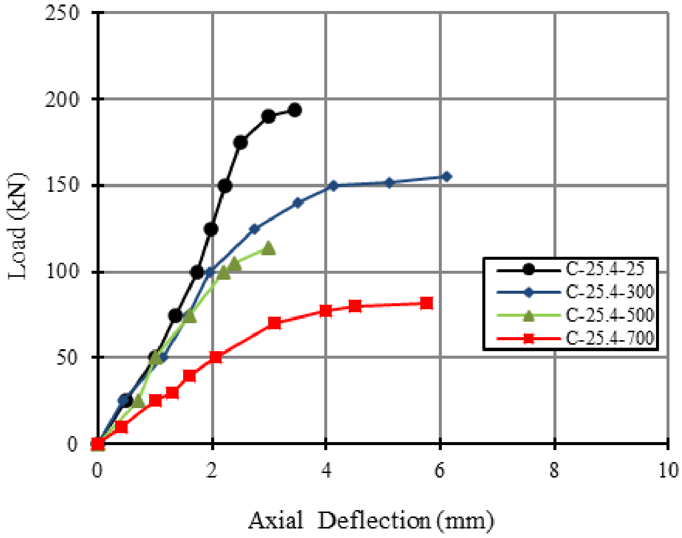

Fig. 7 Load-Axial Deflection for Specimens with Hollow Size 25.4 mm.

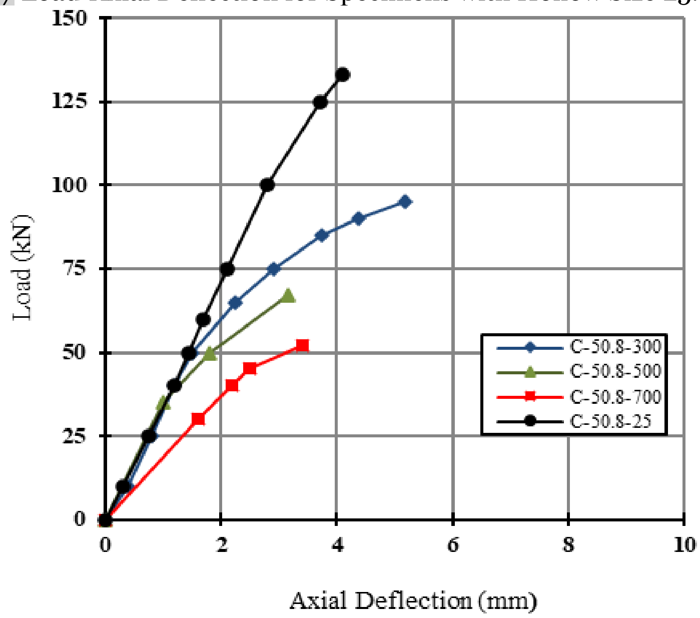

Fig. 8 Load-Axial Deflection for Specimens with Hollow Size 50.8 mm.

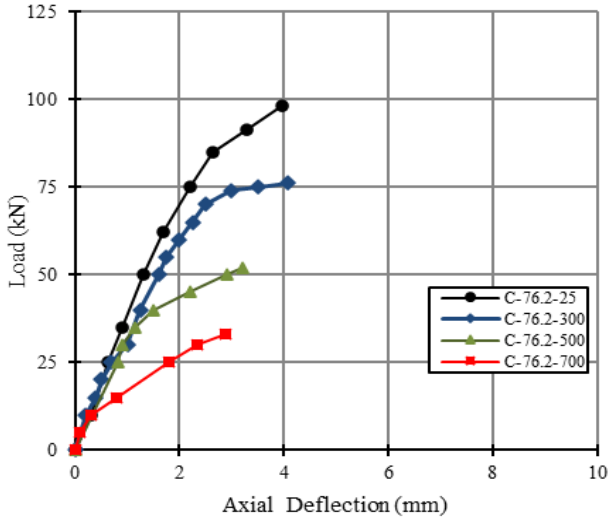

Fig. 9 Load-Axial Deflection for Specimens with Hollow Size 76.2 mm.

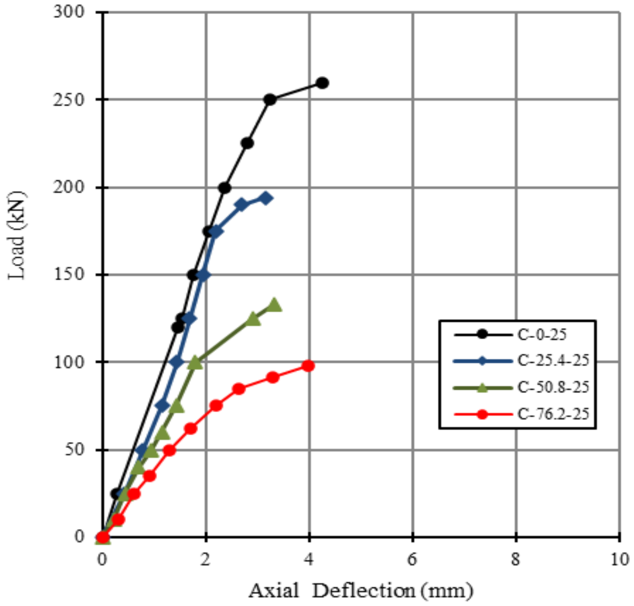

Fig. 10 Load-Axial Deflection for the Unburnt Specimens.

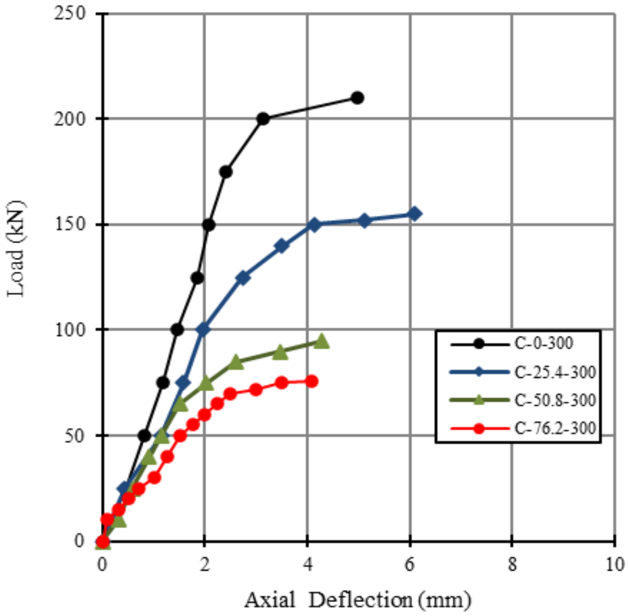

Fig. 11 Load-Axial Deflection for the Specimens Burnt at 300 °C.

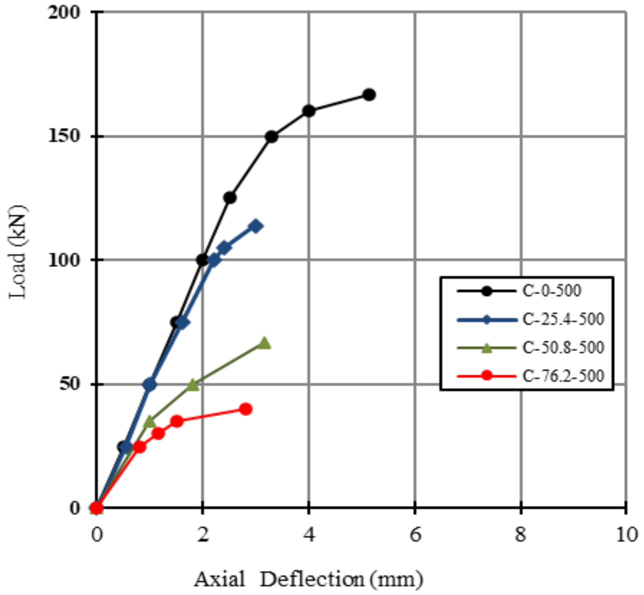

Fig. 12 Load-Axial Deflection for the Specimens Burnt at 500 °C.

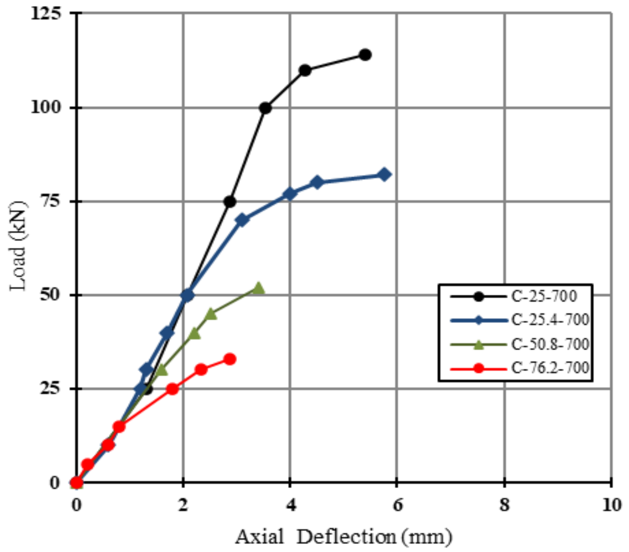

Fig. 13 Load-Axial Deflection for the Specimens Burnt at 700 °C.

4. CONCLUSIONS

The present study discussed the influence of the fire burning temperature and hole size on the behavior of reinforced concrete columns. The following main conclusions can be summarized:

1- Narrow cracks with random spread appeared on the surfaces of the RC columns exposed to a fire flame. These cracks were deeper and more widespread with increased flame temperature.

2- The spallation of the concrete cover at the corners of the RC columns exposed to fire occurred at an earlier stage of testing load, and this spallation increased with the temperature.

3- With an identical cross-sectional area for the RC columns, the axial load capacity decreased with increasing fire flame temperature from 250 °C to 700 °C. The reduction ranged from 22.31% to 56.15% for solid specimens, 20.10% to 57.73% for 25.4mm hollow specimens, 28.57% to 68.42% mm hollow specimens, and 22.45% to 66.33% for 76.2 mm hollow specimens, with respect to the corresponding unburned RC columns, respectively.

4- At the same burning conditions, the axial load capacity reduced with increasing hollow diameter. For the unburnt specimens, the reduction in the axial load capacity increased to 62.31% as the hollow diameter increased to 76.2mm. The intensity drops of 76.2mm hollow specimens exposed to 300, 500, and 700 °C were 62.38%, 68.86%, and 71.05%, respectively, with respect to the solid specimen.

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