EXPERIMENTAL PERFORMANCE OF REINFORCED CONCRETE HOLLOW COLUMNS EXPOSED TO FIRE

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ABSTRACT

This paper experimentally investigates the effect of high-temperature fire on the structural behavior of reinforced concrete hollow columns. Sixteen square (120×120mm) columns were fabricated with 600mm length. The experiment's parameters were: the hollow size and the temperature of fire. Twelve specimens were cast with a hollow cross-section by inserting PVC pipes centrally along their length; these columns were categorized into three groups depending on the hollow diameters: 25.4, 50.8, and 76. 2mm. The remaining samples were solid and gathered in one group. Each group contained four samples; three of them were burnt at 300, 500, and 700 ^{o}C for one hour, and the fourth one was a reference not exposed to fire. All columns were tested under an axial compressive loading applied progressively up to the column’s collapse. The experiment results indicated that the collapse load of columns, having a same cross-sectional area, decreased with increased the temperature. The decline in columns’ strength ranged from 20.00% to 68.67% for specimens exposed to 300-700^{o}C temperature, respectively. Additionally, for columns exposed to the same temperature, the collapse load descended as the hollow size augmented. A decrease of failure load varied from 21.86% to 65.38% for 25.4 to76.2mm hollow size columns, respectively. Finally, columns' stiffness reduced with increasing the temperature and the hollow size.

Keywords: hollow columns, fire exposure, temperature, collapse load, axial stiffness.

ألاداء ألتجريبي للأعمدة الخرسانية المسلحة ألمجوفة ألمعرضة ألى ألنار

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ألخلاصة

يتحرى البحث تجريبيا تأثير الحرارة المرتفعة على السلوك الانشائي للاعمدة الخرسانية المسلحة المجوفة. تم أنشاء ستة عشرة عمود مربع بابعاد 120 ×120 ملم وبطول مقداره 600 ملم . متغيرات التجربة كانت كلا من حجم التجويف و درجة الحرارة . اثنى عشر عينة كانت مجوفة من خلال مد أنبوب بلاستيكي (PVC) مركزيا على طول العينة. تم تصنيف هذه العينات بالاعتماد على قطر

الانبوب (25.4 و 50.8و 76.2 ملم). النماذج المتبقية كانت ذات مقطع صلد و جمعت في مجموعة واحدة. كل مجموعة تحتوي على اربع نماذج, ثلاث منها معرضة الى درجات حرارة مختلفة (300و 500و 700 مْ) والنموذج الرابع هو نموذج مصدري لم يتعرض الى النار. جميع الاعمدة تم فحصها من خلال تسليط حمل انضغاط محوري مسلط تدريجيا على النموذج الى حد الفشل. نتائج التجربة بينت ان الاعمدة ذات المقطع العرضي المتشابه تفشل بحمل يتناقص مع ازدياد درجة الحرارة. ان النقصان في مقاومة الاعمدة تترواحت من 20% الى 68.67% عند تعرضها الى درجة حرارة تتراوح من 300 الى 700 مْ. بالاضافة الى ذلك ان الاعمدة المعرضة الى نفس درجة الحرارة فشلت بحمل يتناقص مع ازدياد حجم التجويف. حيث تغير الانخفاض في حمل الفشل من 21.86% الى 65.38% للاعمدة ذات تجويف يتراوح من 25.4 ملم الى 76.2 ملم. أخيرا, ان صلابة الاعمدة تنخفض مع ازدياد كلا من درجة الحرارة وحجم التجويف.

1. INTRODUCTION

The hollow reinforced concrete columns are desirable to employ in constructions, especially in seismic zones because of minimizing the superstructures' weight and subsequently the seismic response. The using of hollow columns reduces the loadings transferred to foundations; hence smaller foundations are required. Therefore, hollow columns are an economic choice in areas where the concrete cost is comparatively high. Finally, the hollow columns allow easy to access different services like pipes for electric wiring and plumbing (**Kim et al., 2012**).

The exposure to high temperature is one of the risk issues facing the constructions. The structural elements should be designed with an adequate resistance to fire in order to protect the structures from a collapse, or at least, provide suitable time for occupants to escape before the collapse. The columns are the most important elements in constructions since they shore the structures and carry the loads to the footings. Therefore, any column deterioration may lead to a partial or complete collapse of the structure (**Sakai and Sheikh, 1989**).

The local and international areas have seen many studies investigating the effect of fire exposure on the structural elements, especially for columns. In 2005, **Kodur et al.,** examined the behavior of three confined reinforced concrete columns using Fiber -Reinforced Polymer (FRP) sheets and exposed to fire. The cross-sections of two specimens were circular (400 mm in diameter), and the third specimen was square (406 mm in width). The length of three columns was 3810mm. The experimental results observed that the FRP sheets were sensible to the influences of high temperatures and needed a suitable fire protection. The well protected strengthened columns performed structurally better than the unstrengthened columns.

The behavior of axially loaded reinforced self-compacting concrete was investigated experimentally by **Izzat in 2012**. Twelve columns were exposed to various temperatures (300, 500, and 700 ^{o}C); two methods for cooling were used; gradually by air and suddenly using water spray. The results revealed that the failure loads of the column decreased with increasing the temperature. The ultimate strength of the suddenly cooled specimens was 10% lesser than that of gradually cooled columns.

Kadhum in 2013, examined experimentally the influences of temperature, load eccentricity, concrete strength, and spacing of ties on the structural performance of 120 columns. The results showed that the ultimate capacity of specimens decreased significantly when burning with fire flame. The effect of fire exposure was more severe for columns tested under loads of high eccentricity. An increase in the ties spacing caused an increment in the maximum crack width.

Bikhiet et al. In 2014, presented an experimental and theoretical study conducted on the R.C short columns exposed to fire. In this study, fifteen specimens were constructed to investigate the effect of concrete grade, duration of fire, steel strength and the percentage of the main reinforcement. The major conclusion was that the specimens exposed to fire failed at loads 20-40% smaller than that corresponding unexposed specimen. The specimen constructed with high-grade steel failed at load 55% higher than that of the column with mild steel. Using the water jet in cooling down the column reduced the residual strength by 17% compared with the column cooled gradually.

In the same year, the fire performance of light- weight concrete columns was presented by **El-Shaer**. The light- weight concrete was made of expanded clay aggregate; four specimens were constructed. The specimens were exposed to elevated temperature and subjected to an axial load. The results illustrated that the ultimate capacity and stiffness of the unexposed light weight columns reduced slightly compared with normal-weight columns. Perversely, the load carrying capacity of the light-weight specimens enhanced after exposing to high temperature, the author did not show the cause of this conclusion.

Echevarria et al. in 2015, studied the performance of protected concrete-filled fiber-reinforced polymer tube and conventional reinforced concrete (RC) bridge columns after exposing to fire. The specimens were similar in the axial and flexural strengths, and the study parameter was the duration of the high temperature (one and two hours). The conventional RC columns showed lower axial strength and stiffness retention compared to the protected columns after fire exposure.

Although of increasing the use of hollow section columns in constructions, there is a lack of experiments conducting on the hollow columns subjected to elevated temperatures. The current paper aims at fill this gap by introducing an experimental program. The program explored the influences of hollow size and temperature level on the structural performance of R.C hollow columns.

2. TEST COLUMN SPECIMENS

In order to evaluate the effect of fire exposure on the structural performance of R.C. hollow section columns loaded axially, sixteen specimens were manufactured and tested in the concrete laboratory in the engineering College of Wasit University. The specimens were square in the cross-section with dimensions of 120 ×120 mm; their length was 600mm. All columns were reinforced longitudinally with four deformed bars of 10mm diameter. The bars were positioned at the ties' corners. The transverse reinforcement consisted of 6mm in diameter ties spaced at a distance of 120mm center to center as sketched in **Figure (1).** The yield strengths of main and tie reinforcement, obtained from test, were 436 and 381 MPa, respectively.

The test variables were the hollow size and the burning temperature. Four columns were solid and gathered in the first group. The remaining twelve specimens were fabricated with circular hollow sections by inserting PVC pipes longitudinally through the specimens' center; they were classified into three groups in accordance with the pipe diameters: 25.4, 50.8, and 76.2mm, respectively. Each group contains four specimens, **Table (1)**.

In all groups, three columns were burnt at 300, 500, and 700 ^{o}C temperature. The fourth specimen was kept without the fire exposure and kept at room temperature (25^{o}C) as a reference specimen.

The columns were designated by letter C followed by two numbers separated by hyphen symbol (-). The first number refers to the hollow diameter divided by 25.4 while the second one refers to the burning temperature divided by 100 (i.e. the designation C3-5 refers to a column having a hollow diameter equal to 76.2 mm and burnt at 500 ^{o}C temperature.). The second number for control specimens was set as (0).

A one concrete mix design was utilized throughout the experimental investigation. It composed of ordinary Portland cement, sand, and crushed gravel (10mm maximum size) in the following weight proportions 1:1.7:2, respectively. The water to cement ratio was 0.54.

The specimens of each group were cast in one concrete batch, three standard cubes (150×150×150mm) were taken to assess the compressive strength of batch, **Table (1)**. Before the casting of columns, the PVC pipes were put centrally inside the reinforcement cages as shown in **Figure (2)**. Then, the cages were placed inside wood moulds leaving a clear concrete cover of 10mm from all sides. The columns were casted in the side position. A good compaction was guaranteed using a vibratory table.

3. BURNING AND TESTING

After completing the curing period (28 days), the twelve column specimens were burnt inside a diesel furnace with 770×520×450 mm dimensions. The columns were divided into three batches (four specimens for one batch). Each batch was burnt separately to a target temperature for one hour. The target temperatures for three batches were 300, 500, and 700 ^{o}C, respectively. The temperature inside the furnace was monitored through the furnace digital screen.

Next accomplishing the burning process, the furnace was turned off and its door was opened. The specimens left inside the furnace to cool gradually as shown in **Figure (3)**. Then, the specimens were taken out, and their surfaces were examined accurately. Cracks distributed randomly were noticed, they became deeper and more numerous for specimens exposed to the higher temperature as shown in **Figure (4)**. Moreover, these samples displayed a concrete cover spalling off, especially at their corners. The burnt columns were kept at a room temperature before the testing.

Finally, all specimens (burnt and references) were subjected to an axial loading; the eccentricity of load was carefully avoided. The load was applied gradually using a universal machine (150 ton capacity) up to the specimen's failure. Two steel plates were inserted between the specimen ends and the testing machine to avert the problem of stress concentration. A dial gauge of 0.01 mm accuracy was employed to measure the axial displacement of specimens as shown in **Figure (5)**.

4. DISCUSSION OF EXPERIMENT RESULTS

The test results are discussed in three terms: mode of failure, ultimate strength of columns, and load-axial displacement response for all samples as following.

4.1. Mode of Failure

The unexposed reference samples displayed, firstly, tiny cracks in the outer thirds of their length. The first cracks initiated at loads of 120, 100, 75, and 50 kN for samples C0-0, C1-0, C2-0, and C3-0, respectively; their number, depth, and width increased rapidly as the applied load increased. They developed preliminary vertically parallel to the samples' longitudinal axis, and thereafter they inclined toward the column's corners. At a collapse, the samples experienced a concrete crushing at the specimen’s ends, where the stress concentration was relatively high. On the other hand, the largest hollow size sample, C3-0, spilled longitudinally at collapse load as illustrated in **Figure (6)**.

There was a difficulty in recording the cracking loads of fire-exposed specimens. Since they displayed, during burning, tiny cracks spreading arbitrarily on the samples’ surfaces. Generally, they suffered concrete crushing occurring on wider area compared with unexposed similar columns. The concrete cover spalling was observed at earlier loads, where concrete fell down as a powder, especially for specimens burnt at 700^{o}C. At the failure, a complete cover spalling of at corners, and concrete crushing were noticed in the burnt columns as displayed in **Figure (7)**. Furthermore, the largest hollow burnt specimens did not exhibit a longitudinally split, on the contrary unexposed reference column C3-0.

4.2. Ultimate Strength of Columns

The ultimate axial loads for all samples are summarized in **Table (2)**. The fire exposure strongly influences the column load capacity, where the increase in the exposure temperature decreased the column strength as plotted in **Figure (8)**. This can be imputed to the following reasons accompanying with elevated temperatures: the loss in a concrete strength contributing a large percentage of the columns' strength, especially for those loaded axially. The second reason is the spalling of a concrete cover leading to minimize the columns' cross-section area. Thirdly, a damage in the bond strength between the reinforcement steel and the surrounding concrete besides a deterioration of the interconnection between the concrete components as the result of a formation of earlier fire cracks. The final cause is the expansion of the main reinforcement as well as the shrinkage of the concrete during fire exposure.

In group one including solid specimens, reductions in the load capacity of 21.82%, 34.55%, and 52.73% were recorded for specimens C0-3, C0-5, and C0-7 exposed to 300, 500, and 700^{o}C compared to the unburned specimen C0-0, correspondingly.

The decreases in the columns' strength, at 300, 500, and 700^{o}C, were :20.00%, 38.10% and 53.81% for 25.4mm hollow columns, 26.67%, 46.67%, and 62.00% in columns of a 50.8mm hollow, and 18.18%, 40.91%, and 59.09% for largest hollow columns, comparing with the corresponding unexposed columns, respectively.

It is worth mentioning that the columns’ load capacity declined approximately linearly with raising the temperature as illustrated in **Figure (8)**. The best-fitting linear equations, representing the variation of column strength with temperature, were derived using a computer program (Excel 2013), as follows.

For solid specimens,

$$Y=276.4-0.203X \tag{1}$$

For specimens of a 25.4mm hollow diameter,

$$Y=212.3-0.163X \tag{2}$$

For specimens of a 50.8 mm hollow diameter,

$$Y=149.7-0.135X \tag{3}$$

For specimens of a 76.2 mm hollow diameter,

$$Y=112.9-0.094X \tag{4}$$

Where;

Y is a column ultimate strength in kN

X is a temperature fire.

Since the amount of fire- affected concrete diminished with enlarging the hollow size, the reduction rate of column strength with temperature minimized while the hollow diameter maximized as illustrated in **Equations (1) to (4)**.The reduction rate was 20.3% for solid specimens, and 16.3%, 13.5%, and 9.4% for hollow specimens of diameter 25.4mm, 50.8mm, and 76.2mm, respectively.

The failure loads of all four specimens subjected to a same temperature were compared together to evaluate the influence of a hollow size as shown in **Figure (9)**. It can be seen that the column ultimate load decreased rapidly as the hollow diameter increased up to (50.8 mm). Then the reduction rate became slow, especially for specimens exposed to temperature higher than 300 ^{o}C.

The drops in the failure load for 25.4, 50.8, and 76.2 mm hollow columns compared to the corresponding solid columns were: 23.64%, 45.45%, and 60.00% for unexposed columns, 21.86%, 48.84%, and 58.14% for 300^{o}C fire-exposed columns, 27.78%, 55.56%, and 63.89%) columns burnt at 500 ^{o}C, and 25.38%, 56.15%, and 65.38% for columns exposed to 700^{o}C, respectively.

4.3. Load-Axial Displacement Response

The curves, representing the relationships between applied load and vertical displacement, were plotted in **Figure (10)** for solid specimens and in **Figures (11) through (13)** for specimens having a hollow diameter of 25.4, 50.8, and 76.2mm, respectively. From these figures, it can be observed that the columns' axial displacement, at the same load, increased as the temperature fire raised. Because the column's axial stiffness dropped when they exposed to fire due to the loss in both the column's effective cross-sectional area and a concrete modulus of elasticity (**Kodur, 2014)**.

In general, the load-axial deformation responses of 300 ^{o}C fire-exposed columns were very close to those of similar unexposed columns at loads smaller than 175, 100, and 75 kN for solid, 25.4mm hollow, and 50.8-76.2 mm hollow specimens, respectively. Since the severe fire effect, on structural elements, takes place after exceeding 300 ^{o}C. Moreover, this rapprochement becomes clearer for largest hollow specimens because of a reduction in the quantity of fire-affected concrete.

Finally, the presence of PVC pipes, inserted along the column samples, caused a considerable reduction in the column's axial stiffness due to minimizing the column's cross-sectional area. **Figures (14) through (17)** show load-vertical displacement curves for samples subjected to the same temperature: 0, 300, 500, and 700^{o}C, respectively. It is obvious from these figures that the axial displacement of columns, subject to an identical load, increased with enlarging the hollow size, especially for columns having a hollow size greater than 25. 4mm.

5. CONCLUSIONS

The main conclusions of the current experimental program are listed as following;

1. The fire-exposed columns displayed tiny cracks after the burning processes. These cracks distributed in a random configuration around the column's surfaces; their number and depth increased with elevating the temperature.
2. All column specimens experienced a compression failure, where a concrete crushing appeared at their outer-thirds.
3. For identical columns, the axial load capacity reduced as the temperature fire raised to 300-700^{o}C. The corresponding reductions were: 21.82% -52.73 % for solid columns, 20.00% -53.81% for 25.4mm hollow columns, 26.67% -62.00% for specimens with 50.8mm hollow size, and 18.18% -59.09% for 76.2 mm hollow columns, respectively.
4. The variation of columns' strength with temperature is nearly linear. Furthermore, the reduction rate of columns' strength with temperature dropped as the hollow size maximized. The reduction rate was 20.3% for solid specimens, and 16.3%, 13.5%, and 9.4% for hollow specimens of diameter 25.4mm, 50.8mm, and 76.2mm, respectively.
5. For same temperature, the column's strength decreased with maximizing the hollow size. In the unburnt columns, the drop in the column capacity increased to 60.00% when the hollow size augmented to 76.2mm. The strength decline of 76.2mm hollow columns exposed to 300, 500, and 700 ^{o}C were 58.14%, 63.89%, and 65.38%, compared to the corresponding solid columns, respectively.
6. The columns' axial stiffness descended as the temperature fire and the hollow size increased, especially for columns having a hollow size greater than 25.4 mm and burnt at temperature exceeding 300 ^{o}C.

6. REFERENCES

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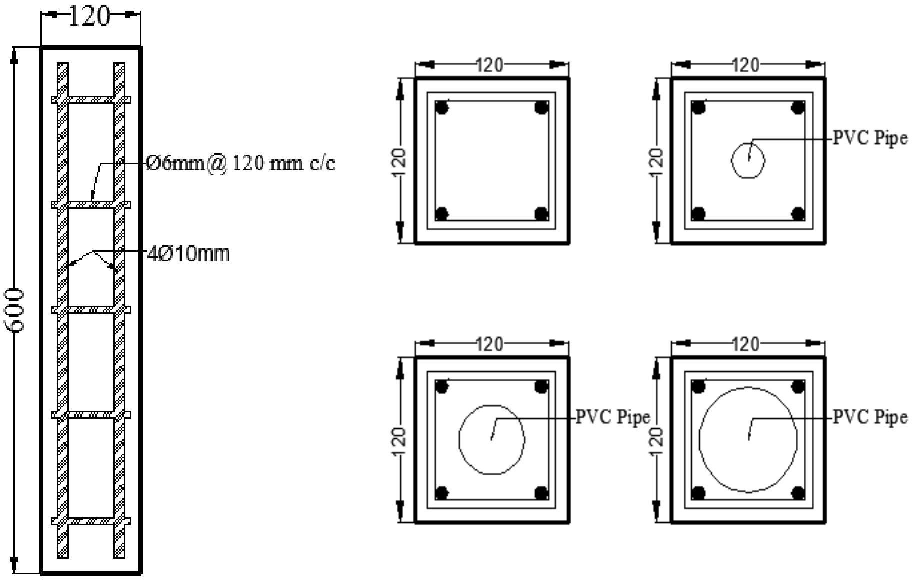
Table (1): Details of Test Specimens.

Group No.	Column Designation	Hollow Diameter(mm)	Temperature ^oC	Concrete Compressive Strength (MPa)
1	C0-0	0.0	25	31.5
	C0-3		300	
	C0-5		500	
	C0-7		700	
2	C1-0	25.4	25	32.2
	C1-3		300	
	C1-5		500	
	C1-7		700	
3	C2-0	50.8	25	33.6
	C2-3		300	
	C2-5		500	
	C2-7		700	
4	C3-0	76.2	25	31.1
	C3-3		300	
	C3-5		500	
	C3-7		700	

Table (2): Specimens' Collapse Loads.

Group No.	Column Designation	Temperature ^oC	Collapse Load (kN)	% Decrease in Collapse Load
1	C0-0	25	275	reference
	C0-3	300	215	21.82
	C0-5	500	180	34.55
	C0-7	700	130	52.73
2	C1-0	25	210	reference
	C1-3	300	168	20.00
	C1-5	500	130	38.10
	C1-7	700	97	53.81
3	C2-0	25	150	reference
	C2-3	300	110	26.67
	C2-5	500	80	46.67
	C2-7	700	57	62.00
4	C3-0	25	110	reference
	C3-3	300	90	18.18
	C3-5	500	65	40.91
	C3-7	700	45	59.09

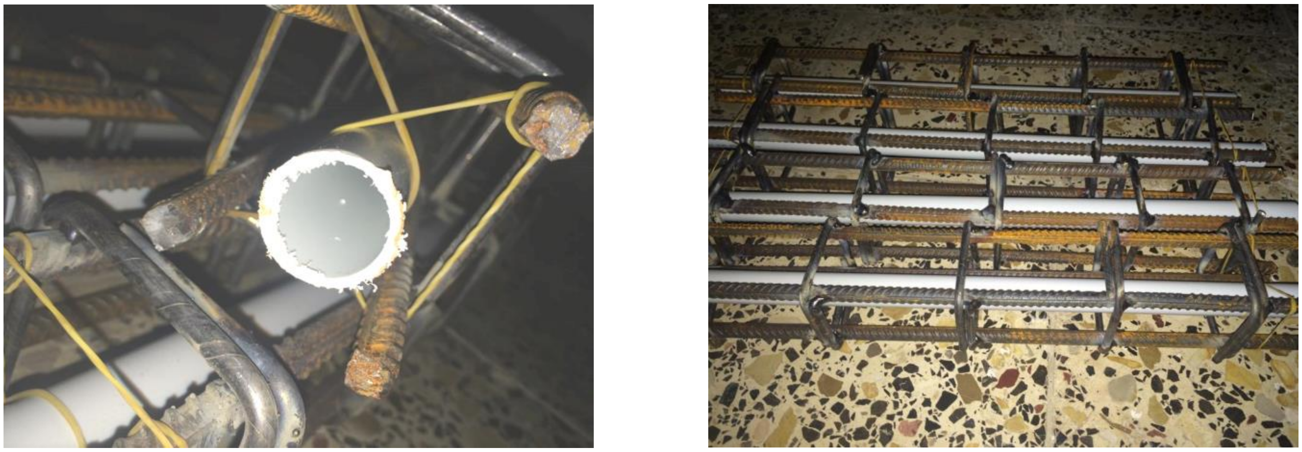


(a) Specimens dimensions

(diameter=50.8mm)(diameter=76.2mm)

All dimensions in mm.

Figure (1): Details of Column Specimens.



(a) Positioning the PVC pipe at the reinforcement cage center

(b) Preparing the reinforcement cage

Figure (2): Details of Reinforcement for Column Samples.

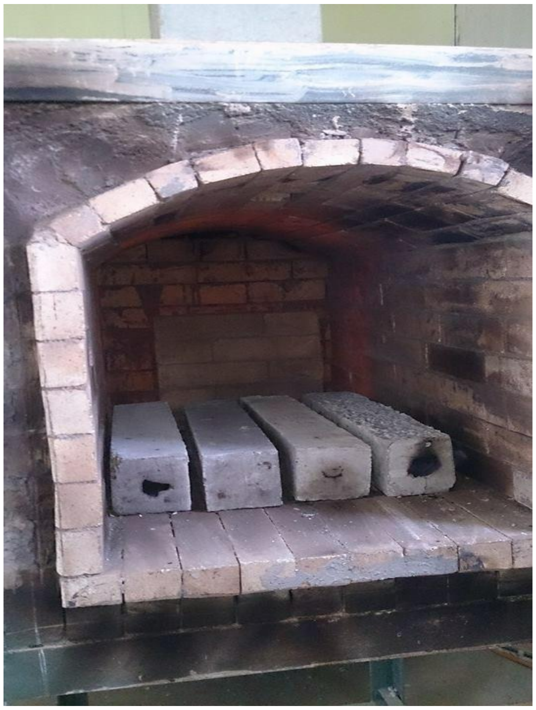


Figure (3): Gradually Cooling of Specimens.

Figure (4): Typical of Fire Cracks Distributed Randomly over The Specimen

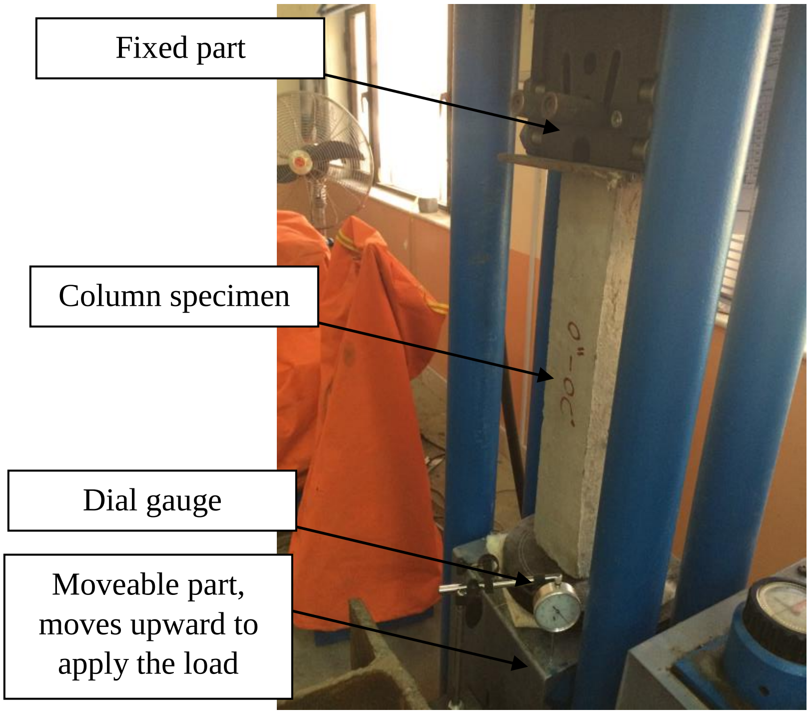


Figure (5): Sample Being Tested.

(a) Column C1-0 (b) Column C2-0 (c) Column C3-0

Figure (6): Crack Patterns for Unexposed Specimens.

(a) Column C1-7 (b) Column C2-7 (c) Column C3-7

Figure (7): Crack Patterns for Specimens Exposed To 700 ^{O}C.

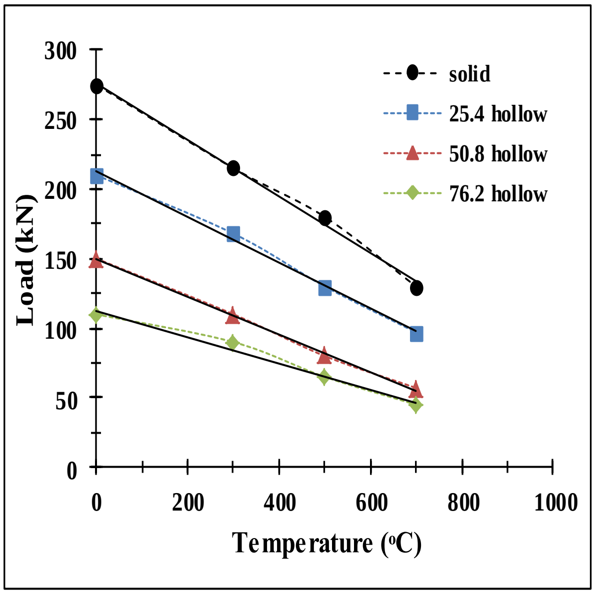


Figure (8): Column's Strength versus Temperature.

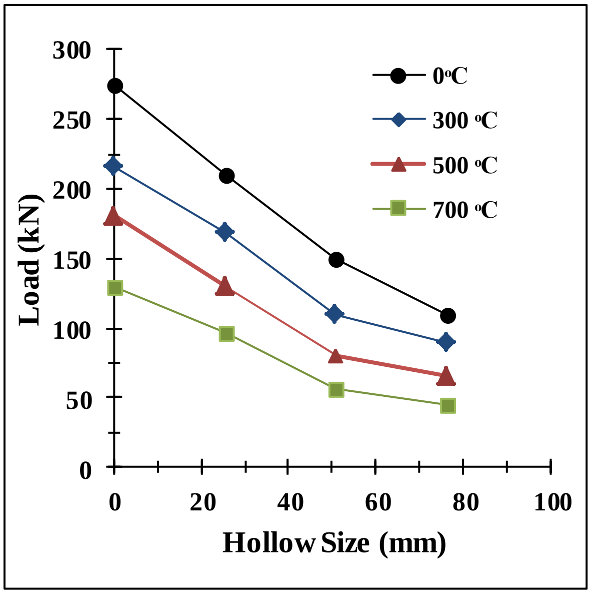


Figure (9): Column's Strength versus Hollow Size.

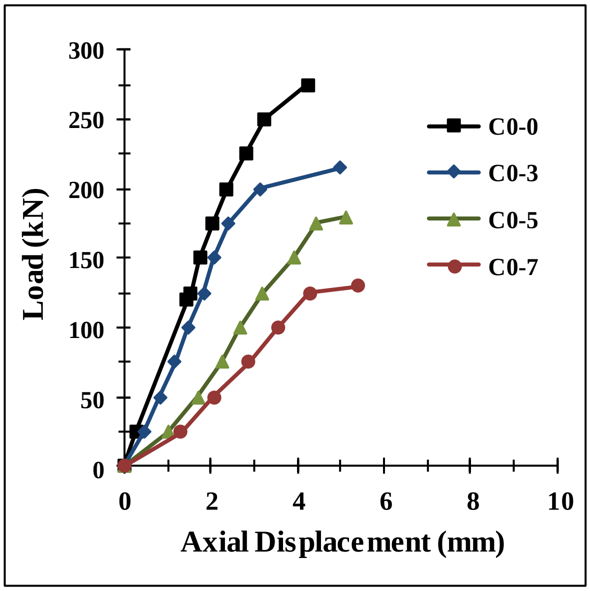


Figure (10): Load-Axial Displacement **for** Solid Specimens

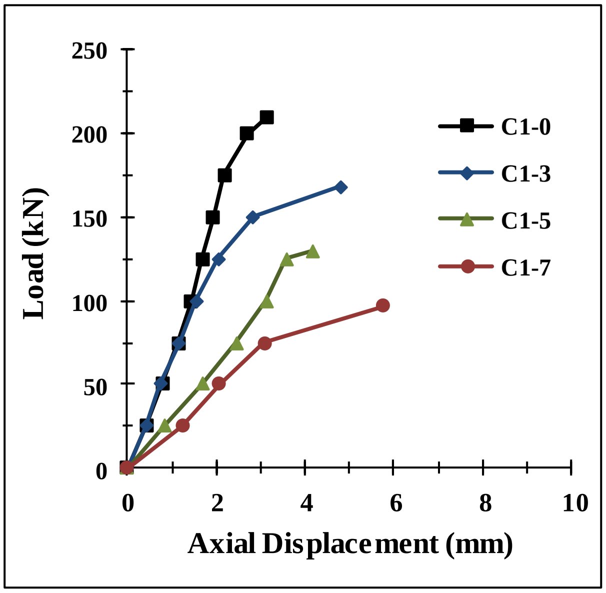


Figure (11): Load-Axial Displacement for 25.4 mm Hollow Specimens

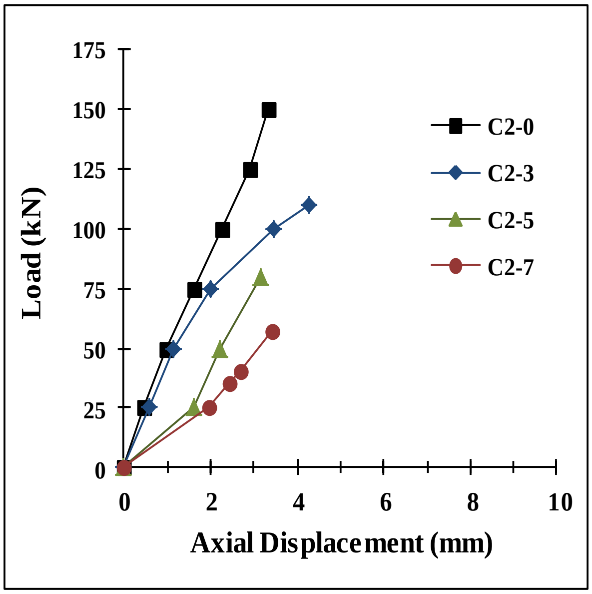


Figure (12): Load-Axial Displacement for 50.8 mm Hollow Specimens

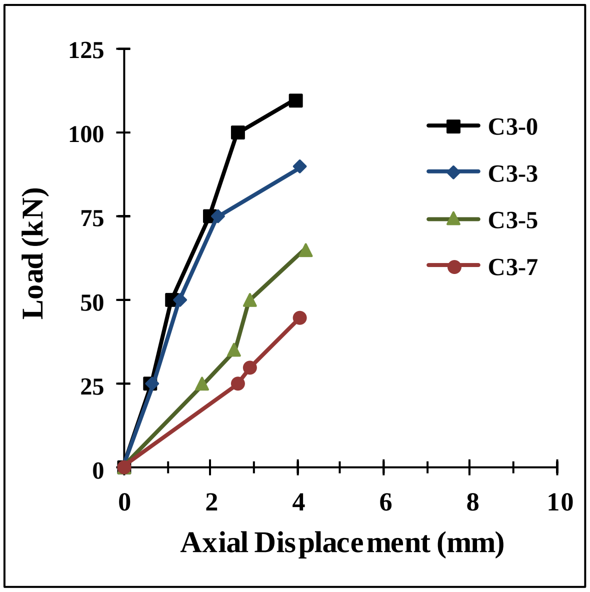


Figure (13): Load-Axial Displacement for 76.2 mm Hollow Specimens

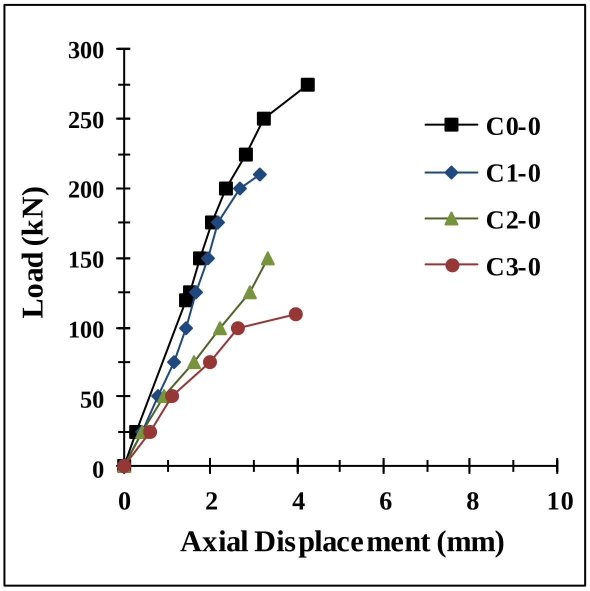


Figure (14): Load-Axial Displacement Unexposed Specimens

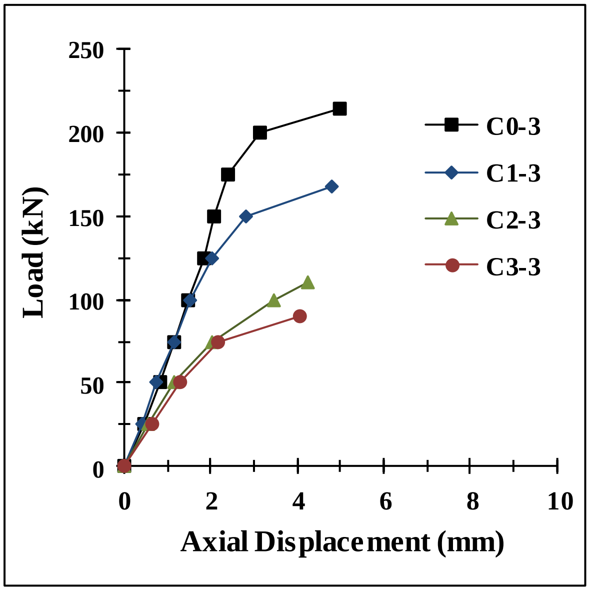


Figure (15): Load-Axial Displacement Specimens Exposed to 300°C

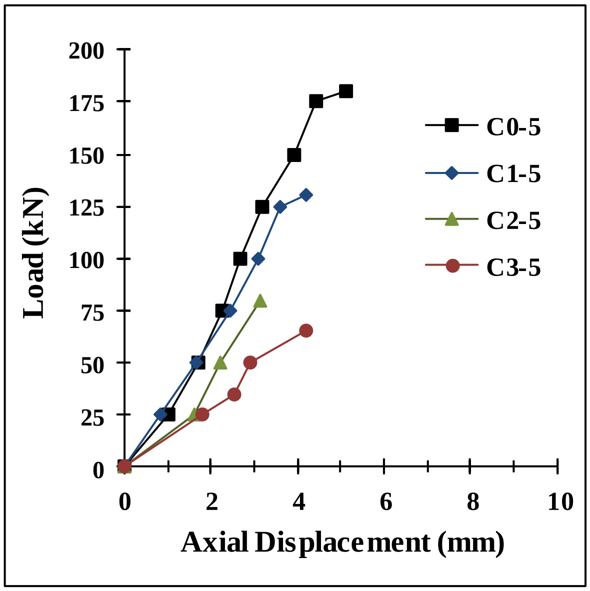


Figure (16): Load-Axial Displacement Specimens Exposed to 500°C

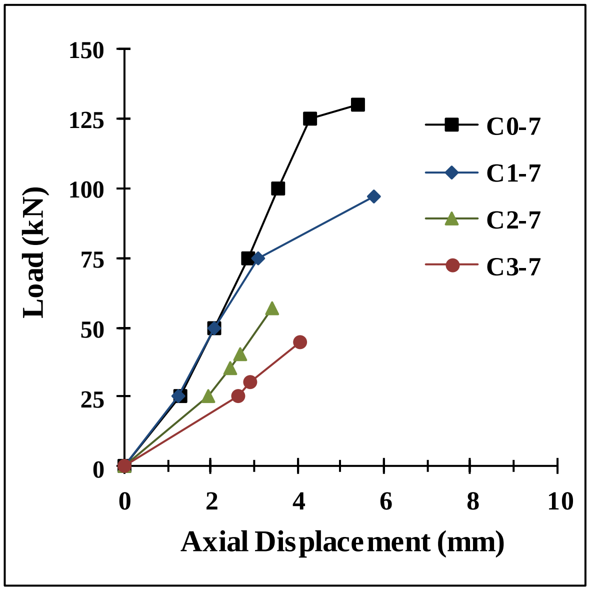


Figure (17): Load-Axial Displacement Specimens Exposed to 700°C