Effect of High Temperature (Fire Flame) on the Behavior of Post-tensioned Concrete Beams

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Abstract:

Experimental research was carried out to investigate the effect of fire flame (high temperature) on the load capacity of post-tensioned concrete beams to determine the residual strength after burning. To simulate the real practical fire disaster, six specimens were exposed to high temperature, (fire flame; 300, 500 and 700 ºC), for one hour using special furnace manufactured for this purpose. Next, cooling was performed gradually by leaving the beams in air or suddenly by splashing them with water. After that, the beams loaded till failure to determine the effect of different cooling rate on the residual strength of specimens. The results were compared with the behavior of post-tensioned beam without burning (reference beam). The average percentage of residual cubic concrete compressive strength after exposure to 300, 500, and 700 °C were found to be 80, 55, and 45 % for the beams cooled gradually and 73, 50, and 40 % for the beams cooled suddenly (high rate of cooling), respectively. The residual value of the modulus of rupture was 91, 79, and 43 % for the beams cooled gradually and 89, 74, and 35 % for the suddenly cooled beams, respectively. The ultimate load capacity of the beams decreased with increasing fire flame temperature, at a burning temperature of 300, 500, and 700°C; the average residual ultimate load capacity for gradually cooled beams were 84, 72, and 60 %, respectively. For the beams cooled suddenly, the average residual ultimate load capacity was 80, 64, and 52 %, respectively, for the same burning temperatures.

Keywords: - burning temperature, fire flame, gradual cooling and sudden cooling.

1. Introduction

Concrete has a compressive strength that is several times greater than its tensile strength. Pre-tensioning or post-tensioning is a popular technique that is used to increase the efficiency of concrete members, subject to flexure. This process involves the application of an initial compressive stress to a concrete member that offsets tensile stresses created under service loading.

When concrete is exposed to high temperature, its composition suffers from self-deterioration due to the difference in the thermal expansion of its components. Fletcher et al. [4] illustrated that, when a concrete is heated, the free water in it evaporates and that, above approximately 100 °C, the chemical water bonds in the hydrated calcium silicate begins releasing. In some cases, the surface layer of concrete specimen cannot resist the pressure of the water and steam, resulting in spalling. In case the concrete does not spall, the release of water causes shrinkage of the hydrated cement paste, while the aggregate and the reinforcing bars are subjected to thermal expansion. Consequently, stresses get developed in the composite material, and from approximately 300 °C, microcracks begin piercing through the matrix. Above approximately 400 °C, the crystals of calcium hydroxide begin decomposing into calcium oxide and the water process reaches its highest intensity at above 535 °C.

While, Kodur [7] stated that, a slight decrease in the compressive strength at up to 400 °C, followed by a further rapid decrease where it reached 50 % of its initial value at about 600 °C and then rapidly reducing with increasing temperature till complete disappearance of the strength at approximately 1000 °C.

Myers, and Bailey [9] reported that only limited researches have been performed to investigate how elevated temperature affects the properties of prestressing reinforcements. Because of the significant behavior difference between unstressed specimens tested after burning and cooling and the real situation of prestressing reinforcements that exposed to both stressing and heating. Elices, and Atienza. [3], concluded that, the exposure to high temperatures, causes stress relaxation losses and the permanent damage of mechanical properties of steel wires.

Several theoretical researches have been conducted to study the behavior of different structural elements exposed to high temperature, (Obaidat and Haddad [10]; Lakhani et al. [8]; Toriū et al. [12]).

This research was carried out to predict the effect of fire flame (high temperature) on the load capacity of post-tensioned concrete beams to determine the residual strength after burning.

2. Experimental program

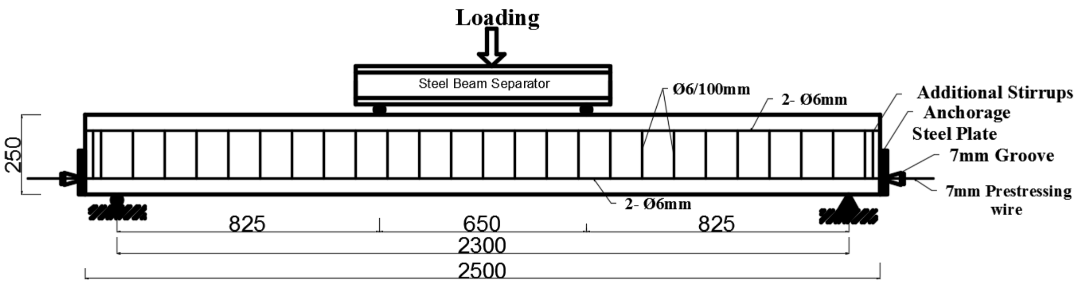
2.1. Setting up the beams

The experimental program included casting of seven prestressed concrete beams divided into four groups (Table 1), all of which had the same geometric layout and reinforcement details (Fig.1). Their dimensions were 2500x250x125 mm of its length, depth, and width, respectively. These specimens were reinforced with ordinary 6 mm nominal diameter bars (5.78 mm, measured diameter) of 450 and 550 MPa yield stress and ultimate strength, respectively. Plastic tubes of 9-mm inner diameter were used as a duct for the prestressing wire of 7 mm diameter, (Grade 270), with a breaking strength of 70 kN, which was placed later at 50 mm above the soffit of the beam.

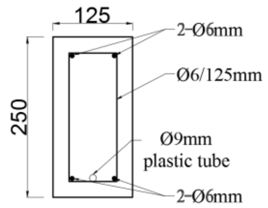
Table 1. Details of the tested beams.

Groups No.	Beams designation	Burning temperature ^oC	Cooling mode
Reference	R	- *	-
Group I	G_1	300	gradually
	S_1		suddenly
Group II	G_2	500	gradually
	S_2		suddenly
Group III	G_3	700	gradually
	S_3		suddenly

* Without burning, left at Lab temperature 35 ^oC



A- Beam dimensions.



B- Beam cross section.

Fig. 1 Details of the beam reinforcement.

After casting and curing the beams with their control specimens, which consisted of six 150 mm cubes, cylinders of 100 mm diameter x 200 mm length, and 100x100x400 mm prisms for each beam, the properties of hardened concrete before and after burning was determined. The prestressing wire extended through the intended duct with an adequate end bearing steel plate of 4 mm thickness by 70x70 mm dimensions and an adequate grip at each end; 45 kN tension force was applied using mono-hydraulic jack from one end. Camber was measured using a dial gauge of 0.002 mm sensitivity placed at the midspan of the beam. The average measured upward deflection (camber) of the prestressed concrete beams was 0.5 mm, with a deviation of 3.2 %.

Six beams were exposed to fire flame, each pair was burned at a temperature of 300, 500, and 700 °C, where one of them was cooled suddenly by using water splashing technique (high rate of cooling) and the other was left at the lab temperature to cool gradually.

2.2. Burning procedure

To simulate the disaster of fire underneath the floor, the furnace was manufactured using 3 mm thick steel plate with two L-shape bends to burn one beam at a time, with its control specimens, as shown in Plate 1 and Fig. 2. The clear space around the beam was of 500 mm (height) x 400 mm (width) x 2600 mm (length). These dimensions were selected to maintain enough space around the beam so that the fire flames could reach from the source, which was a network of methane burners nozzles, to the beam, and also to ensure that the flame are not concentrated on a limited area, rather than distributed on a wide area of the beam bottom and sides, the nozzles were positioned, four on each side of the furnace at a lower point. Two thermocouples type K (Nickel-Chromium/Nickel-Nickel-Aluminum) with a digital logger were used to monitor the temperature; the sensing end of the thermocouple wire was in contact with the top beam surface and the temperature was controlled manually by the amount of supplied methane gas. After reaching the target temperature of 300, 500, and 700 °C by about 15, 30, and 60 min., respectively, the beam was kept at the same temperature for 1 hour. Time-camber (upward deflection) was measured during the burning and cooling processes by a dial gauge of 0.002 mm sensitivity placed at the midspan point of the beam **Fig.2**.

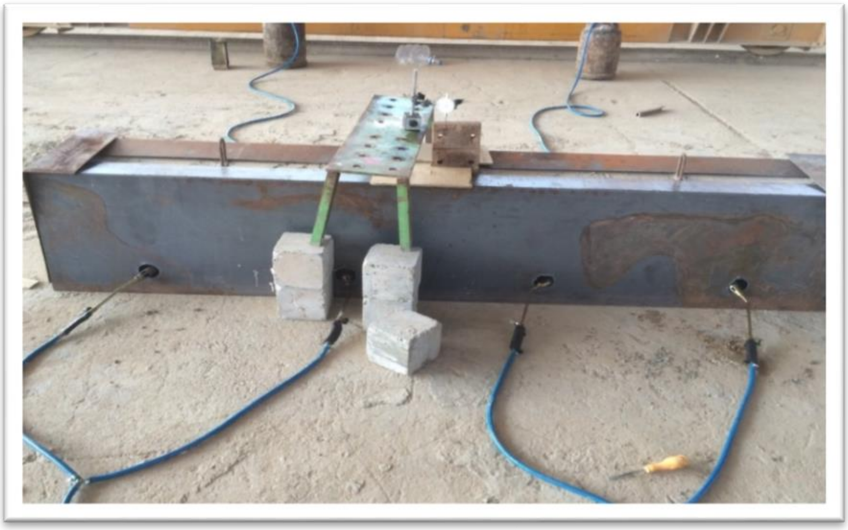


Plate 1. The furnace with a network of methane burners nozzles.

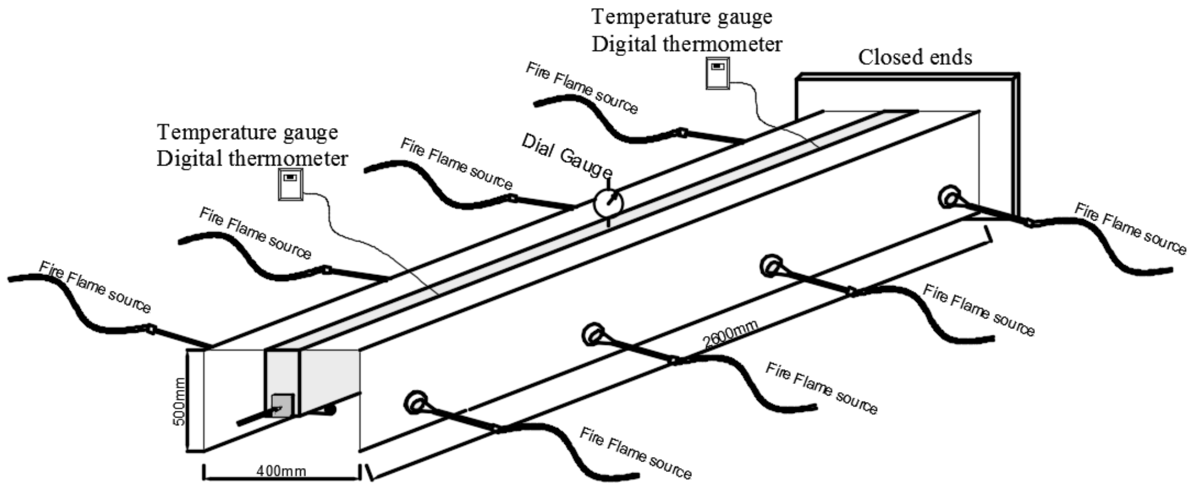


Fig. 2 Manufactured furnace with the nozzles and other measurements instrumentations during the burning.

3. Results and discussion

3.1 Compressive strength

Test results shown in Table 2 of testing 100x200 mm cylinders after exposing to fire flame showed that increasing the temperature resulted in reducing the compressive strength. In addition, the cooling method affected the compressive strength of the cylinders, where specimens that cooled suddenly by spraying them with water exhibited lesser strength than the others that were cooled gradually at room temperature. The results showed that the compressive strength varied with the fire flame temperature (Fig. 3); it decreased with increasing exposure temperature, the results agreed with that concluded by Aslani [1] and Aslani and Samali [2]. The average percentage of residual compressive strength after exposure to 300, 500, and 700°C was 80, 53, and 45 %, respectively, for specimens that were cooled gradually. The decrease in the compressive strength of concrete was due to the breakdown of interfacial bond due to incompatible volume change between the concrete components during heating and cooling (Georgali and Taskiridis [5]; Koksal et al. [6]). While for the specimens that were cooled suddenly (high rate of cooling), the residual compressive strength was comparatively lesser (they were 73, 50, and 40 % at the exposure temperature of 300, 500, and 700 °C, respectively). This observation can be attributed to the grading progression of decreasing temperature (cooling), which was not uniform throughout the concrete cross-section as the decreasing temperature was delayed for the inner concrete compared to that for the outer concrete, resulting in a difference in the thermal conductivity of the concrete components; this process will create internal damage stresses, which will worsen with increasing cross-section of the concrete. This conclusion is in concordance with the results obtained by Poon et al. [11].

3.2 Modulus of rupture

The effect of elevated temperature and the method of cooling on the modulus of rupture similar to that of the factors on the compressive strength (Table 3). The percent of the residual modulus of rupture after exposing to 300, 500, and 700 °C were 91, 79, and 43 %, respectively, for the beams which cooled gradually. For the specimens that cooled suddenly (high rate of cooling), the residual modulus of rupture was lesser than that of the gradually cooled specimens (89, 74, and 35 %, respectively, at the same above-elevated temperatures shown in Fig.4 and Table 3). Moreover, it can be seen that, with increasing burning temperature, the variation between sudden and gradual cooling increases was 2, 7, and 23 % for burning temperatures 300, 500, and 700 °C, respectively. Therefore, at high burning temperatures, the modulus of rupture is more sensitive to the mode of cooling and the burning temperature than the compressive strength, which approaches with the reports of Umran [13], who concluded that the flexural strength is more sensitive to fire flame temperatures than compressive strength. This could be because of the formation of cracks due to the increase in temperature, which formed and propagated with increasing burning temperature and the rate of cooling, which will affect the modulus of rupture, because the required net tension area decreases. This difference in thermal expansion increased during the cooling process and had a significant effect in the sudden cooling method.

Table. 2 Effect of fire flame on compressive strength *f*´c *.

Specimen	Temperature °C	Type of cooling	Average *f*´c (MPa)	Residual *f*´c %	Variation of *f*´c (Gradual /sudden) cooling%
R	ambient	-	40	100	-
G_1	300	gradually	32	80	10
S_1		suddenly	29	73	
G_2	500	gradually	22	55	10
S_2		suddenly	20	50	
G_3	700	gradually	18	45	12.5
S_3		Suddenly	16	40	

*Average of three specimens of 100mm x 200mm cylinders.

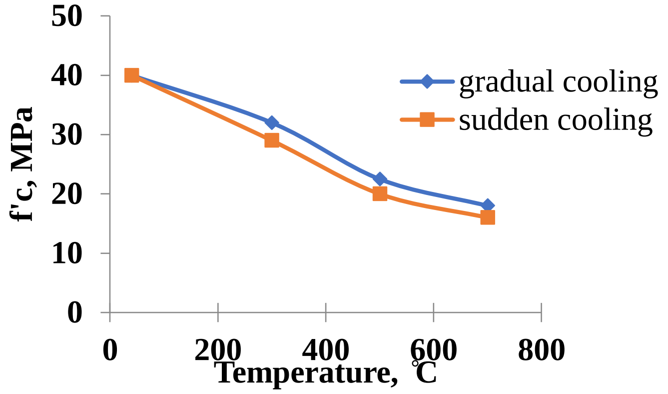


Fig. 3. Burning temperature versus concrete compressive strength.

Table. 3 Effect of cooling method and temperatures on modulus of rupture *f*′r *.

Specimen	Temperature *°C*	Type of cooling	Average *f*′r (MPa)	Residual *f*′r %	Variation of *f*′r (Gradual /sudden cooling) %
R	ambient	-	3.34	100	-
G_1	300	gradually	3.04	91	2
S_1		suddenly	2.97	89	
G_2	500	gradually	2.64	79	7
S_2		suddenly	2.47	74	
G_3	700	gradually	1.44	43	23
S_3		suddenly	1.17	35	

*Average of three prism specimens of 100 x 100 x 400 mm .

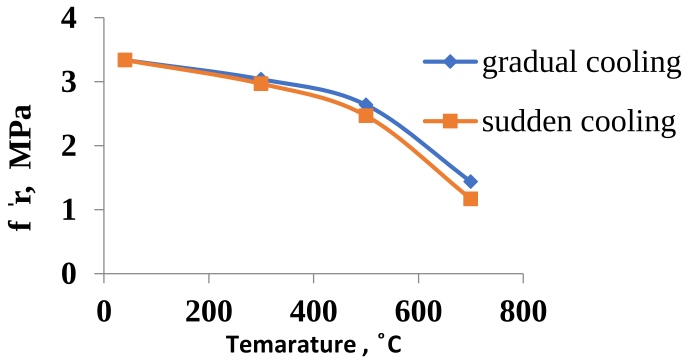


Fig. 4 Burning temperature versus modulus of rupture.

3.3 Burning cracks

Cracks were noticed on the concrete surface of the beams after burning and cooling and the effect of the two cooling conditions were compared after burning the beams G_3 and S_3 at 700 °C, (Plates 2-A and B, respectively). It can be seen from these illustrations that sudden cooling results in the development of more defects on the concrete than gradual cooling, for instance, sudden cooling in S_3 had a greater effect on the cracks formation than gradual cooling in G_3, which can be attributed to the fact that the rate of increasing temperature was less than that of the decreasing temperature (sudden cooling), which had much worse effect on the interfacial bond between the concrete components. Since the thermal conductivity reduced with increasing temperature and the quenching water of the heated concrete beams did not produce uniform cooling. At 300 °C, no apparent visual discoloration was noted in the concrete. The concrete beams subjected to more than 500 °C suffered from noticeable color change.

3.4 Camber at burning and cooling stages

Six prestressed concrete beams were used, where each pair exposed to the same temperature level of 300, 500, or 700 °C for the time period of 1 hour, the transition period to reach the above target temperature was approximately 15, 30, and 60 min., respectively. Then, the beams were cooled by two methods - sudden and gradual. These processes affect the value of the midspan camber of the prestressed concrete beams which was initiated by prestressing the wire.

Figs.5, to 7 reveal the time history curves of the camber at the burning temperatures of 300, 500, and 700 °C, respectively. As shown in these figures, the behavior (pre-camber) of each pair of the beams that burned at the same temperature but cooled in a different way exhibited similar trend during the burning stage, while they were different and the curves deviated from each other during the cooling stage. Influenced by the concrete ingredients and their properties in cooling processes, the beams that were cooled gradually showed significant differences in the behavior of midspan camber as well as in the residual camber at the end of the cooling stage as compared to those that were cooled suddenly (Table 4). Despite the fire flame being positioned along the lower core of the beam’s two sides at the level of prestressing reinforcement toward the upper cored of the beam, the concrete showed more defects than the prestressing reinforcement relaxation, probably due to the direct effect of the fire flame on the concrete that is a composite of different materials, each with a different thermal expansion, the formation of cracks, and the loss of bond between concrete components, which leads to an increase in the midspan camber during the burning process. During the cooling stage, the concrete strength cannot be reserved due to the formation of cracks, in contrast with the prestressing wire that tends to reserve its strength that was lost by relaxation due to the thermal expansion of the reinforcement, which leads to more increase in the midspan camber.

Figs.5, to 7 show the differences in the behavior between the two cooling methods, where the sudden cooling exhibit a drop in the midspan camber than that of the gradual cooling method, due to the high rate of temperature dispersion.

A-Beam (G3) 700℃ gradual cooling. **B-Beam (S3) 700 ℃ sudden cooling**.

Plate 2. Craks formation at different condition of cooling and exposure temperature of 700 C .

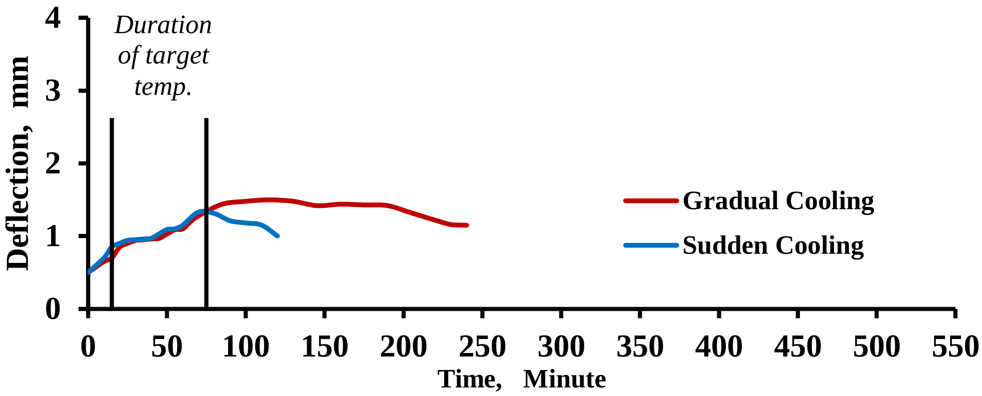


Fig. 5 Midspan camber -time history for group I beams which burned at 300 *ºC.*

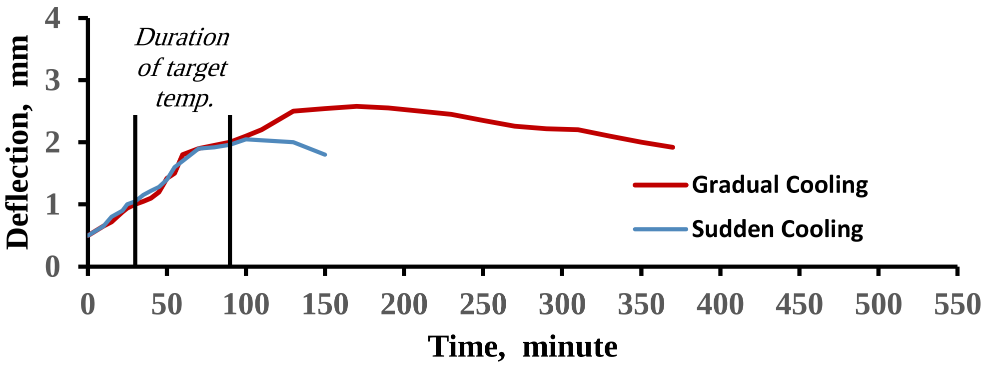


Fig. 6 Midspan camber -time history for group II beams which burned at 500 *ºC.*

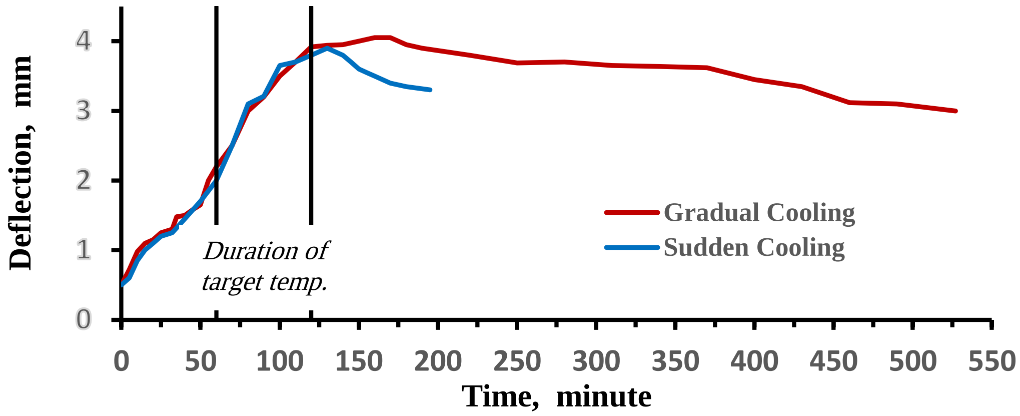


Fig. 7 Midspan camber -time history for group III beams which burned at 700 °C.

Table. 4 Residual camber for beams after burning and cooling processes.

Beam	Burning temperature °C	Method of cooling	End camber (mm)
G_1	300	Gradually	1.15
S_1	300	Suddenly	1.00
G_2	500	Gradually	1.92
S_2	500	Suddenly	1.80
G_3	700	Gradually	3.00
S_3	700	Suddenly	3.30

While the beams that cooled gradually, the midspan camber continued to rise for some time after ending the burning period, after which the curve began to descend.

Figs.8 and 9 show the time history of midspan camber at different burning temperatures for the beams that cooled suddenly and gradually, respectively, during both the burning and cooling periods. These figures reveal that, as the burning temperature increases, the midspan camber increases due to the increase in the formation and propagation of concrete cracks developed owing to the difference in the thermal expansion of the concrete composition, which leads to debonding between these components in contrast to the prestressing reinforcement affected in a lesser manner than that of the concrete. In addition, the cooling time required to reach the lab temperature also increased. In all of the beams, the midspan camber decreased at the end of the burning and cooling cycles due to the concrete shrinkage and the prestressing wire that reserved its strength; these facts prevent the beams to return to its original shape because of the deterioration of the concrete, especially that of the top cord that leads to reduction in the concrete tensile strength, while the eccentric post-tensioning wire tends to compress the concrete. Table 4 shows the residual midspan camber for each beam after the burning and cooling processes; it can be seen that the residual midspan camber for the gradually cooled beams was slightly greater than that of the suddenly cooled ones for the beams that were burned at 300 and 500 °C, in contrast with those that were burned at 700 °C.

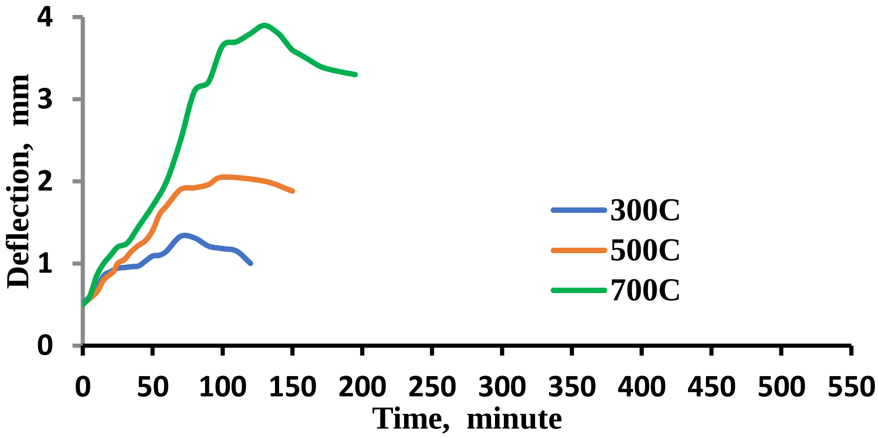


Fig. 8 Midspan camber -time history for suddenly cooled beams S_1, S_2 and S_3 at different burning temperatures.

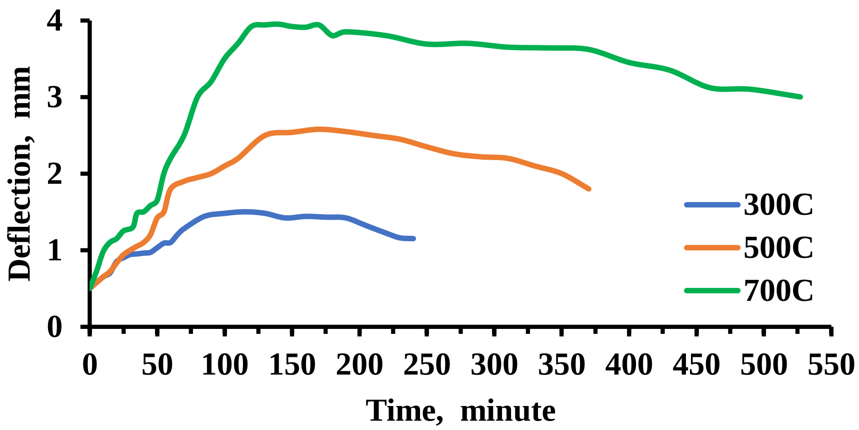


Fig. 9 Midspan camber -time history for gradually cooled beams G_1, G_2 and G_3 at different burning temperatures.

3.5. Static load carrying capacity

After accomplishing the study of the behavior of the post-tensioned concrete beams during the burning and cooling processes, all beams, including the reference beam that had not been exposed to burning, were tested as simply supported beams using a four-point loading with a shear span to depth ratio (a/d) of 3.7; a steel distributor beam was used to generate the two concentrated loads, as shown in Plate 3. For this reason, the beams were transmitted to the testing rig, the dial gauge was removed, and the value of measured final residual midspan camber of the burning stage test could not be kept.

The failure loads of the tested beams in this investigation are listed under Table 5. As shown in this table, the ultimate load capacity decreased with an increase in the burning temperature; the percentage decrease in the ultimate load at the burning temperature of 300, 500, and 700 °C was 16, 28, and 40 %, respectively, for the beams that cooled gradually, while it was 20, 36, and 48 %, respectively, for the beams that were cooled suddenly.

The results indicate that exposure to a burning temperature of 700 °C revealed the worse defects on the post-tensioned concrete beams. In addition, comparison of the effect of cooling mode on the ultimate beam load capacity exhibited that sudden cooling had more effect in reducing the ultimate load carrying capacity than gradual cooling by about 5, 11, and 13 % for the burning temperatures of 300, 500, and 700 °C, respectively. Therefore, the greatest reduction in the ultimate load capacity was found at the burning temperature of 700 °C, with a sudden cooling mode, i.e., beam (S_3).

Plate 3. The beam beams under load.

Table. 5 Load capacity for beams test result.

Beam	Burning temperature	Method of cooling	Load capacity (kN)	% of residual load capacity*	% of sudden / gradual capacity
R	ambient	-	50	100	---
G_1	300 ^oC	Gradually	42	84 (16)	95
S_1	300 ^oC	Suddenly	40	80 (20)	
G_2	500 ^oC	Gradually	36	72 (28)	89
S_2	500 ^oC	Suddenly	32	64 (36)	
G_3	700 ^oC	Gradually	30	60 (40)	87
S_3	700 ^oC	Suddenly	26	52 (48)	

*The value between the brackets are the percentage of decrease in load carrying capacity with respect to R- beam.

3.6. Modes of failure

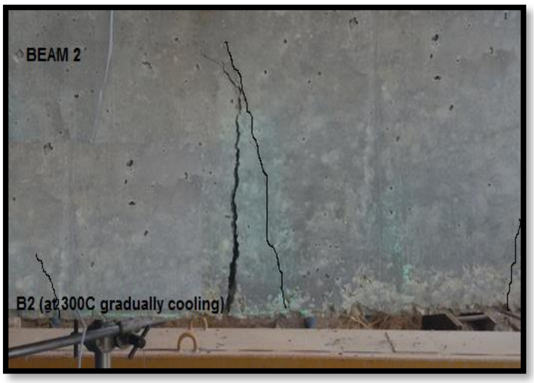
Failure of the beams tested in this study had approximately the same flexural mode of failure, as presented in Plates 4 to 7, by excessive deflection and bottom tension cracks at the midspan zone with the yielding of steel reinforcement, followed by rupturing of the post-tensioning wire.

3.7. Load- midspan deflection

The load-midspan deflection curves are the best criterion to evaluate and compare the efficiency of the structural members.
Figs. 10 and 11 show the effect of burning temperature on the midspan deflection of post-tensioned concrete beams that had been cooled gradually and suddenly, respectively. It can be seen that, with increasing burning temperature, the midspan deflection also increased. In addition, the beam stiffness, which is the slop of the curve at the first initial approximate straight line, decreased with an increase in the burning temperature, indicating an increase in the internal defects; the reduction in beams stiffness with respect to that of the reference beam R was found to be 55, 66, and 84 % for the gradually cooled beams at 300, 500, and 700 °C, respectively, while it was 63, 75, and 86 % for those which had been cooled suddenly.
As shown in Figs. 10 and 11, it can be seen that the reference beam R had a typical smooth behavior containing a straight part that represents the elastic zone, and the slop of the curve decreased near the ultimate load with a ductility less than that of all other beams due to the brittleness behavior of the prestressed concrete beams. In contrast, the other beams did not show the same behavior as that of the reference beam; they exhibited

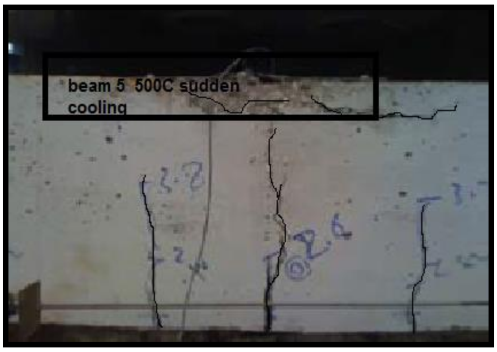
more flatten curves due to the defects of the concrete that manifested during the burning and cooling stages. The ratio of the maximum midspan deflection of the beams burned at 300, 500, and 700 °C followed by gradual cooling with that of the reference beam R revealed an increase of 25, 40, and 45 %, respectively. Similar behavior was observed for the beams burned and then cooled suddenly; they were 40, 50, and 65% for the same above burning temperatures, respectively. This result suggests that the formation and propagation of cracks were worse in the case of sudden cooling method compared to that in the gradual cooling method. Figs.12 to 14 show the comparisons between each pair of beams exposed to the same burning temperature, but cooled using different methods. These figures exhibit, approximately similar behavior at the first loading stage, and then the slop of the suddenly cooled beam was slightly more decreased than that of the gradually cooled beam.

Plate 4. Failure mode of reference beam R.



A- Beam G_1. **B- Beam S_1.**

Plate 5. Modes of failure of beams G_1 and S_1 which were burned at temperature 300 ^oC.



A-Beam G_2. **B-Beam S_2.**

Plate 6. Modes of failure of G_2 and S_2 which were burned at 500 ^oC.

A- Beam G_3. **B-Beam S_3.**

Plate. 7. Modes of failure of G_3 and S_3 which burned at 700 ^oC.

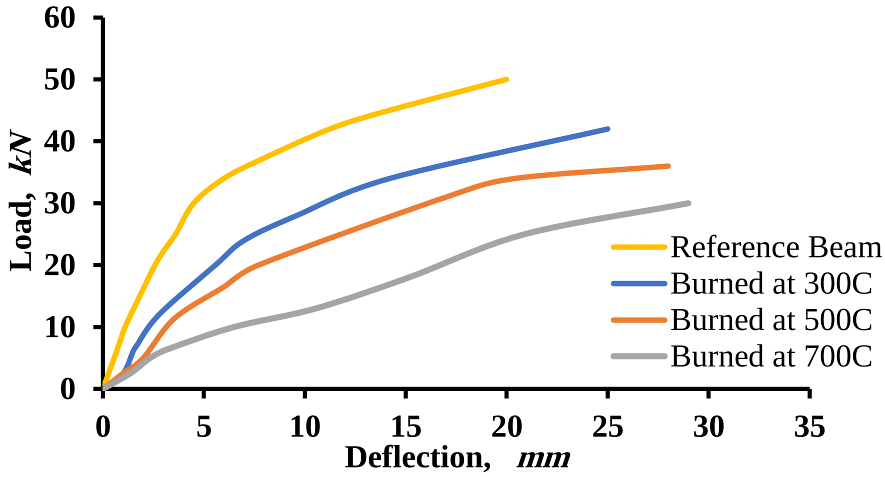


Fig. 10 Load-midspan deflection for burned beams G_1, G_2 and G_3 then gradually cooled and R beam.

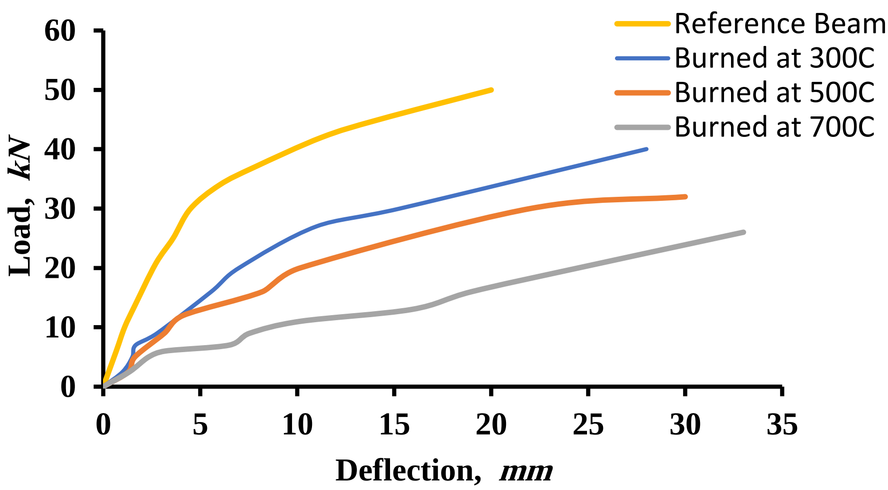


Fig. 11 Load-midspan deflection for burned beams S_1, S_2 and S_3 then suddenly cooled and R beam.

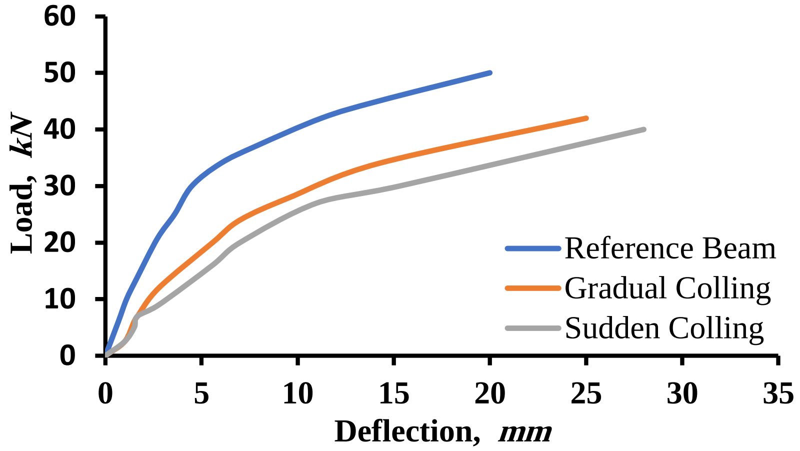


Fig. 12 Load- midspan deflection of group I beams which burned at 300 °*C* and R beam.

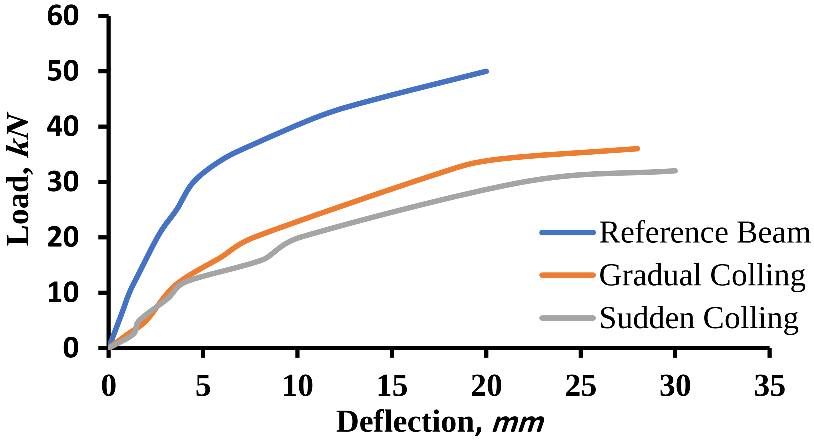
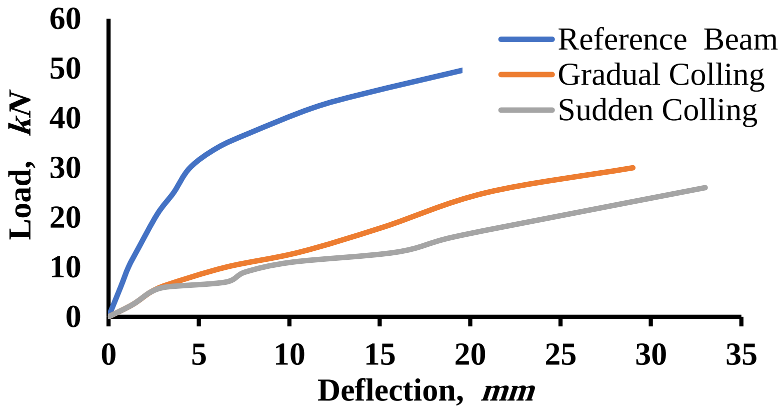


Fig. 13 Load- midspan deflection of group II beams which burned at 500 °*C* and R beam.



- The probability of spalling the concrete covers near the beam corners increased with the increase in the burning temperature. This phenomenon was observed at earlier stages of loading test of the beams that were exposed to high temperature compared to the others. Also, in the beams that were cooled suddenly more than the beams which were gradually cooled.
- The ultimate load capacity of the beam specimens decreased with increasing fire flame temperature. At the burning temperatures of 300, 500, and 700 °C, the average residual ultimate load capacity for gradually cooled beams were 84, 72, and 60 %, respectively. For the beams that cooled suddenly (high rate of cooling), the average residual ultimate load capacity was 80, 64, and 52 % at the burning temperatures of 300, 500, and 700 °C, respectively.
- The beam stiffness decreased with increasing burning temperature, indicating the increase in the internal beam defects.

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Fig. 14 Load- midspan deflection of group III beams which burned at 700 *°C* and R beam.

4. Conclusions

- The average percentage of residual compressive strength after exposure to 300, 500, and 700 °C was 80, 55, and 45 %, respectively, for the specimens cooled gradually. For the specimens cooled suddenly (high rate of cooling), the residual compressive strength was comparatively lesser (they were 73, 50, and 40 % for the exposure temperatures of 300,500, and 700 °C, respectively.
- The average percentage of residual modulus of rupture after exposure to 300, 500, and 700 °C was 91, 79, and 43 %, respectively, for specimens cooled gradually. For the specimens cooled suddenly (high rate of cooling), the residual modulus of rupture was comparatively lesser (they were 73 and 35 % for the exposure temperatures of 500 and 700 °C, respectively).
- Cracks were observed on the concrete surface of the beam specimens after burning the beams; these cracks deepened with increasing fire flame temperature, and the sudden cooling process had a significant effect on crack formations.

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تأثير الحرارة العالية (لهب النار) على تصرف العتبات الخرسانية اللاحقة الجهد

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الخلاصة: -

دراسة عمليه اجريت لبحث تأثير حرارة اللهب (الحرارة العالية) على تحمل العتبات الخرسانية لاحقه الجهد لإيجاد قابليه التحمل المتبقية بعد الحرق. لمحاكات الحالة الحقيقية للكارثة، تم تعريض ست نماذج للحرارة العالية (حرارة اللهب: 300، 500، و700 سيليزي) لمده ساعة باستعمال فرن خاص تم تصنيعه لهذا الغرض. بعدها، تم تبريد النماذج بطريقه تدريجيه بترك النماذج في الهواء بظروف المختبر وكذلك بالطريقة السريعة برش النماذج برذاذ بالماء. بعد ذلك، تم تحميل النماذج حتى الفشل لإيجاد تأثير اختلاف معدل التبريد على المتانة المتبقية للنماذج. نتائج الفحص قورنت مع تصرف عتبات خرسانيه لاحقه الجهد غير معرضه للحريق (عتبات مصدريه). معدل المتبقي لمقاومه المكعبات بعد التعرض الى الحرارة العالية (300، 500، و700 سيليزي) كانت 80، 55، و45% للنماذج التي بردت بالطريقة التدريجية وكانت 89، 74، و35% للتي بردت بالطريقة السريعة. قابليه التحمل العظمى للعتبات قلت مع ازدياد درجات الحرارة للهب، حيث لوحظ عند التعرض الى درجات الحرارة 300، 500، و700 سيليزي فان المتبقي من التحمل للنماذج المبردة بصوره تدريجيه 84، 72، و60% بالتوالي بينما للتي بردت بالطريقة السريعة كانت 80، 64، و52% بالتوالي لنفس درجات الحرارة.

الكلمات المفتاحية: - حرارة الحرق، حرارة اللهب، تبريد تدريجي، تبريد سريع.