Post-Fire Behavior of Non-Prismatic Beams with Multiple Rectangular Openings Monotonically Loaded

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Abstract-The main objective of this paper is to study the behavior of Non-Prismatic Reinforced Concrete (NPRC) beams with and without rectangular openings either when exposed to fire or not. The experimental program involves casting and testing 9 NPRC beams divided into 3 main groups. These groups were categorized according to heating temperature (ambient temperature, 400°C, and 700°C), with each group containing 3 NPRC beams (solid beams and beams with 6 and 8 trapezoidal openings). For beams with similar geometry, increasing the burning temperature results in their deterioration as reflected in their increasing mid-span deflection throughout the fire exposure period and their residual deflection after cooling. Meanwhile, the existing openings situation was compounded. The burned NPRC beams were left to gradually cool down under ambient laboratory conditions, and afterward, they were loaded until failure. The influence of temperature on the residual ultimate load-carrying capacity of each beam was studied by comparing these beams with unburned reference beams. Increasing exposure temperature reduces the ultimate strength of solid NPRC beams exposed to temperatures of 400°C and 700°C by about 5.7% and 10.84% respectively. Meanwhile, NPRC beams with trapezoidal openings showed ultimate strength reductions of 21.13% and 32.8% (for beams with 8 openings) and 28% and 34.4% (for beams with 6 openings) under the same burning conditions. The excessive mid-span deflections for these three types of beams were 2%–30.8%, 1.33%–21.8%, and 1.5%–17.4% under the same burning conditions.

Keywords-burning temperature; non-prismatic beams; openings number

I. INTRODUCTION

Reinforced Concrete (RC) is often used in high-rise structures and other buildings. Ensuring the fire safety of structural components is an important part of building design because fires are among the most dangerous environmental phenomena that may affect a structure during its life cycle. This requirement can be attributed to the fact that when other fire control measures fail, structural integrity becomes the last line of defense of a building. Experimental investigations have been conducted in the past to highlight the effect of fires on the material characteristics of concrete with several mix proportions under different fire scenarios [1-4]. High temperature has been reported to reduce the material characteristics of concrete, including strength [5]. Reinforcing steel is more sensitive than concrete at high temperatures [6]. While concrete and steel show a similar thermal expansion at temperatures up to 400°C, the latter significantly expands at higher temperatures. In addition, at 700°C, the steel bearing capacity of these materials reduces by about 20% [7]. Structural failure mostly occurs when the reinforcement loses its effective strength via heating. Therefore, researchers argue that a reinforcement with adequate cover has a sufficient fire resistance [8]. Authors in [9] designed a numerical model in the form of a computer program to track the fire behavior of RC beams over the entire load range from pre-fire conditions to fire collapse. Three stages were examined in their analysis, namely establishing the fire temperature–time development, calculating the heat transfer of fire through the structure, and interpreting the structural analysis results. Authors in [10] studied the fire resistance of 6 RC beams and found that the fire resistance of HSC beams is lower than that of NSC beams. Moreover, HSC beams exhibit a high level of spalling, which is largely affected by concrete permeability, fire exposure type, load level, and restraint conditions. Similarly, the type of fire scenario, axial restraint, and load level significantly affect the overall fire resistance of RC beams.

Authors in [11] tested 9 rectangular beams to study the effect of multiple web openings along the span length of RC beams on their bending behavior. The plastic failure mechanism for beams having multiple openings is much longer than those for beams with a single opening. Authors in [12] studied experimentally and theoretically the effect of strengthening on improving the flexural and shear strength of 12 simply supported, high-strength Non-Prismatic RC (NPRC) beams with openings. Experimental results show that when NPRC beams are strengthened by a carbon fiber bar, the ultimate load for flexural and shear strengths increases by 16% and 15% respectively. Authors in [13] investigated 4 RC beams with a rectangular cross-section under 3-point load until failure and found that perforating an RC beam with small web openings slightly reduces its ultimate load and increases its

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ultimate deflection. Authors in [14] studied the serviceability of reinforced concrete gable roof beams with openings under static loads obtaining good agreement between the analytical and the experimental results. Authors in [15] investigated the structural behavior of RC beams with Fiber-Reinforced Polymer (FRP) bars and large rectangular openings and found that the presence of openings leads to the early formation of cracks at the locations of these openings. However, no study thus far has examined the high temperature resistance of NPRC solid beams or beams with openings.

II. BEAM SETUP

The experimental part was executed by manufacturing 9 scaled down (1/4) simply supported non-prismatic archetype roof beams. As shown in Figure 1, these beams have a width of 10cm, an overall horizontal lower chord length of 300cm, and inclined upper chord heights of 40cm and 25cm at the mid-span and ends respectively. All beams were reinforced identically with 4-Ø6mm arranged by 2 layers in the top chord and 2-Ø6+2-Ø 12mm arranged by 2 layers in the bottom chord (Figures 2-4). Transverse steel bars made of 6mm steel bars were provided at the solid ends of the solid beam GB and the other test specimens, and the openings were equally spaced at 10cm. Closed shear stirrups made of 4mm ordinary steel bars were provided over the entire span of the upper and lower chords of the test sample with 5cm spacing. Each beam was tested using a simple scheme with an effective span of 280cm. The tested beams were divided into 3 groups depending on the heating temperature (ambient, 400°C, and 700°C). Each of these groups has 3 NPRC beams (solid beam, and beams with 6 and 8 trapezoidal openings).

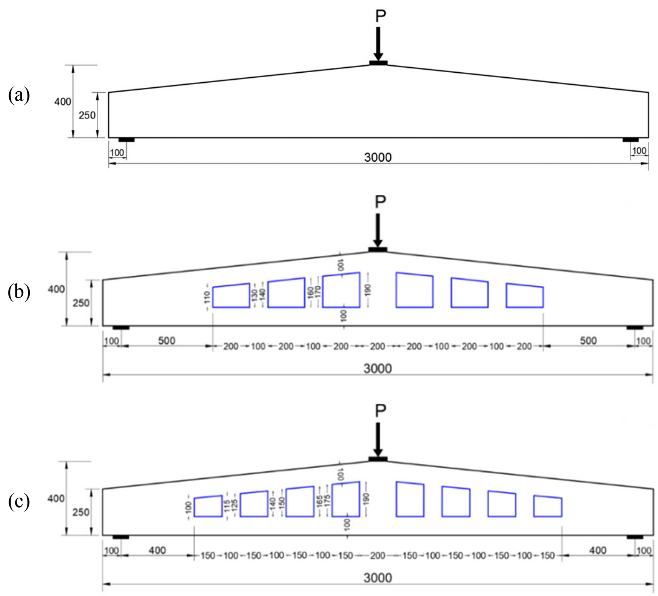

Fig. 1. Schematic layout of NPRC beams (all dimensions are in mm). (a) Solid NPRC beams GB, GB-400, and GB-700, (b) NPRC beams with trapezoid openings GT6, GT6-400, and GT6-700, (c) NPRC beams with trapezoid openings GT8, GT8-400, and GT8-700.

Table I and Figure 1 show the parametric details of the tested beams, where G denotes the NPRC beams, B denotes the beams without openings, and T denotes the ones with trapezoidal openings. The number that follows each symbol represents the number of openings in each specimen. Figures 2-4 show the configuration of the test beams and the reinforcement arrangement of the control and other NPRC beams. In all beams with openings, the length of solid ends ranges from 40cm to 50cm to override shear or end bearing failure. Meanwhile, a 20cm wide column was directly realized under mid-span load.

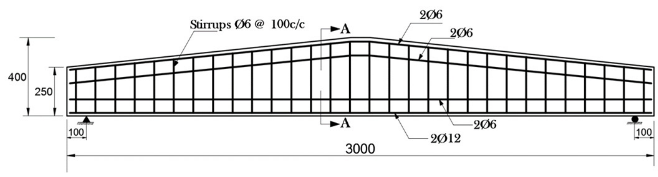

Fig. 2. Steel reinforcement of GB, GB-400, and GB-700. Section A-A (all dimensions are in mm).

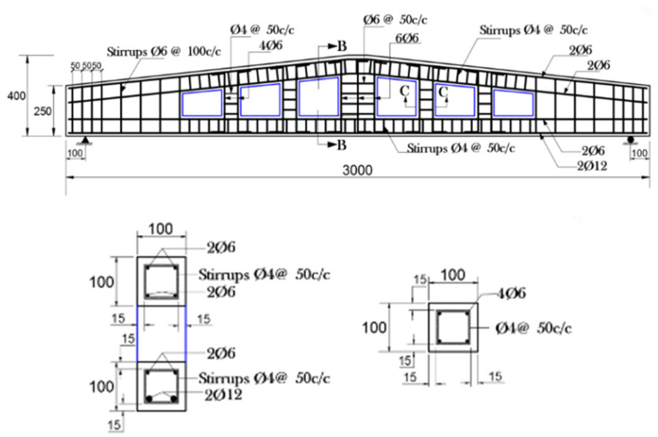

Fig. 3. Details of steel reinforcement of GT6, GT6-400, and GT6-700. Sections B-B and C-C/

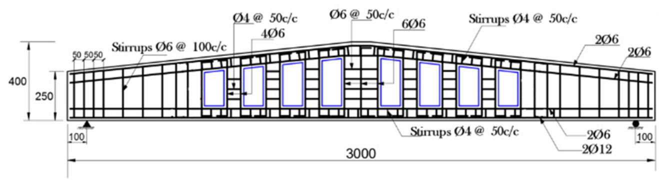

Fig. 4. Details of steel reinforcement of GT8, GT8-400, and GT8-700.

Normal concrete was used in the beams. The characteristics of concrete (e.g. modulus of elasticity, compressive and splitting tensile strength) were measured using steel cylindrical molds with 300mm height and 150mm diameter. The reinforcing steel bars had diameters of 4, 6, and 12mm, and the average yield, ultimate strength, and modulus of elasticity were determined by performing standard tests on the steel bars. The characteristics of the normal concrete and steel reinforcements used in this work are shown in Tables II and III.

TABLE I. DETAILS OF TESTED NPRC BEAMS

Group ID	Beams ID	Openings shape	Number of openings	Total area of openings (mm^2)	Width of openings (mm)	$\frac{weight_{rafter}}{weight_{GB}}$	Fire Temperature (^oC)
I	GB	-	-	0	-	1.0	Amb.
	GT6	Trapezoid	6	180000	200	0.81	Amb.
	GT8	Trapezoid	8	174000	150	0.81	Amb.
II	GB-400	-	-	0	-	1.00	400
	GT6-400	Trapezoid	6	180000	200	0.81	400
	GT8-400	Trapezoid	8	174000	150	0.81	400
III	GB-700	-	-	0	-	1.00	700
	GT6-700	Trapezoid	6	180000	200	0.81	700
	GT8-700	Trapezoid	8	174000	150	0.81	700

TABLE II. MATERIAL PROPERTIES

Material	Ø (mm)	Yield stress (MPa)			Compressive strength (MPa)			Ultimate tensile strength (MPa)		
		Amb.	400	700	Amb.	400	700	Amb.	400	700
Conc.	--	--	--	--	32.6	25	12.6	--	--	--
Steel	4	390	352	262	--	--	--	590	547	456
	6	580	524	390	--	--	--	650	602	503
	12	610	570	496	--	--	--	722	657	549

TABLE III. MODULUS OF ELASTICITY

Material	Ø (mm)	Modulus of elasticity (GPa)		
		Amb.	400	700
Concrete	--	26.86	20.1	13.1
Steel	4	200	200	194
	6	200	200	194
	12	200	200	194

III. TESTING PROCEDURE

The experimental program involved casting and testing of the NPRC beams. They were monotonically loaded after exposure to high temperatures, as follows:

A. *Burning Stage*

The burning process was conducted in a furnace manufactured with a 4mm thick box-shaped steel plate to restrict heat and to burn one or more NPRC beams simultaneously (Figure 5). The furnace had an inner clear space of 0.8m height, 2m width, and 3.5m length and had the capability of maintaining 20 methane flames (nozzles). Eight compressed air nozzles were positioned at the lower furnace level near the base to maintain enough space underneath the NPRC beams, so the flames from the methane would be able to reach the NPRC beams, simulating the burning of simply supported NPRC beams. The upper level of the furnace had many small openings for thermocouple wires (K-type). The burning stage involved positioning each NPRC beam above its idealized simply supported ends and reading the mid-span deflection from dial gauges. The NPRC beams and control specimens were exposed to burning temperatures of 400°C or 700°C following the fire standard rate of ASTM E-119 [16]. The flame was supplied at the lower level of the furnace for an exposure period of 1h after reaching the target temperature. After this period, the flame was turned off, the furnace cover was removed, and the NPRC beams were gradually cooled down under ambient air.

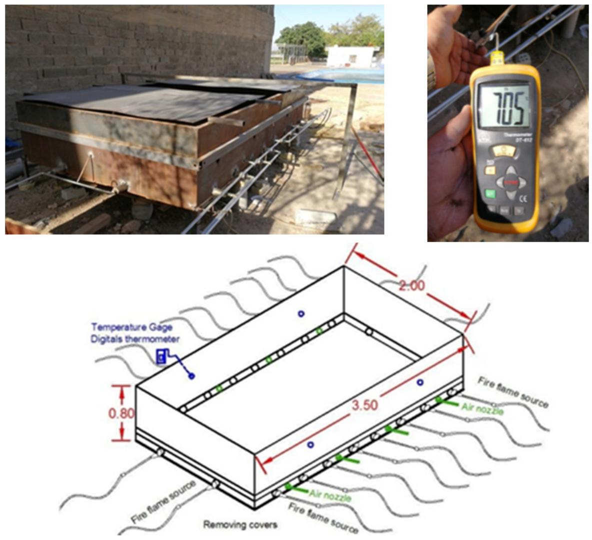

Fig. 5. Furnace and burning process.

B. *Load Test Stage*

Figure 6 presents a schematic of the test setup. The NPRC beams were simply supported by steel rollers with a solid steel plate. The left roller was welded to the bearing plate to simulate hinge support, whereas the right roller was not welded. To eliminate the difference in load due to the variations in the sizes and locations of the openings, the load was applied on a thick 10cm × 10cm steel plate positioned at the tapered crest end of a non-prismatic beam that was flatted horizontally. A hydraulic jack with a 50-ton capacity was used to apply load on the beams. The applied load was controlled using a load cell with a digital load reader. The load was applied with 2.5kN increments. A dial indicator was used to measure the vertical deflection at 150mm from the support, under each post, and at the mid-span. The beam was loaded until failure. Deflection and the resulting strain were measured, the crack propagation was marked, and the crack width was measured at different load levels.

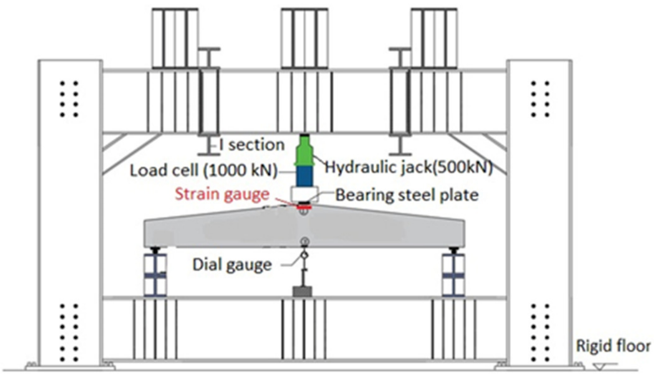

Fig. 6. Test setup.

IV. Experimental Results and Discussion

A. Deflection at Burning and Cooling Stages

The target temperatures of 400°C and 700°C were reached after 7 and 10min respectively. They are approximately similar to those specified in ASTM E-119 [15] as shown in Figure 7. After removing the furnace cover, the NPRC beams were gradually cooled under ambient laboratory conditions.

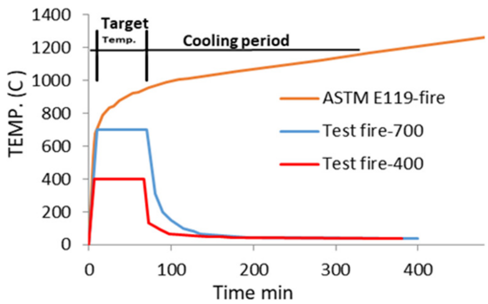

Fig. 7. Fire scenarios used in the burning test.

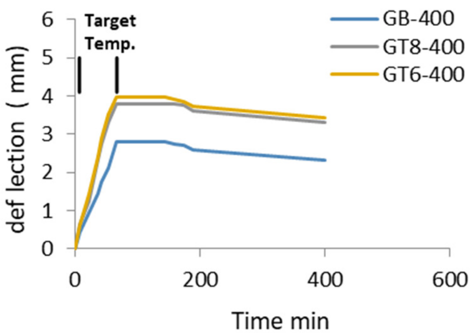

Fig. 8. History of mid span deflection Group 400.

Figures 8 and 9 present the mid-span deflection versus time history of groups exposed to similar burning conditions. Groups 400 and 700 correspond to the burning temperatures of 400°C and 700°C respectively. The mid-span deflection rate caused by heating increased through the burning periods of rising and target temperatures. Thereafter, some of this deflection was restored during the cooling (third) period. Meanwhile, the NPRC beams with openings demonstrated a higher deflection increase rate after heat exposure. The recovery rate of GT6 was slightly greater than that of GT8. Table IV presents the effect of openings, burning temperatures, and residual deflection of NPRC beams at each exposure period.

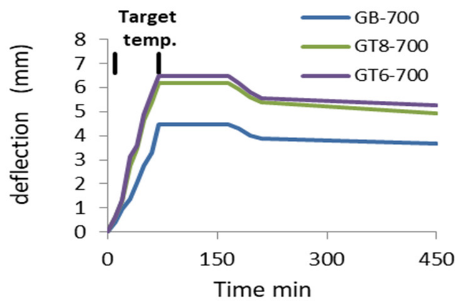

Fig. 9. History of mid span deflection Group 700.

TABLE IV. RESIDUAL DEFLECTION AT THE END OF THE BURNING PERIOD AND THE COOLING CYCLE.

Group	Beam ID	Residual deflection		
		At the third period (mm)	NPRC beams (with/ without) openings (%)	NPRC beams exposed to (700/400) °C (%)
400	GB-400	2.31	100	159
	GT8-400	3.32	143	148
	GT6-400	3.43	148	154
700	GB-700	3.67	100	
	GT8-700	4.92	134	
	GT6-700	5.27	143	

B. Monotonic Load Test Post Fire Results

1) Cracking and Failure Loads and Modes of Failure

Visible or not, most NPRC beams cracked evenly during the fire exposure test stage. The first crack load is indicative of two things, the flexural crack load or the widening of post-fire cracks. All NPRC beams cracked during the loading stage for loads varying between 17.5% and 23.5% of the corresponding load of failure. Such disparity between cracking and the ultimate loads was clear for the unburned NPRC beams (17.5%–20%) and decreased along with increasing temperature (20%–23.2% and 19.9%–23.5% at 400°C and 700°C respectively) as shown in Table V. Figure 12 shows the crack patterns of the tested beams. In all NPRC beams, cracking occurred at loads below their respective service loads, although the ultimate load decreased with increasing temperature. Therefore, the trustworthy design of these structural elements may be controlled by serviceability requirements. The average crack spacing was 60mm to 75mm for the NPRC beams in the unburned group, 55mm to 70mm for the NPRC beams exposed to 400°C, and 50mm to 65mm for the beams exposed to 700°C.

TABLE V. CRACKING AND ULTIMATE LOADS OF THE TESTED NPRC BEAMS

Group	Beam ID	No. of openings	Net area of the beam A_{net} (mm^2)	First cracking load P_{cr} (kN)	$\frac{A_{net}}{A_{net,GB}}$ (%)	$\frac{P_{cr}}{P_{cr,GB}}$ (%)	Failure load P_{ult} (kN)	$\frac{P_{cr}}{P_{ult}}$ (%)
Unburned	GB	------	982500	18	------	------	90	20
	GT6	6	802500	14	81.7	77.8	77.8	18
	GT8	8	808500	14	82.3	77.8	80.2	17.5
400	GB-400	------	982500	17	------	------	84.91	20
	GT6-400	6	802500	13	81.7	76.5	56	23.2
	GT8-400	8	808500	13	82.3	76.5	63.25	20.6
700	GB-700	------	982500	16	------	------	80.24	19.9
	GT6-700	6	802500	12	81.7	75	51.06	23.5
	GT8-700	8	808500	12	82.3	75	53.9	22.3

Relatively short surface hairline cracks began to form at 400°C and became very obvious at 700°C. Apart from the effect of temperature, Figures 10-11 show the correlation between the savings in concrete used in producing the tested NPRC beams with openings and the percentage reduction in the load carrying capacity of these members. The maximum ratio of reduction in concrete consumption to the reduction in load-carrying capacity for NPRC beams with openings was 1.72 for GT8 at ambient temperature, whereas the minimum ratio was 0.45 for GT6 exposed to 700°C. Meanwhile, the ratio of reduction in concrete consumption to the reduction in load-carrying capacity decreased along with increasing burning temperature. Due to the exposure circumstance, the denominator (load-carrying capacity) showed a greater reduction than the numerator (concrete consumption). Comparing the NPRC beams with 8 openings with those having 6 openings reveals that the ultimate load-carrying capacity increased by 3.1%, 13%, and 5.5% at ambient temperature of 400°C, and 700°C respectively.

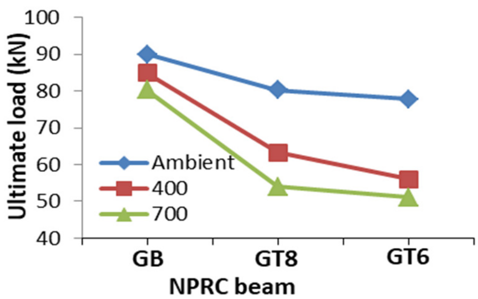

Fig. 10. Effect of openings and the temperature on the ultimate capacity.

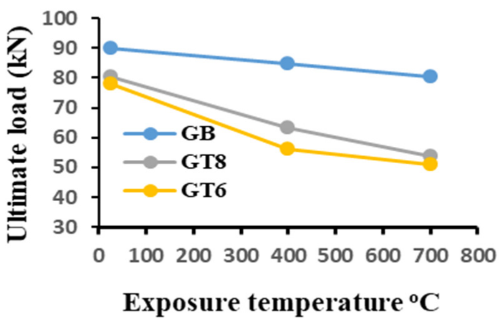

Fig. 11. Failure load vs. exposure temperatures.

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)

Fig. 12. Crack patterns. (a) GB, (b) GT6, (c) GT8, (d) GB-400, (e) GT6-400, (f) GT8-400, (g) GB-700, (h) GT6-700, (i) GT8-700.

2) Load-Deflection Relationship

Tables VI, VII and Figures 13-15 show the mid-span deflection at different loading stages (20kN, 40kN, and ultimate load). At the ultimate load, the excessive mid-span deflection increased for the NPRC beams with openings. The mid-span deflections of beams exposed to ambient temperature, 400°C, and 700°C ranged from 42.3% to 57.7%, 41.6% to 57%, and 32.4% to 41.5% respectively, depending on the number of posts between the openings and their total area. The stiffness of all NPRC beams decreased with increasing burning temperature due to the deterioration of concrete during its exposure to fire, which in turn led to the increased deflection of these beams. A high rate of defects was observed at 700°C.

TABLE VI. LOAD FOR TESTED NPRC BEAMS AT ULTIMATE STAGE

Group	Beam ID	Openings number	Failure load P_{ult} (kN)	Percentage of reduction (%)
GB	GB	---	90.0	----
	GB-400	---	84.9	5.7
	GB-700	---	80.24	10.8
GT8	GT8	8	80.2	----
	GT8-400	8	63.25	21.13
	GT8-700	8	53.9	32.8
GT6	GT6	6	77.8	----
	GT6-400	6	56.0	28
	GT6-700	6	51.1	34.3

TABLE VII. LOAD AND CORRESPONDING DEFLECTION FOR THE TESTED NPRC BEAMS AT DIFFERENT LOADING STAGES AND FIRE EXPOSURE CONDITIONS

Group	Beam ID	At 20 kN		At 40 kN		At ultimate load		Failure load P_{ult} (kN)	Percentage of reduction (%)
		Deflection (mm)	Percentage of increase (%)	Deflection (mm)	Percentage of increase (%)	Deflection (mm)	Percentage of increase (%)		
Unburned	GB	2.62	------	6.4	----	16.8	----	90.0	----
	GT6	4.02	53.4	9.96	55.6	26.5	57.7	77.8	13.6
	GT8	2.76	5.3	8.36	30.6	23.9	42.3	80.2	10.9
400	GB-400	4.43	----	8.32	----	17.1	----	84.9	----
	GT6-400	6.28	41.8	13.76	65.4	26.9	57.0	56.0	34
	GT8-400	5.11	15.3	11.61	39.5	24.2	41.6	63.25	25.5
700	GB-700	5.43	----	10.4	----	21.9	----	80.24	----
	GT6-700	10.1	86.3	19.8	90	31.1	41.5	51.1	36.4
	GT8-700	7.43	36.8	18.1	74	29.1	32.4	53.9	32.8

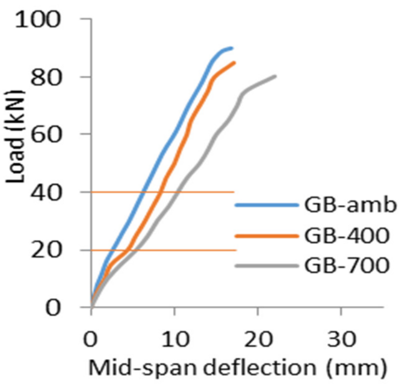

Fig. 13. Load-deflection curves, GB group.

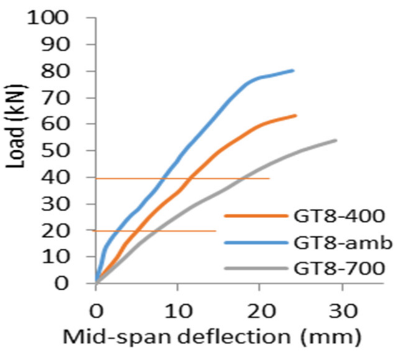

Fig. 14. Load-deflection curves, GT8 group.

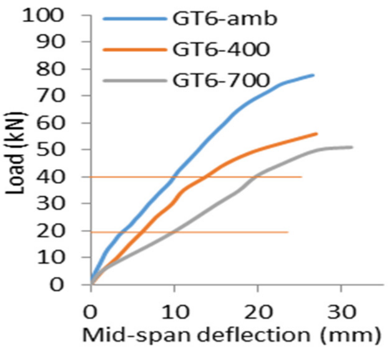

Fig. 15. Load-deflection curves, GT6 group.

V. CONCLUSIONS

- Increase in the burning temperature increased the mid-span deflection of NPRC beams at all burning and cooling cycle periods. A similar increase was reported for residual deflection, which amounted to 143% and 148% for beams with 8 and 6 openings, respectively, at 400°C and to 134% and 143% at 700°C.
- Cracks began to form on the concrete surfaces of NPRC beams after the burning and cooling processes. The number and width of cracks increased with burning temperature.
- All NPRC beams cracked during the loading stage at 17.5% to 23.5% of the corresponding failure load. The disparity between cracking and ultimate loads was obvious among the unburned NPRC beams (17.5% to 20%) and decreased with increasing temperature (20%–23.2% and 19.9%–23.5% at 400°C and 700°C burning temperatures).

- Increase in the exposure temperature reduced the ultimate strength of solid NPRC beams by about 5.7% and 10.84% after exposure to 400°C and 700°C. The corresponding reductions for NPRC beams with 8 and 6 trapezoidal openings were 21.13%–32.8% and 28%–34.4% respectively. Under these same conditions, the excessive mid-span deflections for these beams were 2%–30.4%, 1.3%–21.8%, and 1.5%–17.4% for ambient temperature, 400°C, and 700°C respectively.

- For the same length of extended beams, increasing the number of openings with a small area, which coincides with reducing the total area of openings by increasing the number of posts, improved the flexural behavior of NPRC beams. Relative to that of beams with 6 openings, the load-carrying capacity of NPRC beams with 8 openings increased by 3.1%, 13.0%, and 5.5% when exposed to ambient temperature, 400°C, and 700°C respectively.

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