Advances in Science and Technology Research Journal
Volume 13, Issue 2, June 2019, pages 150–156
https://doi.org/10.12913/22998624/109055

Received: 2019.03.21
Revised: 2019.04.05
Accepted: 2019.04.20
Available online: 2019.05.01

Studying the Flexural Behavior of Reinforced Concrete Beams under the Effect of High Temperature: A Finite Element Model

Hamadallah Al-Baijat[1*], Mohammad Alhawamdeh[2], Aya Khawaldeh[3]

[1] Department of Civil Engineering, Faculty of Engineering, Tafila Technical University, P. O. Box (179) Tafila 66110, Jordan

[2] Department of Civil Engineering, Faculty of Engineering, Tafila Technical University, P. O. Box (179) Tafila 66110, Jordan

[3] Department of Civil Engineering, Faculty of Engineering, Jordan University of Science and Technology, P. O. Box (3030) Irbid 22110, Jordan

* Corresponding author's e-mai: albaijath@yahoo.com, hamadallah@ttu.edu.jo

ABSTRACT

The strength of concrete elements can be greatly affected by elevated temperature as in fires, and so a great concern must be taken regarding its behavior under such condition. In this paper, a finite element model was built up using ABAQUS software to investigate the flexural behavior of reinforced concrete (RC) beams subjected to service load under elevated temperature. The beam was simply supported and was loaded at one-third and two-third of span length. The study consisted of three RC beams models; the first model simulated a control beam specimen at ambient temperature 20 °C, while the other two models demonstrated damaged beams specimens according to two high temperatures 400 °C and 800 °C, respectively. Each RC beam had 2 m span length, 300 mm height and 200 mm width. The steel reinforcement configuration was 3ϕ16 mm (Grade 60) main bars at the positive moment region in the beam bottom, 2ϕ14 mm (Grade 60) secondary bars at the beam top, and ϕ10 mm /150 mm closed stirrups. The model was validated by comparing its results with the theoretical results from ACI code and literature. Several mechanical properties were investigated including concrete compressive strength, modulus of elasticity, and reinforcing steel yielding strength. The test results showed a reduction in the flexural capacity of the RC beams, tested at 400 °C and 800 °C, of 17.6% and 88.2%, respectively, with respect to the control beam. The maximum service load carried by the beam, at one-third and two-third of the span length, decreased by 17.1% and 88.1% for the 400 °C and 800 °C high temperature, respectively. The results also showed an increase in deflection when the temperature increased due to the loss in stiffness.

Keywords: flexural behavior, reinforced concrete beam, high temperature, fire, finite element model, deflection.

INTRODUCTION

Extreme loading scenarios might influence the durability and solidity of the structural elements. These loadings can be expressed as external loads, external moments, elevated temperature, and any other loads which can affect the structure during the operational lifetime. Concrete as a structural material has relatively high compressive strength, but significantly lower tensile strength, because of that it is usually reinforced with materials that are superior in tension such as steel. Reinforced concrete structures may be exposed to natural fire during their lifetime. Therefore, it is very important to study the behavior of reinforced concrete during and after fire, and also to study the degree of temperature and duration it can endure. The study of real behavior for reinforced concrete structures during and after fire is very important to achieve a high level of safety.

The strength and stiffness of flexural concrete members are decreased during fire exposure depends on many factors including type of exposure, concrete and reinforced steel rebar properties, the load level, and boundary conditions [Kodur and Agrawal, 2016]. Kowalski [2010] indicated that concrete mechanical properties are significantly influenced by temperatures above 400°C to 500°C. Huang et al. [1999] indicated that the design against thermal loading in reinforced concrete structures is based on simplistic techniques, which have been created from the standard fire tests that do not take the real behavior of building during a fire. According to Knaack et al. [2011], there is a need for a predictive structural performance based on fire design principles as an alternative to the existing design methodology. The mechanical properties of the structural materials such as different grades of concrete and reinforced steel, the boundary conditions and all types of loading including thermal loading should be taken into design requirements and considerations.

Chen et al. [2006] Performed an experimental study on two different steel grades at elevated temperatures. High strength and mild structural steel used to investigate the mechanical properties, young's moduli and yield strengths at different levels of strain, while the thermal elongation and ultimate strengths for the two steel grades obtained at different values of temperatures. The test showed that the ACI code and some other codes are conservative for temperature increased up to 1000 °C in terms of yield strengths but unconservative in terms of young's moduli obtained from the case of transient-state tests. Ellingwood and Lin [1991] conducted a research program to investigate the behavior of reinforced concrete beams subjected to fire. Six reinforced concrete beams, designed to ACI 318-11 specifications, with a 20 ft (6.1 m) span and a 6 ft (1.8 m) cantilever were tested. Beams were casted using Normal weight concrete and Grade 60 reinforcing rebars, and were divided into two groups. The first group was tested according to ASTM E119 fire exposure of 550 °F to 1600 °F high temperatures for four hours, while the second group was subjected to a short duration high intensity (SDHI). At this technique, fire rapidly increased to 1860 °F for the first 45 min, then rapidly cooled to 600 °F during 1 hr 40 min. Test results showed that flexural cracks were developed in the positive moment region of the span after 30 min of fire, and continued to widen up to ¼ in through three hours and a half of fire exposure duration. The most important parameter affected by the elevated temperature of the reinforced concrete flexural member, beam, was the reinforcement temperature history.

Most of the previous studies focused on the mechanical properties (concrete compressive strength, steel yeilding strength, and the modulus of elasticity) of concrete and reinforcing steel while avoiding to assess the effect of increasing temperatures.The objectives of this study are to investigate the flexural behavior of RC beams subjected to different elevated temperature and to evaluate the reduction in the beams' bending capacity due to increase in temperature. The design of the RC beams will be conducted according to ACI 318-14 specifications.

METHODOLOGY

A finite element model were constructed using ABAQUS software to study the structural behavior of reinforced concrete beams subjected to elevated temperatures. The model consisted of a RC beam with 2 m span length, 300 mm height, and 200 mm wide. The steel reinforcement comprised of 3ϕ16 mm (Grade 60) main bars at the positive moment region in the beam bottom, 2ϕ14 mm (Grade 60) secondary bars at the beam top, and ϕ10 mm /150 mm closed stirrups, as shown in Figure 1. The beam design procedure followed ACI 318-14 specifications. Table 1 illustrates the theoretical design data for the control beam specimen.

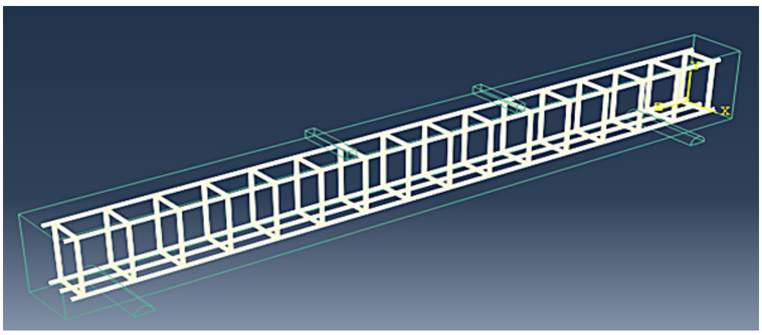

Figure 1. Beam reinforcement details

Table 1. The theoretical design data for the control beam specimen

Main steel reinforcement (at bottom)	A_s	$603.2\ mm^2$
Secondary steel reinforcement (at top)	A_s'	$307.9\ mm^2$
Yield strength of steel reinforcement	f_y	$420\ MPa$
Concrete compressive strength	f_c'	$28\ MPa$
Compression depth	c	$51.74\ mm$
Yield strain of main steel reinforcement	ϵ_y	0.002
Strain in secondary steel reinforcement	ϵ_s'	0.0006807
Strength in secondary steel reinforcement	f_s'	$142.947\ MPa$
Nominal moment capacity	M_n	$59.505\ kN.m$
Nominal load	P_n	$85\ kN$

where:
f_c' – average uniaxial concrete compressive strength of standard cylinder at 28 days (MPa),
f_y – yield strength of steel reinforcement (MPa),
f_s' – strength in secondary steel reinforcement (MPa).
A_s – main steel reinforcement (mm^2),
A_s'– secondary steel reinforcement (mm^2),
c – compression depth (mm).
ϵ_y – yield strain of main steel reinforcement.
ϵ_s' – strain in secondary steel reinforcement.
M_n– nominal moment (moment capacity in kN·m).
P_n – nominal load (load capacity in kN).

MODELING

Concrete

Concrete damaged plasticity model was used in ABAQUS to simulate concrete behavior in beams. To achieve this model, the strength and the corresponding longitudinal strain of confined concrete were represented by the following relationships [Tsai, 1988]:

$$E_c = 8200 \times f_c'^{0.375} \quad (1)$$

$$\varepsilon_{cc} = \frac{f_c'^{0.25}}{1153} \quad (2)$$

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \quad (3)$$

$$r = \frac{f_c'}{5.2} - 1.9 \quad (4)$$

$$n = \frac{7.2}{f_c'^{0.375}} \quad (5)$$

$$f_{cc}' = \frac{n x f_c'}{1+\left(n-\frac{r}{r-1}\right)\times x+\frac{x^r}{r-1}} \quad (6)$$

$$f_t' = \frac{f_{cc}'^{\,0.5}}{3} \quad (7)$$

$$\varepsilon_{to} = \frac{f_t'}{E_c} \quad (8)$$

where:
E_c is the concrete modulus of elasticity (MPa),
x is the ratio of concrete strains,
ε_c is the longitudinal compressive concrete strain,
ε_{cc} is the maximum confined concrete strain,
f_{cc}' is the compressive strength (peak stress) of confined concrete,
f_t' is the tensile strength of concrete,
ε_{tO} is the tensile rupture strain in concrete,
n is the ratio of the initial tangent modulus to the secant modulus,
r is a factor to control the steepness rate for the descending portions of the stress-strain relation.

These relationships yield the conventional stress-strain diagrams of concrete under compression and tension prior exposure to elevated temperature, as shown in Figures 2 and 3. Under uniaxial tension, the behavior of concrete is linear until reaching the micro-cracking, then mutate by softening response in strain.

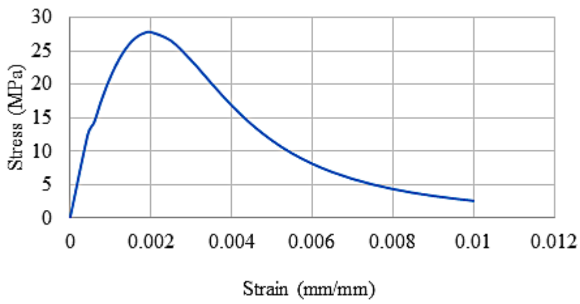

Fig. 2. Typical compressive stress-strain diagram for concrete prior exposure to high temperature

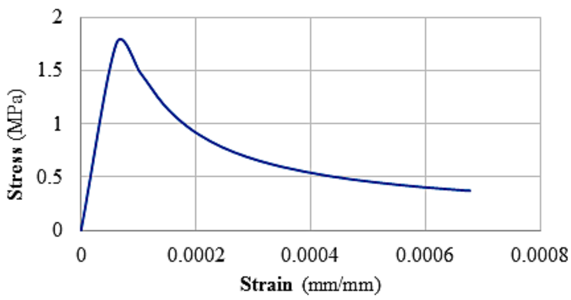

Fig. 3. Typical tensile stress-strain diagram for concrete prior exposure to high temperature

Steel reinforcement

The stress-strain curve of the reinforcing steel bar is assumed to be linear elastic up to the yield stress of steel, followed by perfectly plastic behavior. According to Topçu and Karakurt [2008], The yield strength of reinforcing steel bars is influenced by exposure to elevated temperatures. Figure 4 illustrates the behavior of reinforced steel during elevated temperature.

Post heating model

The post-heating behavior of concrete was characterized using the following equations [Wong, 2011]:

$$\frac{E_T}{E_o} = 1.0 + \frac{T}{2000 \ln\left[\frac{T}{1100}\right]} \qquad for\ 0℃ < T \leq 600℃ \tag{9}$$

$$\frac{E_T}{E_o} = \frac{690\left(1-\frac{T}{1000}\right)}{T-53.5} \qquad for\ 600℃ < T \leq 1000℃ \tag{10}$$

where:

E_O is the modulus of elasticity at ambient temperature,

E_T is the modulus of elasticity at temperature,

T is the elevated temperature.

ABAQUS model

As previously mentioned, a finite element model using ABAQUS software was carried out to obtain the reduction in beam capacity due to elevated temperature. This research comprised of three reinforced concrete beam models, these models simulated a control beam specimen at ambient temperature 20 °C, and two damaged beam specimens subjected to 400 °C and 800 °C, respectively. The beam model, loading condition, and mesh are illustrated in Figures 5 and 6.

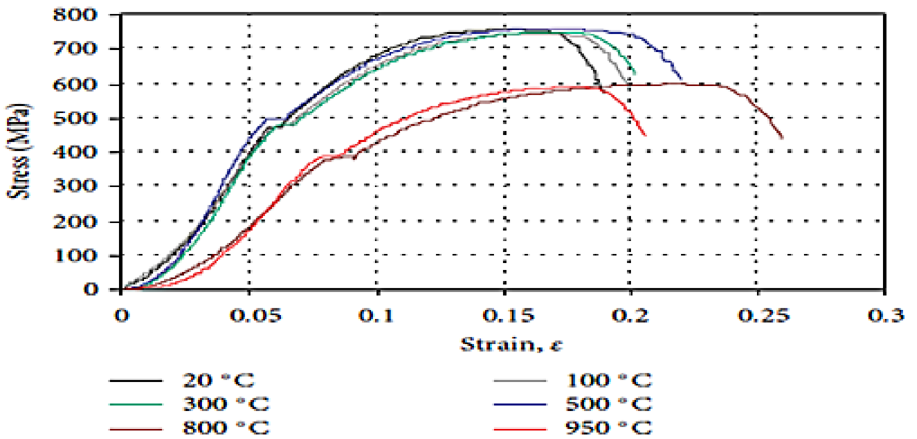

Fig. 4. Stress-strain curve of grade 60 (420 MPa) steel rebar [Topçu and Karakurt, 2008]

a) b)

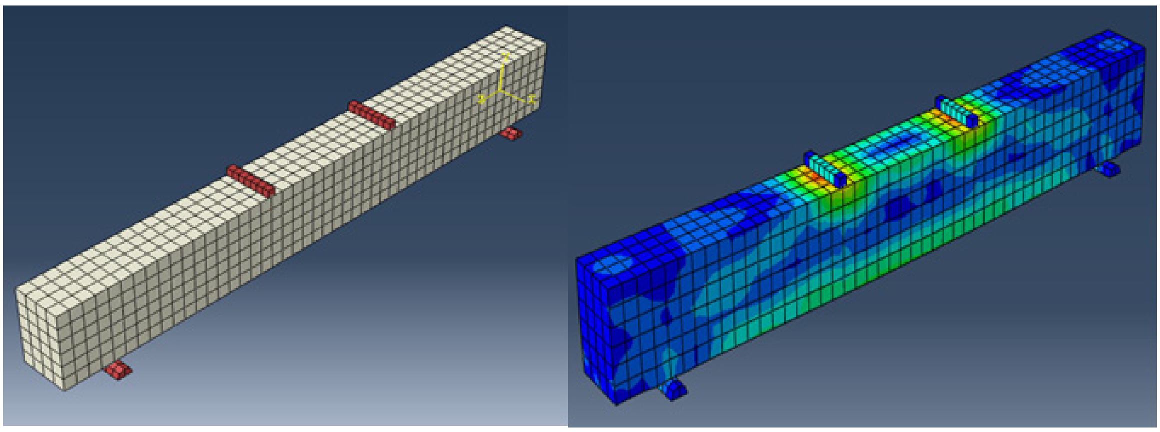

Fig. 5. Beam model with assigned mesh (a) before loading, (b) after loading

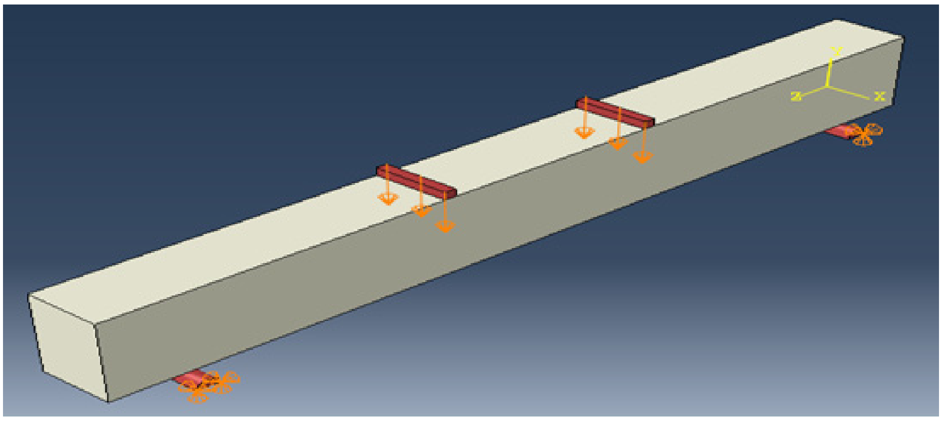

Fig. 6. Boundary and loading conditions used in the beam model (simply supported beam loaded at one-third and two-third of span length)

RESULTS AND DISCUSSION

After running the model, several parameters were evaluated under different temperature to assess the effect of elevated temperature on RC beams. These parameters included the concrete compressive strength, concrete modulus of elasticity, and steel reinforcement yielding strength. Using these parameters, the flexural behavior of reinforced concrete beams prior and post to elevated temperature exposure was obtained. The reasulted data for both control and heated specimens was used to compare between these two conditions as shown in Table 2.

After comparing unheated and heated parameters, the nominal load, nominal moment capacities, and deflection have been obtained from the model as shown in Table 3. The table also provide the decrease in capacity and increase in deflection for the heat-damaged specimens.

The relationship between the increasing service load and deflection was monitored along the model running process. Figure 7 shows the great reduction in stiffness while increasing the temperature. It was estimated that the stiffness decreased by 15.4% and 86.1% at 400 °C and 800 °C, respectively, with respect to the control beam. Figures 8 and 9 show the intensive reduction in moment and load capacity, respectively.

CONCLUSIONS

A finite element model was used to assess the fire behavior of RC beams subjected to increasing service loading. After analyzing the results, the following conclusions were found:

1. The model succeed in describing the behaviour of RC beams under elevated tempera-

Table 2. Comparison between concrete compressive strength, modulus of elasticity, and steel reinforcement yielding strength prior and post to elevated temperature exposure

Specimen	Temperature (°C)	Compressive strength f_c' (MPa)	Modulus of elasticity E_c (MPa)	Steel reinforcement yielding strength f_y (MPa)	Decrease in f_c' (%)	Decrease in E_c (%]	Decrease in f_y (%]
Control	20	28	28537	420	-	-	-
B - 400	400	15.6	22953	402	44.3	19.6	4.3
B - 800	800	0.3	5289	198	98.9	81.5	52.9

Table 3. Comparison between nominal capacity (P_n and M_n) and deflection of unheated and heated specimens

Specimen	Temperature (°C)	Nominal load, P_n (kN)	Decrease in P_n (%)	Nominal moment, M_n (kN·m)	Theoretical strength (MPa)	Decrease in M_n (%)	Deflection at mid-span (mm)	Increase in deflection, (%)
Control	20	85	-	59.92	59.505	-	8.7	-
B - 400	400	70.5	17.1	49.35	-	17.6	9	3.4
B - 800	800	10.1	88.1	7.07	-	88.2	10.2	17.2

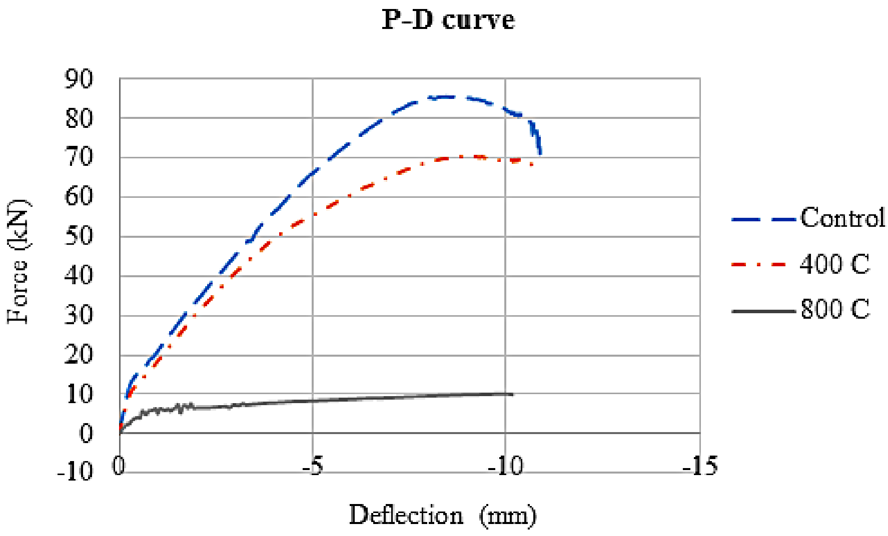

Fig. 7. Load versus deflection at mid-span for different temperature values

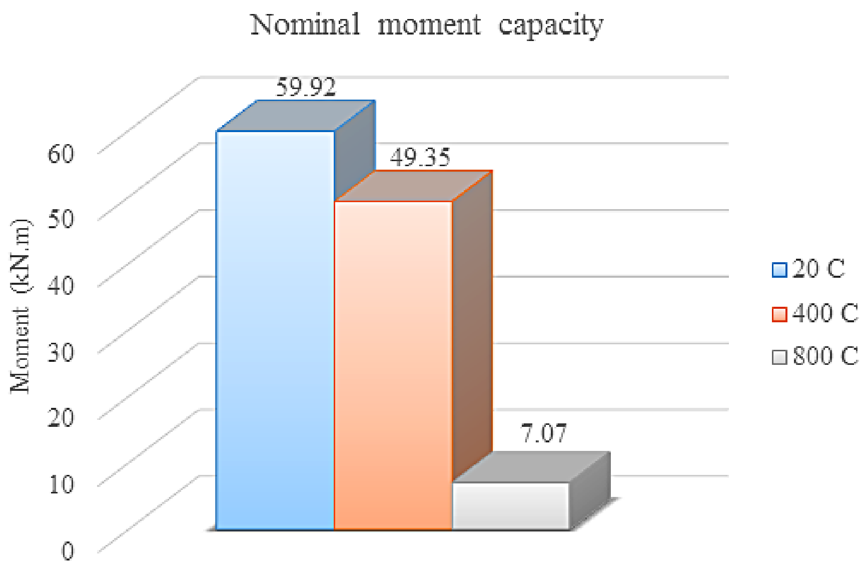

Fig. 8. Moment capacity of the beam for different temperature values

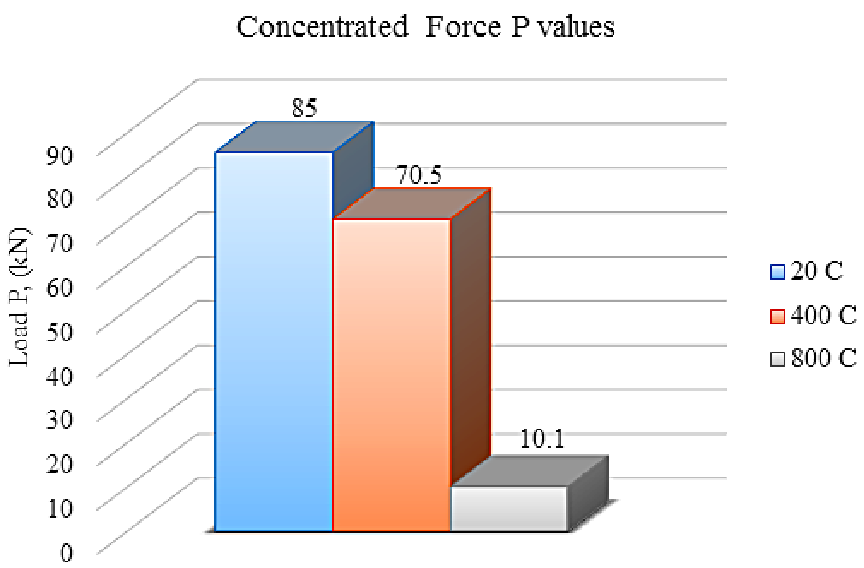

Fig. 9. Load carried by the beam for different temperature values

ture. It was validated by comparing its results with the theoretical results from ACI code and literature.

2. Steel reinforcement was not affected at 400 °C temperature (4.3% reduction in f_y). While it greatly deteriorated at 800 °C (52.9% reduction in f_y).
3. The concrete lost about 44.3% of its compressive strength and 19.6% of its modulus of elasticity at 400 °C. While the reduction severely increased up to 98.9% in the compressive strength and 81.5% in the modulus of elasticity at 800 °C.
4. The reduction in beam's flexural capacity was 17.6% and 88.2% for the 400 °C and 800 °C high temperature, respectively.
5. The maximum service load carried by the beam, at one-third and two-third of the span length, was 85 kN. This load decreased by 17.1% and 88.1% for the 400 °C and 800 °C high temperature, respectively.
6. The maximum deflection (at mid-span) increased by 3.4% and 17.2% for the 400 °C and 800 °C high temperature, respectively. This was referred to the loss in stiffness as temperature increased.
7. Due to the intensive deterioration in steel's yielding strength, concrete's compressive strength, and modulus of elasticity. The flexural and load capacities decreased, at 800 °C, by 90% of their unheated values. Under such reduction, the RC beam is entirely destroyed.

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