BEHAVIOR OF REINFORCED CONCRETE BEAMS EXPOSED TO FIRE

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Abstract

There is a shortage in researches that discuss the effect of fire on building and represent solution for structural elements that exposed to fire [1-19]. Improving the fire resistance for beams, requires studying the response of reinforcing steel and concrete under fire attack. Concrete has a good behavior under fire due to its low thermal conductivity and non-combustibility. Concrete can act as protective cover to steel reinforcement. To understand the thermo-mechanical response of reinforced concrete beams under fire, experimental researches have been carried out to investigate the performance, resistance, and residual strength of beams under elevated temperature [14,15]. There is a lack of numerical studies addresses these types of analysis. This paper numerically investigates the fire performance of reinforced concrete beams subjected to fire exposure. A series of models of RC beams has been studied. Firstly, RC beams were studied under fire exposure on three surfaces following the temperature time history by ISO 834 standard fire curve. Secondly, studying heat transfer in RC beams and its effects on concrete and reinforcement steel with changing concrete cover and many factors through a parametric study. A finite element model using ANSYS program was carried out and accomplish a good correlation with the experimental results in both thermal and structural performance. The element type used for concrete in thermal analysis is Solid 70 while Link 33 is the element type used to represent reinforcing steel. The validated finite element model was used to conduct a parametric study on the behavior of RC shallow beams under fire. Materials nonlinearity was taken into consideration because there effects of the heat transfer in concrete, thermal expansion, and yielding of reinforcing steel. In addition, investigate the residual capacity of RC beams. The parametric study investigates the effects of: (1) concrete compressive strength (f_{cu}); (2) concrete cover (d`); (3) steel reinforcement yield strength (f_y); (4) ratio of main reinforcement (μ %); (5) specific heat of the outer layers (C); (6) thermal conductivity of the outer layers (K); (7) voids area percentage in beam cross-section; (8) shear –span to depth ratio (a/d); and (9) compression reinforcement steel ratio (μ` %).

Key words: Reinforced concrete beams; Fire; Temperature, Thermal behavior, Structural behavior; Residual capacity.

1. Introduction

Fire is one of the greatest threats to buildings. Concrete buildings have good behavior under heat/fire attack due to low conductivity. Steel reinforcement has low resistance than concrete, but concrete cover protects the bars under heat/fire. Generally, the reinforced concrete beams have many advantages over the steel beams, such as: (1) high resistance to high temperature, (2) high resistance to thermal shock, (3) better resistance to fatigue and buckling, and (4) strong resistance against fire, etc. The main problem in the reinforced concrete beams is its poor resistance to tensile stresses. For this reason, an investigation for the thermal effect on the tensile stresses is presented. Numerical model of thermal analysis is presented for the evaluation of thermo-mechanical response of reinforced concrete beams exposed to high temperature, taking into consideration various values of temperature and thermo-physical properties of concrete such as: (1) thermal conductivity (K) and (2) specific heat to consider the difference in temperature along the fire period according to Eurocode 2 [11].

The present study aims to investigate numerically the behavior of RC beams exposed to heat/fire. Therefore, this research provides conclusions about the effect of changing the values of the studied factors on the behavior of R.C beams under the influence of heat/fire and suggests methods to overcome the effects that occur due to heat/fire. To achieve this aim, a nonlinear finite element modeling is conducted. The model represents the beam geometry and accounts for the variation in thermal and mechanical parameters of beams.

The nonlinear analysis is performed using ANSYS 15.0. The numerical predictions are compared with the available results of the experimental and theoretical researches; published in the literature in order to ensure the model suitability for the representation of R.C beams under fire exposure.

2.1 Material Properties

Concrete is a non-homogeneous material. It has a low conductivity (K) and a low heat transfer rate. It endures multiple levels of damage depending on severity of elevated temperature under fire effect and the reached peak temperature.

2..1 Concrete Mechanical and Thermal Properties

For concrete under elevated temperature, the following constitutive relations are followed:

- In compression, the stress strain curve as developed in Eurocode 2 [11] is shown in Figure 1. It depends on peak compressive strength $f_{c,t}$, strain value corresponding to $f_{c,t}$ and the ultimate strain $\varepsilon_{cu1,\theta}$;
- Compressive strength decreases gradually with increasing fire temperature (Cheng et al, (1999) [8]);
- Tensile strength is proposed by an equation depending on the temperature range between 20 C to 800 C in order to consulate the tensile strength for concrete by Chang, Chen, Sheu, and Yao, (2006) [9].
- The thermal properties of concrete depend on (1) Thermal elongation; (2) Density; (3) Specific heat; and (4) Thermal conductivity which are mentioned in details by Mohamed, A. A. (2020) [1].

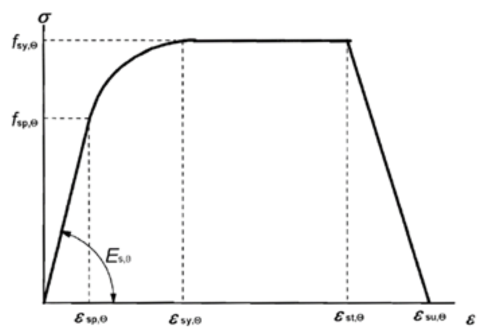


Figure 1: Mathematical model for stress strain curve for uniaxial compression at elevated temperature [11]

2.2 Reinforcing Steel Mechanical and Thermal Properties

Mechanical properties for the reinforcing steel such as: (1) Stress strain curves (Figure 2), (2) Thermal elongation; (3) Density; (4) Specific heat; and (4) Thermal conductivity which are mentioned in details by. Mohamed A. A. (2020) [1].

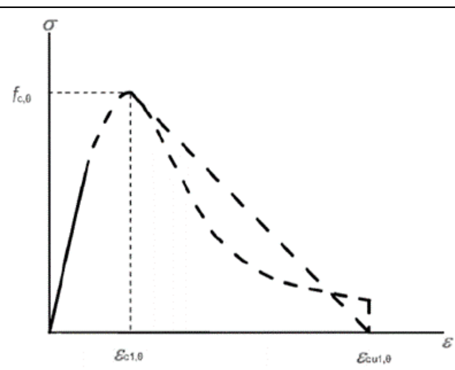


Figure 2: Mathematical model for both reinforcing steel and pre-stressing steel at elevated temperatures [11]

3. Standard Fire Curves

3.1 ASTM E119 Standard Fire Curve

ASTM E119 purposed equation to calculate the temperature-time curves (Lie, 1992 [16])

$$T = T_0 + 750[1 - e^{-3.79553\sqrt{t_h}}] + 170.41\sqrt{t_h} \qquad [1]$$

Where: T_o = initial temperature for the room; and t_h = time in hours.

3.2 ISO 834 Standard Fire Curve

$$T_g = T_o + 345\, Log\,(1 + 8t) \qquad [2]$$

t = time in hours and T_o = room temperature.

3.3 Approaches for Evaluating Post-Fire Residual Capacity

Stage (1): To evaluate the beam capacity at room temperature (no fire) using stress strain curve for concrete and steel. The compressive stress– strain curve for concrete is assumed to be linear elastic until reaches 0.33 f_{cu}, where f_{cu} is the uniaxial compressive strength then it contained bilinear relationship which is elastic until peaked stress for responding to cracking and crushing in concrete.

Stage (2): To evaluate the temperature at nodes for concrete and reinforcement steel at fire phase under certain period fire exposure and mechanical properties follows Eurocode 2 [11]. This nodal temperature considering the initial conditions is used to carry out the structural analysis.

Stage (3): post fire residual capacity after theoretical cooling (Figure 3).

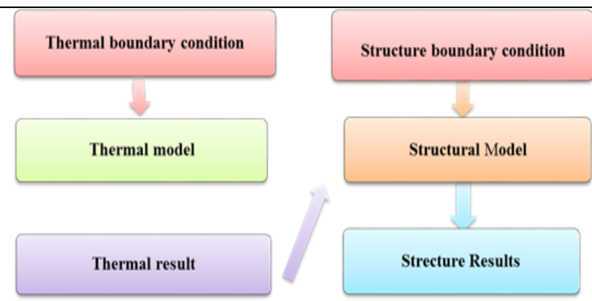
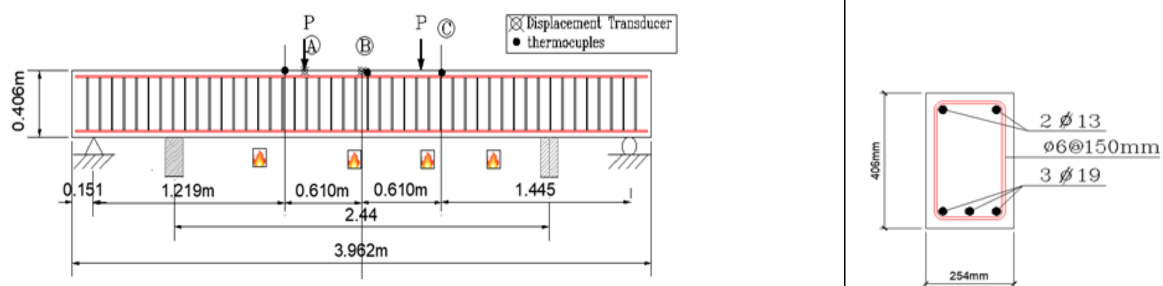


Figure 3: Sequential coupling technique

4. Calibration Model

4.1 Description of Beams

An experimental program presented by Kodur and Agrawal [15] has two full-scale beams named B1 and B2 which were used to calibrate the analysis numerical model. The beams dimensions were 3960 mm long, 254 mm wide and 406 mm total depth as shown in Figure 4.



(a) Longitudinal view (b) Cross- section

Figure 4: Details of beams B1 and B2

There are two scenarios when beams subjected to fire curve:

4.1.1 The Beam Failed Due to Fire Load

The concrete beam is exposed to the operating loads (dead loads + 55% of the live loads) to replicate the fire period. Then the fire was turn on with a given temperature-time graph in minutes and the beam fails during burning, then the thermal response in reinforcement steel and concrete is evaluated.

4.1.2 The Specimen Doesn't Fail Due to Fire Load

The concrete beam is exposed to the operating loads (dead loads + 55% of the live load) to replicate the fire period, then the beam cooled using the designated accessible method whether by reducing the temperature using the temperature-time curve or by allowing the beam to cool (room temperature), then calculate the residual capacity.

Beams B1 and B2 were tested under two fire scenarios, where beam B1 subjected to ASTM E119 while beam B2 was tested under effect of short fire curve (SF) as shown in Figure 5 and Table 1.

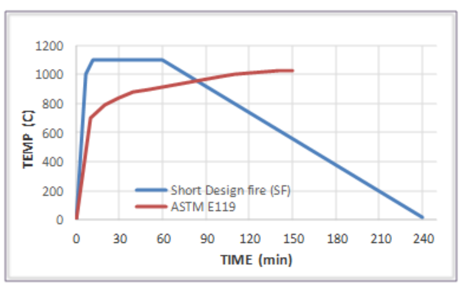


Figure 5: ASTM E119 and short fire curve (SF)

Table 1: Specimen's discerption

Beam	Fire Exposure Curve	Concrete	Initial Load (P)	Time–Temperature
B1	ASTM E19	Normal strength concrete	50 kN	180 min.
B2	Short fire	Normal strength concrete	50 kN	240 min.

4.2 Verification Model for Beam B1

After solving the model of beam B1 using ANSYS program, the predicted thermal results were compared with Kodur and Agrawal experimental results [15] for nodal temperature with respect to time where 3 nodes were used to compare the results. The first node at the reinforcement steel, the second node at quarter depth of the cross section and third node at mid depth of the cross section, are as shown in Figure 6.

4.2.1 Thermal Results

Beam B1 collapsed under fire load according to Kodur's experimental results [15]. Kodur evaluated the fire resistance rate of 180 min. of ASTM E119. Numerical results by ANSYS model of B1 indicate that it dropped below the same fire load from ASTME 119 at 183 min. closing to the Kodur value [15] which is 102 % as shown in Figure 7.

4.2.2 Structural Results

The comparison between Kodur [15] and ANSYS model for mid span deflection show good agreement where $\Delta_{\text{ANSYS}}/\Delta_{\text{Kodur}}$ % = 102 % as shown in Figure 8.

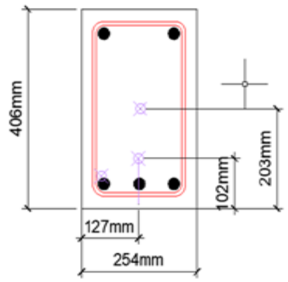


Figure 6: Location of measurements points for temperature for beams B1 and B2

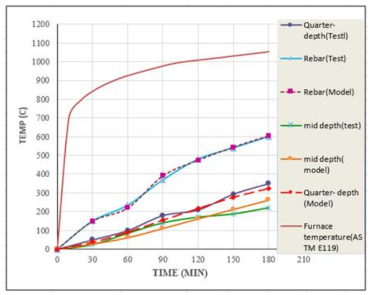


Figure7: Comparison between predicted and measured temperatures for beam B1 during fire exposure due to ASTM E119 curve

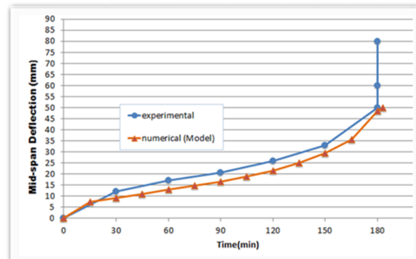


Figure 8: Comparison of mid-span deflection between Kodur and Agrawal results [15] and ANSYS model for Beam B1

4.3 Verification Model for Beam B2

Beam B2 has the same dimensions of beam B1 and it was tested under short fire curve (SF) as a convection load by Kodur [15]. Details of how to apply thermal and structural load are illustrated in details by Mohamed, A. A. (2020) [1].

4.3.1 Thermal Results

The comparison between Kodur measured temperature [15] and the predicted temperature from ANSYS is shown at Figure 9.

4.3.2 Structural Results

The failure load using ANSYS model is 125 kN which is nearly close to Kodur failure load (120 kN) [15] (104 %) which verify ANSYS methodology. The comparison between ANSYS model and Kodur results [15] is expressed in relationship between mid-span deflection and fire exposure period is shown in Figure 10. Figure 11 shows concrete cracks at 55 % of the ultimate load and at failure.

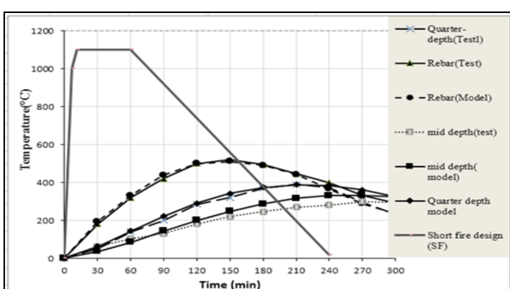


Figure 9: Comparison of predicted and measured cross sectional temperatures during fire exposure due to (SF) curve for beam B2

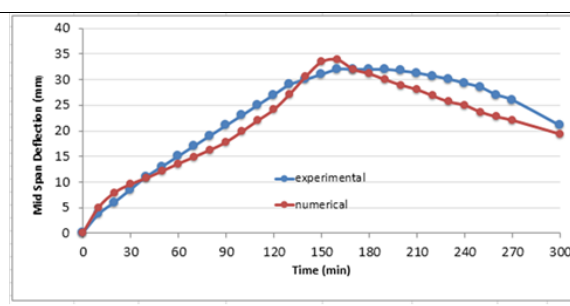
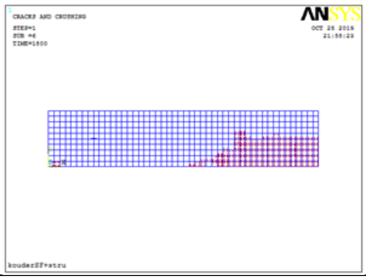
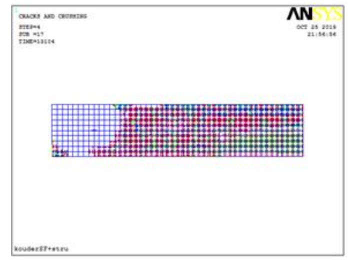


Figure 10.: Comparison between ANSYS model and Kodur and Agrawal results [15] for the mid-span deflection for beam B2



(a) Concrete cracks at 55% P_{ult}



(b) Concrete cracks at failure

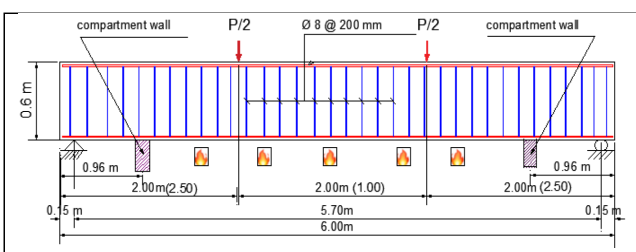
Figure 11: Concrete cracks

5. Parametric Study

Based on the validation studies, a parametric study was performed using the same thermal and mechanical analysis techniques to study the primary variables using ANSY program V. 15. In order to evaluate the effect of the studied parameters on thermal and structural response of reinforced concrete beams, the following parameters are considered:

1. Concrete compressive strength (f_{cu});
2. Concrete cover (d`);
3. Reinforcing steel yielding strength (f_y);
4. Main reinforcement steel ratio (μ);
5. Specific heat of the outer layers (C);
6. Thermal conductivity of the outer layers (K);
7. Voids area % in beam cross section;
8. Shear-span-to-depth ratio (a/d); and
9. Compression steel reinforcement ratio (μ`).

Table 2 shows the design of parametric study program with the parameters under consideration. The beam dimensions, cross-section, location of compartment wall, bearing and loading plates positions are illustrated in Figure 12. The studied beams are investigated under the same fire scenario and convection load mentioned before (short fire curve (SF)). If the beam did not fail after the heating phase, the beam theoretically cooled down to the room temperature (after using SF curve for 4 hrs. fire exposure), then the beam was loaded gradually increased until failure, then the beam's residual capacity calculated.



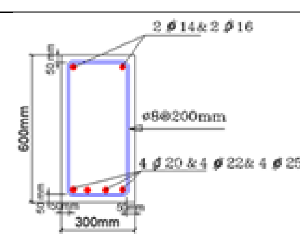


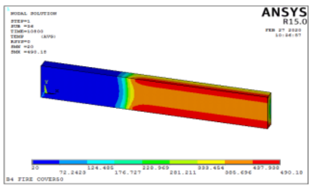
Figure 12: Beam dimensions and cross- section

Table 2 Parametric study program

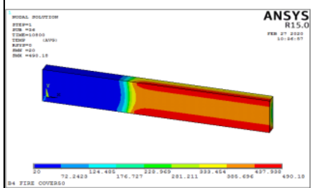
Beam No.	f_{cu} (MPa)	Fire Curve	Initial Load P (kN)	Concrete Cover d` (mm)	f_y (MPa)	(μ / μ_{max})	Specific Heat for the Outer Layers (C) Relative to Concrete	Thermal Conductivity for the Outer Layers (K) Relative to Concrete	Voids Area %	Shear –Span to Depth Ratio (a/d)	Compression Steel Reinforcement ratio $\alpha = (A_s`/ A_s)$ %	Studied Parameters	Notes
B_0	60	-	72	50	360	0.3	1	1	0	3.36	12.25 %	Static Load	Control Static Beam
B_1	50	SF	72	50	360	0.3	1	1	0	3.36	12.25 %	Effect of Concrete Compressive Strength (f_{cu})	
B_2	60	SF	72	50	360	0.3	1	1	0	3.36	12.25 %		Control Thermal Beam
B_3	70	SF	78	50	360	0.3	1	1	0	3.36	12.25 %		
B_4	60	SF	78	40	360	0.3	1	1	0	3.36	12.25 %	Effect of Concrete Cover d`	
B_5	60	SF	78	50	360	0.3	1	1	0	3.36	12.25 %		
B_6	60	SF	80	60	360	0.3	1	1	0	3.36	12.25 %		
B_7	60	SF	80	50	420	0.3	1	1	0	3.36	12.25 %	Effect of Reinforcing Steel Yielding Strength (f_y)	
B_8	60	SF	80	50	360	0.3	1	1	0	3.36	12.25 %		
B_9	60	SF	115	50	360	0.3	1	1	0	3.36	12.25 %	Effect of Main Reinforcing Steel Ratio (μ)	
B_{10}	60	SF	115	50	360	0.4	1	1	0	3.36	21.05 %		
B_{11}	60	SF	115	50	360	0.5	1	1	0	3.36	16.32 %		
B_{12}	60	SF	80	50	360	0.3	0.7	1	0	3.36	12.25 %	Effect of the Specific Heat of the Outer Layers (C)	
B_{13}	60	SF	80	50	360	0.3	1	1	0	3.36	12.25 %		
B_{14}	60	SF	80	50	360	0.3	2	1	0	3.36	12.25 %		
B_{15}	60	SF	80	50	360	0.3	1	1	0	3.36	12.25 %	Effect of the Thermal Conductivity of the Outer Layers (K)	
B_{16}	60	SF	80	50	360	0.3	1	3	0	3.36	12.25 %		
B_{17}	60	SF	80	50	360	0.3	1	5	0	3.36	12.25 %		
B_{18}	60	SF	80	50	360	0.3	1	1	22.22 %	3.36	12.25 %	Effect of Voids Area % in the Beam Cross Section	
B_{19}	60	SF	80	50	360	0.3	1	1	0	4.27	12.25 %	Effect of Shear – Span to Depth Ratio (a/d)	
B_{20}	60	SF	80	50	360	0.3	1	1	0	3.36	30.00 %	Effect of Compression Steel Reinforcement Ratio $\alpha = A_s /A_s$	

5.1 Effect of Concrete Compressive Strength (f_{cu})

The effect of concrete compressive strength is studied by varying the characteristic compressive strength of concrete to 50 ,60 and 70 MPa for the three beams B1, B2 and B3 respectively. The thermal contours after 1 hr. ,2 hrs. ,3 hrs. and 4 hrs. for beam B1 are illustrated in Figure 13. Figure 14 shows temperature distribution at various elevated temperatures at different positions for beams B1, B2 and B3.



After (1hr.)



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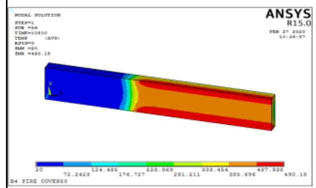
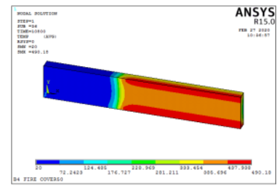
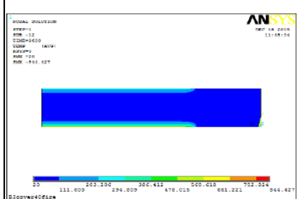


After (3 hrs.)



After (4 hrs.)

(a) Longitudinal



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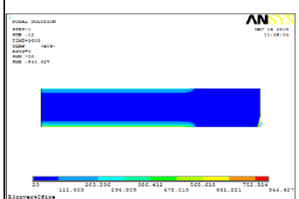

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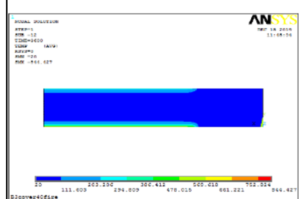
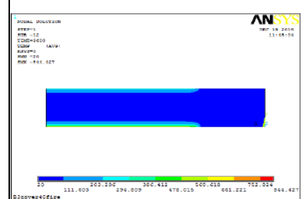
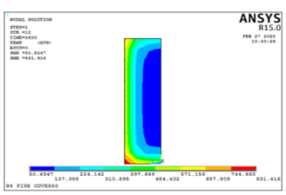


After (3 hrs.)

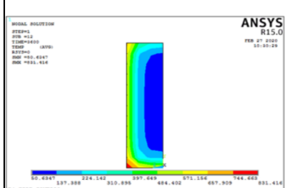


After (4 hrs.)

(b) Back side



After (1hr.)



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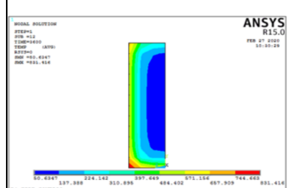

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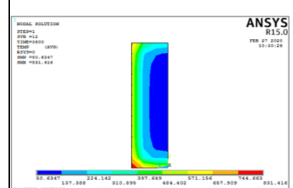

After (4 hrs.)

(c) Cross-section

Figure 13 : Thermal contours for beam B1 after 1hr., 2 hrs., 3 hrs. and 4 hrs

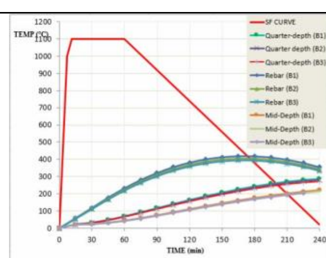

Figure 14 : Temperature distribution at various elevated temperatures at different positions for beams B1, B2 and B3

Figure 15 shows the relationship between fire duration and mid-span deflection for the three beams and Figure 16 shows the relationship between concrete compressive strength and the residual capacity for the beams after theoretical cooling. Table 3 shows the parametric study results.

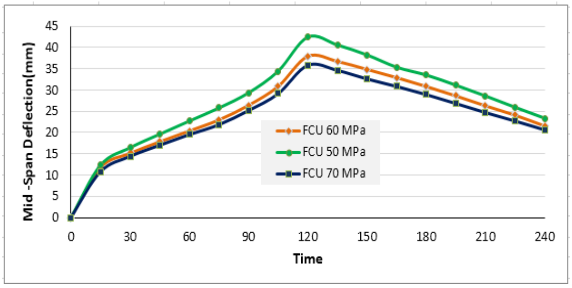

Figure 15: The relationship between fire duration and mid-span deflection for the three beams (B1 , B2 and B3)

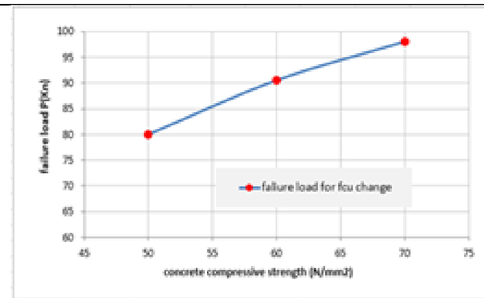

Figure 16: The relationship between concrete compressive strength and the residual capacity

Table 3 Parametric Study Results

Beam No.	Δ_T (mm) Thermal	Δ_S (mm) Static	(Δ_T / Δ_S)%	P_T Thermal (kN)	P_S Static (kN)	(P_T/ P_S)%	Notes
B_0	25.50	25.50	100.0 %	130	130	100.00 %	Control Static Beam
B_1	42.40	70.38	166 %	80	120	66.70 %	Effect of Concrete Compressive Strength (f_{cu})
B_2	38.00	57.00	150 %	90	130	69.70 %	
B_3	35.80	53.34	149 %	97.5	137	71.17 %	
B_4	43.63	74.61	171 %	93.2	138	67.54 %	Effect of Concrete Cover (d`)
B_5	34.86	47.41	136 %	106	141	75.18 %	
B_6	29.00	32.77	113 %	127	156	81.41 %	
B_7	33.18	43.13	130 %	120	162	74.07 %	Effect of Reinforcing Steel Yielding Strength (f_y)
B_8	38.00	56.62	149 %	91	137	66.42 %	
B_9	40.10	62.96	157 %	133	196	67.86 %	Effect of Main Reinforcing Steel Ratio (μ)
B_{10}	34.25	45.90	134 %	165	240	68.75 %	
B_{11}	29.05	32.83	113 %	240	340	70.59 %	
B_{12}	39.62	61.41	155 %	113.7	162	70.19 %	Effect of the Specific Heat of the Outer Layers (C)
B_{13}	33.42	43.78	131 %	119	162	73.46 %	
B_{14}	24.06	22.86	95 %	139	162	85.80 %	
B_{15}	33.42	43.78	131 %	119	162	73.46 %	Effect of the Thermal Conductivity of the Outer Layers (K)
B_{16}	36.11	50.92	141 %	129	162	79.60 %	
B_{17}	38.80	58.98	152 %	137.6	162	84.94 %	
B_{18}	37.00	53.65	145 %	126	162	77.78 %	Effect of Voids Area %
B_{19}	32.89	42.10	128 %	118	162	72.84 %	Effect of Shear – Span to Depth Ratio (a/d)
B_{20}	42.23	69.68	165 %	107	162	66.05 %	Effect of $\alpha = A_S'/A_s$ Ratio

5.2 Effect of Concrete Cover (d`)

To study the effect of change concrete cover, three beams B4, B5 and B6 with concrete cover 40 mm,50 mm and 60 mm respectively were investigated as given in Table 3.

5.3 Effect of Reinforcing Steel Yielding Strength (f_y)

To study the effect of steel reinforcement grade, different types of steel reinforcement with yield strength as 360 and 420 MPa are used in this work for bottom rebars and f_y = 240 MPa for top rebar. All thermal properties are the same for the studied two beams (B7 and B8) as given in Table 3.

5.4 Effect of Main Reinforcement Steel Ratio (μ)

Three ratios for main reinforcement steel were used as 0.3 μ_{max}, 0.4 μ_{max} and 0.5 μ_{max} for beams B9, B10 and B11 respectively where μ_{max} according to Egyptian code [12] as given in Table 3.

5.5 Effect of Specific Heat of the Outer Layers (C)

As given in Table 3, all thermal properties are the same for the studied three beams (B12, B13 and B14) and also the applying fire load (short – fire – curve SF). The only difference is the specific heat for outer layers (concrete cover thickness 50 mm) as coat for resisting fire with C equal 70 % ,100 % and 200 % as that for concrete and compared them with the original specimen (uncoated).

5.6 Effect of Thermal Conductivity of the Outer Layers (K)

As given in Table 3, all thermal properties are the same for the studied three beams (B15, B16 and B17) and also the applying fire load (short-fire-curve SF). The only difference is thermal conductivity of the outer layers (concrete cover thickness 50 mm) as coat for resisting fire with K equal 100 % ,300 % and 500 % as that for concrete and compared them with the original specimen (uncoated).

5.7 Effect of Voids Area Percentage in Beam Cross- Section

As given in Table 3, a central void with dimensions 100 mm width and 400 mm depth was created in beam cross section (B18) to study its effect on both thermal and structural behavior.

5.8 Effect of Shear –Span-to-Depth Ratio (a/d)

As given in Table 3, the only difference is the shear span- to depth ratio (a/d) which equal to 3.36 and 4.27 for beams B2, and B19 respectively.

5.9 Effect of Compression Steel Reinforcement Ratio (μ`)

As given in Table 3, the only difference is the compression steel reinforcement ratio (μ`) relative to the main reinforcement steel ratio (μ) which equal to (μ`/μ %) = 12.5 % and 30 %.

6. Conclusions

From the results of the validation and parametric studies, the following conclusions are drawn:

1. The validation and verification of thermal and structural models using ANSYS program V. 15 indicated that, the analysis can be developed under any fire scenarios to presents complete and true behavior of reinforced concrete beams reinforced with steel bars under fire exposure.

2. The verification models using ANSYS program V. 15 show that, the response of RC beams under fire exposure depending significantly on fire duration and maximum fire temperature which affected on the stiffness reduction factor. ANSYS structural-thermal program V. 15 gives temperature profiles fully agreed with the experimental ones.

3. From the parametric study of some parameters affecting the behavior of the reinforced concrete beams reinforced with steel bars and exposed to fire exposure has been studied and the following conclusions has been dawn:

(a) Increasing concrete compressive strength (f_{cu}), improves the beam resistance to fire exposure due to increasing the elasticity modulus of concrete and consequently, increasing the beam stiffness. This increase was about 8 % due to increasing the concrete compressive strength by about 40 %. Therefore, the concrete compressive strength has insignificant effect on the beam residual capacity.

(b) Increasing concrete cover by 20 % and 50 %, decreases the temperature of the reinforcing steel bars by about 12 %, and 24 % respectively when exposed to the same conditions of fire exposure. `Therefore, the reinforcing steel reaches to the yielding strength slowly with increasing the concrete cover which increase the beam residual capacity.

(c) Increasing the concrete cover, decreases the heat spread into concrete cross section due to fire exposure and increases the concrete compressive zone which improves the beam residual capacity.

(d) The great difference in reinforcement rebars temperature due to its arrangement in the cross section leads to decreasing steel hardening under fire exposure and which affect the beam residual capacity.

(e) Increasing the reinforcement steel yielding strength for beams under fire exposure, decreases the deflection by about 15 %, and increases the residual flexural capacity by about 25 %.

(f) Increasing the tension steel reinforcement percentage (μ %), improves the rigidity due to increasing the bond between concrete and steel bars due to low stresses in the steel bars, and due to reducing the bond degradation after fire exposure which affect the beam residual capacity.

(g) Increasing the specific heat of the outer layer of the beam by using fire resisting coating material or paste a material with higher specific heat than concrete (thermal insulator) improves the beam ability to resist fire exposure (linear proportion) and keeps the steel and concrete properties for a long period of fire duration in order to be able to retain most of the original capacity after fire exposure.

(h) To increase the beam capability to resist fire, the physical properties of the outer layers are enhanced using insulator coating or paste external layers. The increase of thermal conductivity and specific heat is more effective for beams; required to retain most of their original flexural capacity after fire exposure. Increasing thermal conductivity of the outer layers of the beam helps to have the ability to absorb temperature and then distracted it in high rate than concrete.

(i) Hollow sections have more resistance to fire than solid sections and recover about 82 % of the original capacity after exposed to fire.

(j) The shear-span to depth ratio (a/d) has significant effect on the behavior of reinforced concrete beams under fire exposure, where the residual capacity is increased by about 32% due to the increase of the shear-span to depth ratio (a/d) by about 25%.

(k) The increase of the compression reinforcing steel ratio ($\alpha = \mu` / \mu$), increase the beam residual capacity by about 20 % due to increase α to 50 %.

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