Computers and Concrete, *Vol. 19, No. 6 (2017) 711-716*
DOI: https://doi.org/10.12989/cac.2017.19.6.711

Predicting residual moment capacity of thermally insulated RC beams exposed to fire using artificial neural networks

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(Received March 12, 2016, Revised March 1, 2017, Accepted March 4, 2017)

Abstract. This paper presents a method using artificial neural networks (ANNs) to predict the residual moment capacity of thermally insulated reinforced concrete (RC) beams exposed to fire. The use of heat resistant insulation material protects concrete beams against the harmful effects of fire. If it is desired to calculate the residual moment capacity of the beams in this state, the determination of the moment capacity of thermally insulated beams exposed to fire involves several consecutive calculations, which is significantly easier when ANNs are used. Beam width, beam effective depth, fire duration, concrete compressive and steel tensile strength, steel area, thermal conductivity of insulation material can influence behavior of RC beams exposed to high temperatures. In this study, a finite difference method was used to calculate the temperature distribution in a cross section of the beam, and temperature distribution, reduction mechanical properties of concrete and reinforcing steel and moment capacity were calculated using existing relations in literature. Data was generated for 336 beams with different beam width (b_w), beam account height (h), fire duration (t), mechanical properties of concrete (f_{cd}) and reinforcing steel (f_{yd}), steel area (A_s), insulation material thermal conductivity (kinsulation). Five input parameters (b_w, h, f_{cd}, f_{yd}, A_s and $k_{insulation}$) were used in the ANN to estimate the moment capacity (M_r). The trained model allowed the investigation of the effects on the moment capacity of the insulation material and the results indicated that the use of insulation materials with the smallest value of the thermal conductivities used in calculations is effective in protecting the RC beam against fire.

Keywords: fire; thermally insulation material; thermal conductivity; residual moment capacity; reinforced concrete; beam; artificial neural networks

1. Introduction

The beams, columns and floors within various structures must be protected against the effect of fire since the high temperature causes a reduction in the beam material strengths, shear and moment capacities. For example, in a multi-story building in a floor exposed to fire, the temperature can reach 1000℃ at ceiling level resulting in substantial damage to structural elements from the heat that is released. Thermal insulation can prevent harmful effects. To ensure that the insulation material is effective it is important that it has a low thermal conductivity maximum tolerance to temperature, as well as being easily applicable and cost-efficient.

To calculate the reduced moment capacity of the reinforced concrete (RC) beam due to the high temperature, certain calculations such as fire exposure time, temperature distribution in the cross-section, reduction coefficients of the concrete and steel strengths, compressive and tensile forces in section and calculation of the moment capacity must be made sequentially. To obtain these values, the use of artificial neural networks (ANNs) can be considered appropriate.

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For this method, the model needs to be trained and the data can be obtained for given experimental or theoretical value range. Then, the residual moment capacity of RC beam with insulation material exposed to fire can be estimated for the beam width, beam account height, fire duration, concrete compressive and steel tensile strength, steel area, insulation material thermal conductivity coefficient using the trained model.

The literature contains various studies on the behavior of RC structures in fire. Ozbolt *et al*. (2014) presented the numerical study of the behavior of RC beams subjected to standard ISO 834 fire load followed by mechanical loading (Ozbolt *et al.* 2014). Erdem investigated moment capacity of box and *T* RC beams exposed to fire (Erdem 2009 and 2010). Kodur and Dwaikat presented an approach for evaluating the fire resistance of RC beams (Kodur and Dwaikat 2011). Kodur and Agrawal examined an approach for assessing the residual capacity of fire exposed RC beams (Kodur and Agrawal 2016). Hsu and Lin combined thermal and structural analyses to assessing the residual bearing capabilities, flexural and shear capacities of RC beams after fire exposure (Hsu and Lin 2006). Choi *et al.* investigated the effect of temperature distribution, concrete strength, cover thickness, and heating time on the structural behavior of RC beams (Choi *et al*. 2013). Erdem predicted the moment capacity of RC beams exposed to fire using ANNs (Erdem 2015). Bilgehan and Kurtoglu investigated a

 ISSN: 1598-8198 (Print), 1598-818X (Online)

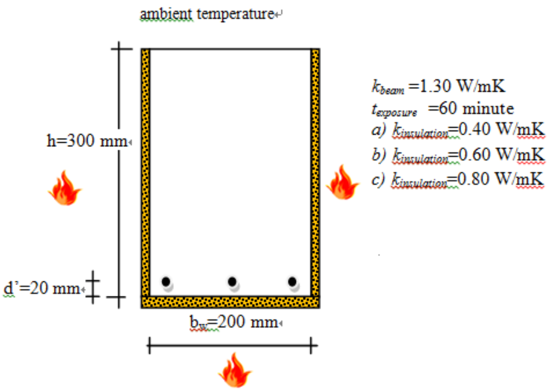
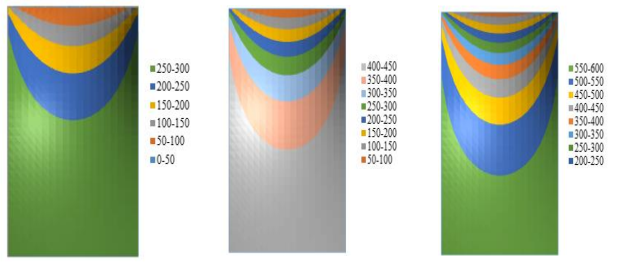


Fig. 1 Thermal conductivity coefficient and temperature distribution of beam segments



(a) $k_{insulation}$=0.40 W/mK (b) $k_{insulation}$=0.60 W/mK (c) $k_{insulation}$=0.80 W/mK

Fig. 2 The temperature distributions obtained for three different conductivities

prediction model in order to determine the bearing moment capacities of reinforced concrete slabs under high temperature (Bilgehan and Kurtoglu 2015). Kadhum investigated fire resistance of reinforced concrete rigid beams (Kadhum 2014). Eamon and Jensen examined reliability analysis of RC beams exposed to fire (Eamon and Jensen 2013).

Concrete is a non-combustible material with low thermal conductivity. But, in case of high temperature due to fire, there is a loss in the strengths of concrete and steels. Insulation of reinforced concrete elements against fire will be beneficial especially in structures with risk of fire such as combustible material stored structures. However, there are a limited number of publications about thermal protection using insulation material and the prediction of the moment capacity of RC elements exposed to fire. Erdem examined the effects of insulation materials on temperature distribution inside RC beams exposed to fire and also investigated the effects of insulation materials on the moment capacity of RC beams (Erdem 2009 and 2010). Firmo *et al.* investigated three dimensional finite element modelling of the fire behaviour of insulated RC beams strengthened with EBR and NSM CFRP strips (Firmo *et al.* 2017).

To obtain the moment capacity of the RC beam with insulation material, sequential calculations must be undertaken. Firstly, the temperature distribution and material strengths are calculated taking into account the thermal conductivity. Then, the tensile and compressive forces and the residual moment capacity are calculated. Approximate calculation techniques are given in Eurocode2 and ACI216. In the given methods, temperature distributions within the section are given for some sections. By determining the temperature of the reinforcement in the graph, the restoring material strength is determined and the moment capacity of the beam is calculated. Due to the above mentioned sequential processes, different cross-sectional dimensions, any fire duration, different fire effectiveness surfaces, both reinforcement and concrete material strength losses are taken into account in the moment capacity calculation. Artificial neural networks can be trained using obtained data. Using the trained ANN models, moment capacities can be estimated for desired cross section, material strength, fire effect form and duration and insulation material properties. In this study, to avoid complexity in the calculation process of the residual moment capacity of thermally insulated beams exposed to fire, ANNs were used. Data were generated using prepared program by author, and used to train ANN model. The trained model was found to be effective in the estimation of the moment capacity. To demonstrate the effects of the use of insulating materials, the moment capacities were predicted using the trained model, and the effects on the moment capacity of RC beam of different thermal conductivity coefficients were examined.

2. Methods

2.1 Temperature-fire exposure time

In this paper, ISO834 temperature-time curve was used (ISO834 1975), in which $T_{ambient}$ is the ambient temperature (°C) and $t_{exposure}$ is the fire duration (minute)

$$T = 345\log_{10}\left(8t_{exposure}+1\right)+T_{ambient} \tag{1}$$

2.2 Reduction coefficients

The reduced concrete compression and steel tensile strengths due to the elevated temperature were calculated using the formula given in Eurocode2 (Eurocode2 1995). k_{steel} and $k_{concrete}$ are the reduction factors for the steel tensile strength and for concrete compressive strength, respectively, f_{sT} and f_{yd} are the steel tensile strengths at the rising temperature and at 20°C, respectively, and f_{cT} and f_{cd} are the concrete compressive strength at the rising temperature and at 20°C, respectively.

$$k_{steel} = \frac{f_{sT}}{f_{yd}} \tag{2}$$

$$k_{concrete} = \frac{f_{cT}}{f_{cd}} \tag{3}$$

2.3 Heat transfer in the cross section

The heat equation for two dimensional, steady-state conditions with no heat generation and constant thermal conductivity given in (Incropera and Dewitt 1996, Çengel

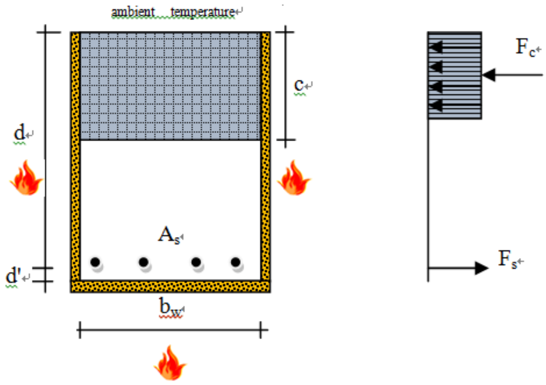


Fig. 3 Insulated reinforced concrete beam exposed to fire from three surfaces

1998) is as follows

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \quad (4)$$

If insulation material is applied to the surfaces of the sample, different thermal conductivity coefficients need to be used for the concrete and insulation materials. In this case, Eq. (4) may be rewritten as

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} = 0 \quad (5)$$

The numerical solution of two-dimensional steady heat conduction in rectangular coordinates can be obtained using the finite difference method. It can also be expressed in the following form

$$k_{m-1,n} T_{left} + k_{m+1,n} T_{right} + k_{m,n+1} T_{top} + k_{m,n-1} T_{bottom} - 4k_{mn} T_{node} = 0 \quad (6)$$

First, the insulated RC beam is divided into M×N segments, then the temperature and material strength of each part is calculated. The temperature distribution of the beam exposed to fire for 60 minutes shown in Fig. 1 was calculated and Fig. 2 gives the results for three different thermal conductivity coefficients. In this study, heat equation for two dimensional, steady-state conditions with no heat generation and constant thermal conductivity is used. No further comparisons were made since temperature curves were obtained for cases under the conditions given in Annex A of Eurocode2.

2.4 Moment capacity of the thermally insulated RC beam exposed to fire

When the tension force and the compressive force is in equilibrium (Fig. 3), the residual moment capacity may be determined as given below, where F_c and F_s are compressive and tensile forces in the beam, respectively, Δx and Δy are the sizes of each part, k_{cij} and k_{sij} are the concrete and steel reduction factors for each part in the RC beam

$$F_s = \sum_{i=1}^{M} \sum_{j=1}^{N} k_{sij} f_{yd} A_{sij} \quad (7)$$

$$F_c = 0.85 \sum_{i=1}^{M} \sum_{j=1}^{\frac{a}{\Delta y}} k_{c_{ij}} f_{cd} \Delta x \Delta y \quad (8)$$

$$M_r = 0.85 \sum_{i=1}^{M} \sum_{j=1}^{\frac{a}{\Delta y}} k_{c_{ij}} f_{cd} \Delta x \Delta y \left(d - \frac{\Delta y}{2} - j\Delta y \right) \quad (9)$$

2.5 Thermal insulation

To protect RC beams in the event of exposure to fire, insulation materials should be used that have low thermal conductivity, the ability to withstand high temperatures and be of sufficient thickness. In addition, the material should be simple to apply and have low cost. Examples of suitable material are; mineral wool ($k_{insulation}$=0.040 W/mK), perlite ($k_{insulation}$=0.058 W/mK), glass fiber ($k_{insulation}$=0.05 W/mK), calcium silicate ($k_{insulation}$=0.05 W/mK) and ceramic fiber ($k_{insulation}$=0.27 W/mK).

2.6 Artificial neural network

ANN is based on the nervous system and working principles of the human brain. It has the ability to produce new knowledge through learning, has the possibility of discovering, thinking and the ability to observe from datasets. Each ANN is created for a specific purpose; it learns through examples and consists of a large number of interconnected processing elements. It can be trained to obtain the desired output using the given input. There are input, hidden and output layers in ANN. The back-propagation (BP) learning algorithm used in ANN learns by checking the output with the target. The correlation coefficient (R) and the mean square error (MSE) are used to check the accuracy of the trained network. The sigmoid activation function used in ANN is written as follows (Kahraman *et al*. 2006)

$$x_o = \frac{1}{1 + \exp(-\sum x_h w_{ho})} \quad (10)$$

An error using the differences between the determined output x_o and the target value t_o is as follows, where D and P are the number of data and output neurons, respectively

$$E = \frac{1}{2} \sum_{S}^{D} \sum_{O}^{P} \left(t_o^{(s)} - x_o^{(s)} \right)^2 \quad (11)$$

The aim of the training process is to decrease the error to ensure the interconnection between layers. The weights are arranged using a BP algorithm. The training process starts with a random set of initial weights. Afterward, the training process continues through a set of w_{ih} and w_{ho} are optimized so that a predefined error threshold is met between the output of network x_o and the corresponding target value t_o.

2.7 Modeling with ANN

This study concerns the estimation of the moment capacity of 336 insulated RC beams exposed to fire using

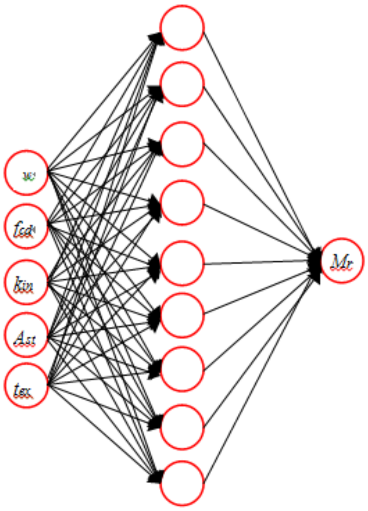


Fig. 4 The architecture of the proposed ANN model

ANN. 336 data are generated for 336 beam by selecting different values of beam width (b_w=200 and 250 mm), reinforcement area (A_{st}=339.12 and 461.58 mm^2) , thermal conductivity coefficient ($k_{insulation}$=0.40, 0.60, 0.80 W/mK), fire duration (t=0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120 minute) and concrete strength values (f_{cd}=20, 25 N/mm^2). The heat transfer was modeled as steady in two dimensions for the RC beam. The temperature and material properties in each piece were obtained by the calculations performed in the spreadsheet. The forces were calculated using the deteriorated material properties from each piece. The residual moment capacity was determined from the equilibrium of the forces. For the ANN model, the input parameters were beam weight (b_w), thermal conductivity coefficient ($k_{insulation}$), steel area (A_{st}) and fire exposure time ($t_{exposure}$), and concrete compressive strength (f_{cd}). M_r was selected as the output parameter. In this paper, the Levenberg Marquardt network (LM) was selected as the learning algorithm. The architecture of the proposed ANN model is shown in Fig. 4.

3 Application and results

3.1 Application of ANN

For the modeling, 336 items of data were used to predict the moment capacity of the insulated RC beam with ANNs. The neurons in the input layer were used as b_w (200, 250), A_{st} (339.12 and 461.58 mm^2), $k_{insulation}$ (0.40, 0.60, 0.80 W/mK), t (0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120 minute) and f_{cd} (20, 25 N/mm^2). The tensile strength of the rebar (f_{yd}) was taken as the constant value of 365 MPa. The beam depth (d) was taken to be 280 mm. In addition, the insulating material was 10 mm thick. The ANN model for this study was developed using Matlab software. The data was randomly divided into three pieces; 70% for training, 15% for testing, and 15% for validation. The data were normalized using maximum parameter values. The changes in the MSE for the LM network training, testing and validation stages are illustrated in Fig. 5. The MSE

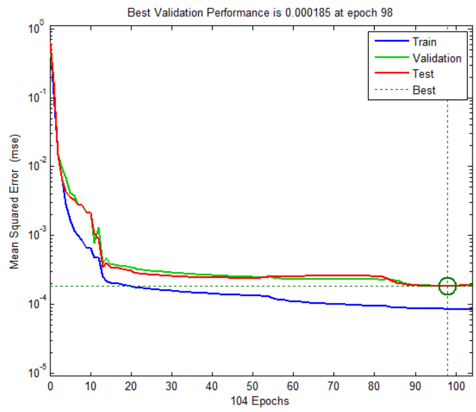


Fig. 5 Training performance of the proposed ANN model

Table 1 MSE and R values for training, validation and testing

	Data number	MSE	R
Training	236	0.000852	0.99926
Validation	50	0.000185	0.99856
Testing	50	0.000184	0.99821

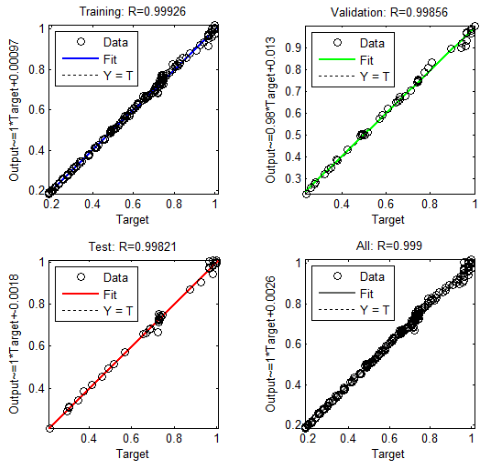


Fig. 6 The correlations for input, training, testing and validation

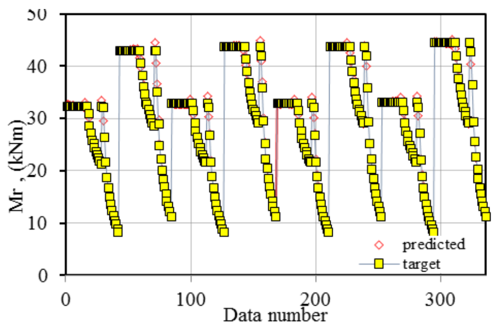


Fig. 7 Comparison between the obtained and predicted values for the dataset

value reduces with the increasing number of epochs. The correlations between the calculated moment capacities and the predicted moment capacities by ANN are shown in Fig. 6. The value of R was 0.99928 in training and 0.99821 in

Fig. 8 The errors between target and predicted moment capacities

Table 2 Data and errors between target and output moment capacity

Data number	b_w mm	f_{cd} N/mm^2	A_{st} mm^2	$t_{exposure}$ minute	k=0.4 W/mK M_r predicted	k=0.4 W/mK M_r target	k=0.4 W/mK ΔM_r	k=0.6 W/mK M_r predicted	k=0.6 W/mK M_r target	k=0.6 W/mK ΔM_r	k=0.8 W/mK M_r predicted	k=0.8 W/mK M_r target	k=0.8 W/mK ΔM_r
1	200	20	339.12	0	32.4	32.62	-0.22	32.4	33.22	-0.82	32.4	33.52	-1.12
2	200	20	339.12	5	32.4	32.58	-0.18	32.4	32.45	-0.05	32.2	29.70	2.50
3	200	20	339.12	10	32.4	32.54	-0.14	32.4	31.72	0.68	26.35	26.44	-0.09
4	200	20	339.12	20	32.4	32.48	-0.08	30.93	30.25	0.68	21.66	21.56	0.10
5	200	20	339.12	30	32.4	32.44	-0.04	28.68	28.86	-0.18	18.61	18.60	0.01
6	200	20	339.12	40	32.4	32.41	-0.01	27.09	27.56	-0.47	16.75	16.59	0.16
7	200	20	339.12	50	32.4	32.40	0.00	25.85	26.34	-0.49	15.04	15.00	0.04
8	200	20	339.12	60	32.4	32.40	0.00	25.31	25.26	0.05	13.63	13.65	-0.02
9	200	20	339.12	70	32.4	32.40	0.00	24.44	24.31	0.13	12.45	12.46	-0.01
10	200	20	339.12	80	32.4	32.40	0.00	23.69	23.51	0.18	11.42	11.39	0.03
11	200	20	339.12	90	32.4	32.39	0.01	23.02	22.88	0.14	10.51	10.46	0.05
12	200	20	339.12	100	32.4	32.37	0.03	22.42	22.41	0.01	9.7	9.68	0.02
13	200	20	339.12	110	32.4	32.31	0.09	21.88	22.12	-0.24	8.97	9.04	-0.07
14	200	20	339.12	120	32.4	32.23	0.17	21.39	22.01	-0.62	8.3	8.56	-0.26

testing. The R and MSE values are given in Table 1. These results demonstrate that the ANN model is extremely feasible for obtaining the M_r. The target and predicted M_r are shown in Fig. 7 and the errors between the target and output M_r are given in Fig. 8. The information concerning the error between target and output moment capacity of the first 14 data of 336 data is given in Table 2. These results demonstrate that ANNs can be used for the prediction of the M_r of RC-insulated beams exposed to fire.

3.2 Effects of insulation materials on the moment capacity

In this section, the moment capacity of the insulation materials in fire was investigated using the trained ANN model. In the first case, different thermal conductivity coefficients and constant insulation thickness were taken into account. In this case, $k_{insulation}$=0.40, 0.60 and 0.80 W/mK, b_w=250 mm, d=280 mm, A_{st}=339.12 mm^2, f_{cd}=20 N/mm^2 and $L_{insulation}$=10 mm were used, and the residual

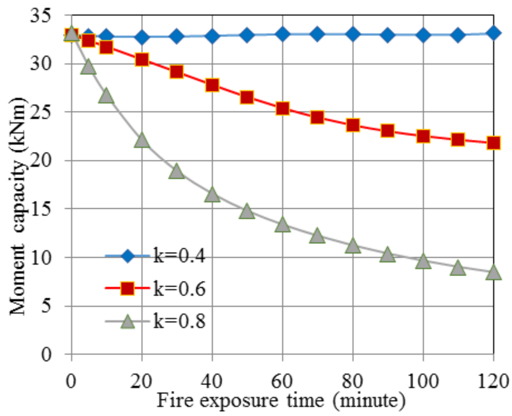


Fig. 9 Moment capacities for different thermal conductivity coefficients

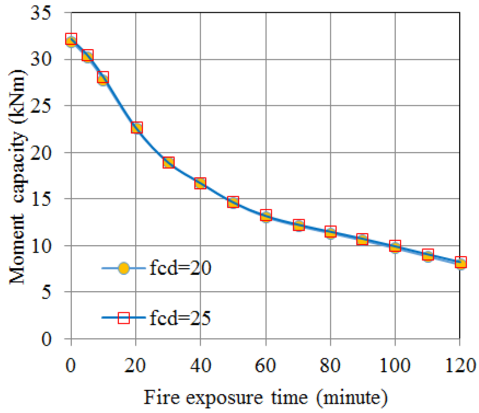


Fig. 10 Moment capacities for different concrete strength thermal conductivity coefficients (0.80 W/mK)

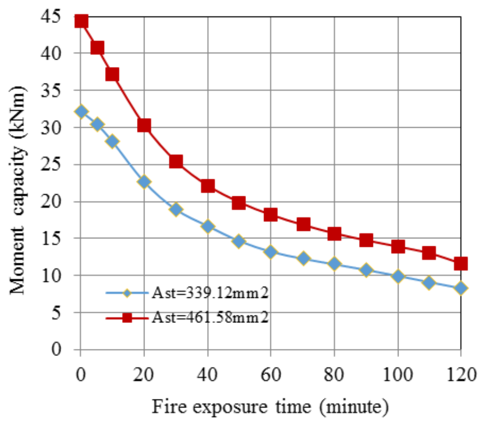


Fig. 11 Moment capacities for different reinforcement area and constant thermal conductivity coefficients (0.80 W/mK)

moment capacity of the RC beam with insulation material was predicted by the ANN model. The predicted moment capacities are shown in Fig. 9. If the value of thermal conductivity coefficient is 0.80 W/mK, the RC beam is rapidly affected by the fire. At $k_{insulation}$=0.60 W/mK, the RC beam is less affected from the fire However, the moment capacity was not affected by the fire when $k_{insulation}$=0.40 W/mK was selected.

In the second case, different concrete compression strengths were taken into account. In this case,

$k_{insulation}$=0.80 W/mK, b_w=250 mm, d=280 mm, A_{st}=339.12 mm^2, f_{cd}=20 and 25 N/mm^2 and $L_{insulation}$=10 mm were used, and the moment capacity of the RC beam with insulation material was predicted by the ANN model. The predicted moment capacities are shown in Fig. 10. The effect on the moment capacity of the concrete compressive strength in fire is observed to be very low.

In the third case, different reinforcement areas were taken into account. In this case, $k_{insulation}$=0.80 W/mK, b_w=250 mm, d=280 mm, A_{st}=339.12 and 461.58 mm^2, f_{cd}=25 N/mm^2 and $L_{insulation}$=10 mm are used, and the moment capacity of the RC beam with insulation material was predicted by the ANN model. The predicted moment capacities given in Fig. 11 show that ANN is effective in determining the moment capacity of the reinforcement area and it would exhibit similar behavior in a fire.

4. Conclusions

Structures may be exposed to high temperatures due to fire, and as with other elements, RC beams are affected. Different types of insulation material can be used to prevent the harmful effects of elevated temperatures. In the estimation of the moment capacity, the calculations of fire exposure time, temperature distribution in the cross-section, reduction coefficients of concrete and steel strengths, compressive and tensile forces in section must be made consecutively. ANN is an effective tool to undertake these calculations. In this study, an ANN was used for the prediction of the residual moment capacity of a thermally insulated RC beam exposed to fire. The effects on the thermally insulated RC beam in terms of the moment capacity of concrete compressive strength, reinforcement area and thermal conductivity coefficient were examined using a trained ANN. But, the trained model, only accurate estimations can be made for selected cross-sectional dimensions, material strengths, conductivity coefficients, and temperature ranges used to train the model. The residual moment capacity was not affected by the fire duration lasting 2 hours when thermal conductivity coefficient was selected as 0.40 W/mK. These findings indicate that the application of insulation material with low thermal conductivity to RC beams is useful in the protection of beams from the high temperatures that occur in a fire. The effect on the moment capacity of the concrete compressive strength in fire is observed to be very low. When choosing different reinforcement areas, a similar loss of residual moment capacity was experienced as expected.

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