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PREDICTING THE RESIDUAL FLEXURAL CAPACITY OF FIRE EXPOSED REINFORCED CONCRETE BEAMS USING GENE EXPRESSION PROGRAMMING

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Abstract- Reinforced concrete (RC) structures are the most commonly used ones in the construction industry; however, they exhibit a tendency of getting damaged when subjected to fire, which can cause significant deterioration and compromise their overall safety. Considering their fire susceptibility, it is critical to predict the residual flexural capacity of their structural elements especially the immediate load distributing elements i.e., RC beams in order to ensure their safety and reliability in fire hazard situations. In an effort to do so, a novel methodology was introduced by this research, utilizing gene expression programming (GEP) to accurately forecast the remaining flexural strength of RC beams after being imperiled to fire. For the evolution of GEP model, a comprehensive database consisting of 280 datapoints as reported in the past literature was used. The database incorporated seven input variables corresponding to the predetermined remnant flexural capacity output of the given beams. The performance of the proposed model was assessed using three widely recognized performance metrics: the mean absolute error, the coefficient of determination, and the root mean squared error. From the performance evaluation results, a robust correlation was found to exist between the target and predicted results with minimum error. Therefore, the proposed model can be assuredly recommended for quickly, accurately, and dependably forecasting the remnant flexural strength of RC beams after being subjected to fire.

Keywords- Fire, Gene Expression Programming, Prediction, Reinforced Concrete Beams, Residual Flexural Capacity.

1 Introduction

1.1 Background

Reinforced concrete (RC) structures are widely used in the construction industry [1], [2] due to their high strength, durability, and cost-effectiveness. However, these structures exhibit a tendency of getting damaged when subjected to fire, which can cause significant deterioration and reduce their overall load carrying capacity [3]–[6]. The reduction in load carrying capacity can compromise the safety of a structure and may lead to catastrophic failure. Among various members of these structures, beams are the most important ones since they are responsible to distribute the load of floor systems to the adjoining columns through transverse loading phenomenon [7]. Considering the importance and fire damage tendency of RC beams, it is critical to predict their residual flexural capacity when subjected to fire in order to ensure the safety and dependability of the aforementioned structures.

In the recent years, several experimental as well as data driven studies have been carried out to assess the behaviour of RC beams when imperilled to fire [8]–[11]. The experimental studies were conducted to explore the performance of these beams whereas the data driven studies were carried out to develop predictive models for their residual strength. The experimental investigations have shown that the residual or remnant flexural strength of fire imperilled RC beams depends on various factors such as fire temperature, fire duration, beam geometry, and material characteristics [8], [10], [12]. However, they are time consuming, costly, and difficult to be conducted for every real-world situation. The data driven studies, on the other hand, were found to successfully forecast the remnant flexural strength of RC beams while avoiding these problems [11], [13]. However, they also have certain limitations as well e.g., the assumption of linear material behavior, which may not be valid for high-temperature situations. Moreover, some studies have not proposed mathematical expressions which is a big concern for their applicability to the real-world problems [11]. To overcome these limitations, genetic algorithm-based approach of gene expression programming (GEP) is often recommended [14]–[18]. It is a form of evolutionary algorithm which has been successfully applied in various fields, including civil engineering, to model complex systems and predict their behaviour under different conditions [19], [20].

In short, forecasting the remaining flexural strength of RC beams is critical to ensure the safety and serviceability of RC structures in fire hazard situations. Traditional methods employed for this purpose have shown some substantial limitations. Therefore, this research aims to develop predictive model for the remnant flexural strength of fire subjected RC beams utilizing GEP. It also aims to provide a simple mathematical expression for future implementation of the intended model. It is further extended to evaluate and validate the performance of intended model to ensure its precision and prediction accuracy.

1.2 Gene Expression Programming

GEP is an evolutionary algorithm which is based on genetic programming. It involves the use of linear chromosomes to represent a tree-like structure of genes. These genes are thereafter articulated in the form of arithmetical expressions or computer programs [14], [21]–[24]. The overall working procedure of GEP can be divided into four basic steps: the generation of preliminary populace, the execution, the fitness evaluation, and the creation of ensuing populations of GEP programs or the derivation of optimal solutions in the form of arithmetical or mathematical equations. All these steps of GEP algorithm are illustrated in Figure 1 [14].

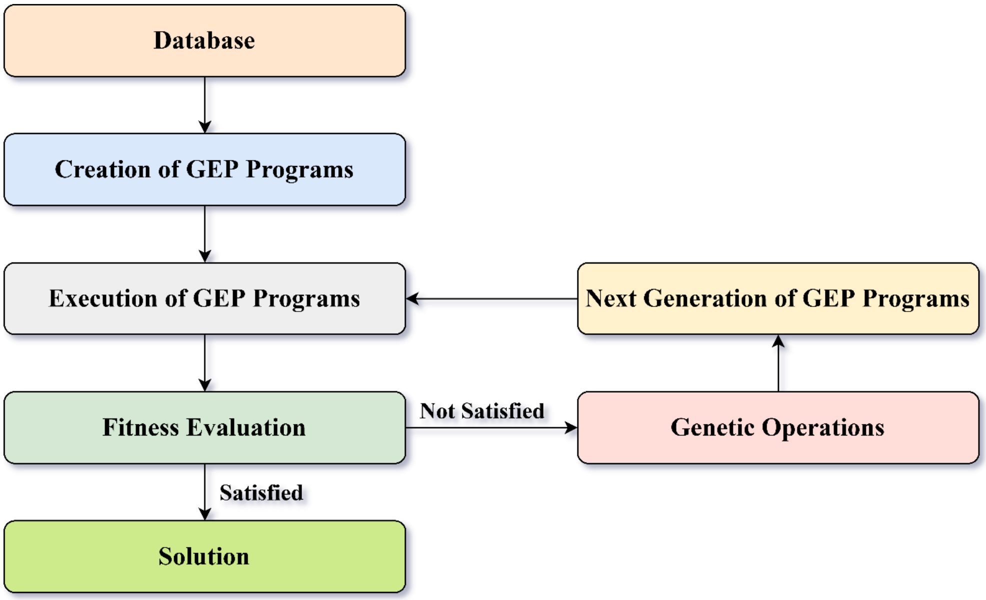

Figure 1: Working Algorithm of GEP

The GEP algorithm begins by randomly generating a population of chromosomes (or GEP programs) from the database, each of which consists of a fixed number of genes, arranged in a linear sequence [14]. After the generation of preliminary populace of chromosomes or GEP programs, they are executed, following which, their fitness is assessed using predefined fitness or performance assessment metrics. If the fitness (or performance) assessment results meet the concluding bench mark, the GEP algorithm concludes, and the optimal solution is presented as an arithmetical or mathematical expression [14]. However, if the fitness (or performance) assessment results fail to meet the concluding bench mark, the whole process is repeated by the generation of an ensuing populace of chromosomes or GEP programs employing the genetic operations of selection, crossover, mutation, and replacement [14].

In summary, GEP is a powerful artificial intelligence (or machine learning) based data processing tool that uses genetic algorithms to evolve computer programs or mathematical expressions. It has the ability to efficiently determine the high-quality solutions by using a combination of genetic operators and fitness-based selection. Considering all its advantageous attributes, this research intends to utilize GEP for accurately predicting the residual flexural strength of RC beams under standard fire conditions.

2 Research Methodology

The evolution of a diagnostic model for estimating the remnant flexural capacity or strength of fire imperilled RC beams consists of three fundamental steps: the creation or selection of a thorough catalogue representing the datapoints of given phenomenon, the identification of model's input and output variables or parameters, and the fruition of the intended GEP model. These steps are further elaborated upon in the succeeding subsections.

2.1 Database

A comprehensive database describing the fire performance of RC beams assembled by Hakan Erdem [11] was selected to evolve the diagnostic model for estimating (or forecasting) the residual flexural strength of aforementioned beams. It consisted of 280 datapoints with 260 exhibiting the fire damage whereas 20 without exhibiting fire damage. The thorough elaboration of the statistical properties of this database is presented in Table 1. It shows the standard deviation, mean, and range of the various input and output variables. The width, depth, area of steel, concrete cover, fire exposure time, and compressive strength of the concrete of RC beams were found to be ranging between 250 to 1000 mm, 280 to 380 mm, 226 to 1527 mm^2, 20 to 90 mm, 0 to 120 minutes, and 13 to 20 MPa respectively. Analysing the statistical characteristics for width and depth, the aforementioned beams in the given database were revealed to be extending from very small cross sections to the very large ones. This shows the comprehensive and inclusive nature of the selected database. The yield strength of the reinforcing steel was however found to be constant at 365 MPa throughout the database (representing single grade of steel). It was not neglected from the database because of its greater importance towards the fire behaviour of RC beams. These statistical characteristics especially the range of parameters in the database must be regarded as the boundary limits of proposed model to which it can be applied.

Table 1: Description of the Statistical Properties of Database

Parameter	**Symbol**	**Unit**	**Type**	**Maximum**	**Minimum**	**Mean**	**STD**
Width	B	mm	Input	1000	250	430	302.78
Depth	D	mm	Input	380	280	320	49.08
Area of Steel	A_{st}	mm^2	Input	1526.81	226.19	722.25	390.06
Concrete Cover	C_c	mm	Input	90	20	34	28.05
Fire Exposure Time	T	min	Input	120	0	56.07	38.81
Compressive Strength	f'_c	MPa	Input	20	13.33	17.33	3.27
Yield Strength	f_y	MPa	Input	365	365	365	0.00
Residual Flexural Capacity	M_r	KN-m	Output	202.63	0.69	13.10	26.23

STD: Standard Deviation.

2.2 Model Parameters

The selection of input variables against the preestablished residual flexural strength output of RC beams (under standard fire conditions) was done on the basis of their statistical and structural importance. The statistical importance was determined in terms of *p*-value calculated using linear regression and analysis of variance (ANOVA) whereas the structural importance was determined based on the engineering knowledge. Employing this strategy, seven input variables were selected to predict the single residual flexural capacity output variable. A detailed description including the name, symbol, measuring unit, and type of all these variables (either the input or output) is presented in Table 1.

2.3 Model Development

The development of remnant flexural strength prediction model of RC beams subjected to standard fire was done utilizing tremendously flexible and efficient GEP based data modelling software GeneXproTools 5.0. The modelling process was initiated by importing an organized Microsoft Excel's database of the given phenomenon consisting of seven input variables against the preestablished output variable to this software. For effective and robust data modelling, the given database consisting of 280 datapoints was randomly split-up into two groups: the training database, consisting of 70% of the total datapoints and testing/validating database, consisting of 30% of the total datapoints [11], [25]. The performance or fitness of GEP models was assessed on the basis of three well-known performance metrics (as recommended by some antecedent research studies [14], [19], [25]): determination metric (R^2), root mean squared error metric ($RMSE$), and mean absolute error metric (MAE). These performance (or fitness) metrics can be computed using equation (1), (2), and (3) respectively [26]. In the aforementioned equations, X describes the known output variable, Y describes the estimated (or forecasted) output variable, and p describes the number of datapoints. Based on the results obtained for these performance (or fitness) metrics, the model owning best fitness was presented for imminent estimating or forecasting the remnant flexural strength of fire imperiled RC beams.

$$R^2 = \left[\frac{p \sum_{i=1}^{p} (X_i Y_i) - \left(\sum_{i=1}^{p} X_i\right)\left(\sum_{i=1}^{p} Y_i\right)}{\sqrt{\left[p \sum_{i=1}^{p} X_i^2 - \left(\sum_{i=1}^{p} X_i\right)^2\right]\left[p \sum_{i=1}^{p} Y_i^2 - \left(\sum_{i=1}^{p} Y_i\right)^2\right]}} \right]^2 \quad (1)$$

$$RMSE = \sqrt{\frac{1}{p} \sum_{i=1}^{p} (Y_i - X_i)^2} \quad (2)$$

$$MAE = \frac{1}{p} \sum_{i=1}^{p} |Y_i - X_i| \quad (3)$$

3 Results

The results of the research on the predictive modelling of residual flexural strength of RC beams subjected to standard fire can be divided into three parts i.e., the formulation, validation, and performance evaluation of aforementioned capacity prediction model. A comprehensive and in-depth insight into all these parts has been provided in the succeeding subsections.

3.1 Residual Flexural Capacity Prediction Model

The remnant flexural strength prediction model of RC beams imperilled to standard fire was developed using GEP based GeneXproTools 5.0. This software offers the results in the form of expression trees which are tree like data structures with each node representing a unique expression. The expression tree obtained for this model was found to be a combination of three sub-expression trees which were linked via division operation. To make this model applicable to the scenarios of real physical world, this expression tree was decrypted into the mathematical expressions as presented in equations (4)-(6). All the symbols involved in these equations have been described in Table 1.

$$M_r = \frac{2.19X_1X_2}{B} \tag{4}$$

$$X_1 = D + 4A_{st} - 7.29C_c \tag{5}$$

$$X_2 = \frac{Bf_c'}{f_y(4.23+T)} - \frac{1.53TB}{C_cf_y(4.23+T)} \tag{6}$$

3.2 Model Validation

To ensure the strength and accuracy of the GEP models, it is common practice to perform sensitivity and parametric analysis [14], [25]. The sensitivity analysis assesses the impact of individual input variables on the output of the GEP model whereas the parametric analysis investigates the effects of varying the model parameters on its performance. The results of both the aforementioned analyses have been presented in the succeeding subsections for a comprehensive understanding.

3.2.1 Sensitivity Analysis

Sensitivity analysis is used to investigate the relative impact (or benefaction) of input parameters (or variables) towards the overall model development. It was conducted on the basis of procedure presented by Asghar et. al. [14]. From the sensitivity analysis results as presented in Figure 2, *T* was found to be the most significant input parameter of the proposed model followed by C_c and f'_c whereas *B* was found to be the least significant one. These results were discovered to be in good agreement with that presented by Hakan Erdem [11] which validates the robustness of this model.

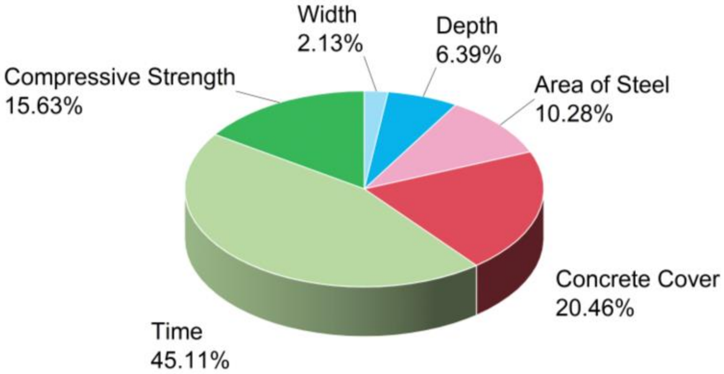

Figure 2: Contribution of Input Parameters to the Development of Proposed Model

3.2.2 Parametric Analysis

Parametric analysis is used to explore the impact of certain variation in the input parameter on the predicted output of the given model. It was conducted on the basis of procedure laid out by Asghar et. al. [14]. From the parametric analysis results as presented in Figure 3, the remnant flexural strength of RC beams imperilled to fire was found to be increasing with the increase in *B*, *D*, A_{st}, and f'_c whereas decreasing with the increase in *T*. It is because the beams with lesser B and D experiences more concentrated effect of fire (or heat), the beams with greater A_{st}, and f'_c can better mitigate the fire hazard conditions due to their superior performance characteristics, whereas the beams with prolonged *T* can lead to the increase in temperature attained by their concrete and reinforcement. The residual flexural strength of the aforementioned beams was also found to exhibit a direct relationship with C_c which is because a thicker clear concrete cover provides enhanced insulation by slowing down the transfer of heat from the surroundings to the steel reinforcement. This slowing down of heat transfer allows it to stay cooler for a longer period of time, therefore, reducing the risk of premature failure and exhibiting higher residual flexural strength. The parametric analysis results were found to be in good agreement with that presented by Hakan Erdem [11] which validates the robustness of the proposed model.

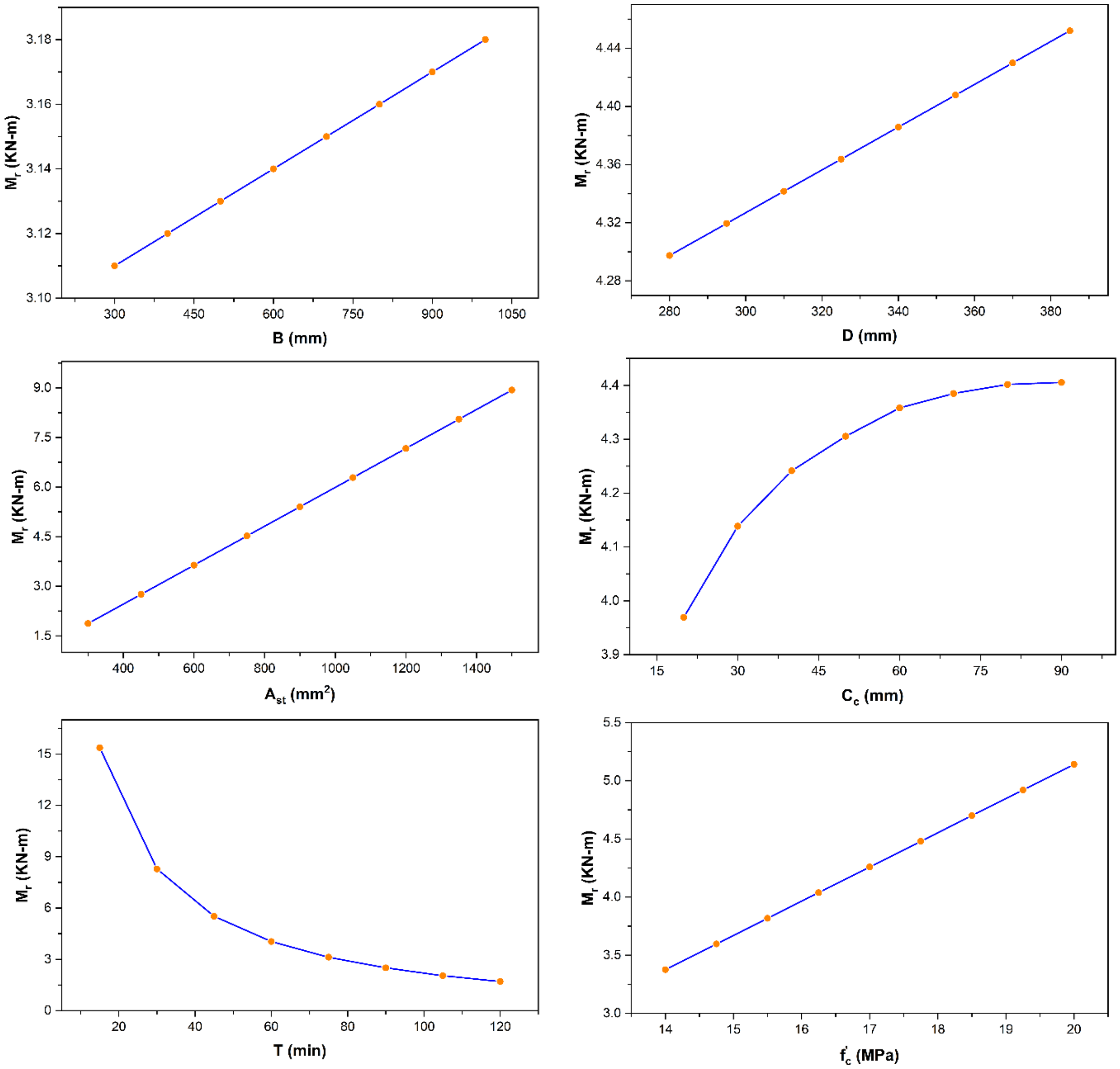

Figure 3: Parametric Analysis Results of Proposed Model

3.3 Performance Evaluation

The performance (or fitness) of proposed residual flexural strength estimation (or forecasting or prediction) model of fire exposed RC beams was evaluated based on three well-known performance (or fitness) indicators i.e., R^2, *RMSE*, and *MAE*. Among these fitness indicators, R^2 was determined in decimal points whereas *RMSE* and *MAE* were determined in KN-m. From the performance evaluation results as presented in Figure 4, these performance indicators were found to be 0.9737, 4.16, and 2.13 correspondingly for training database whereas 0.9813, 1.80, and 1.36 correspondingly for testing or validating database. Analysing these fitness metrics (or indicators), it was found that a robust (or strong) relationship (or association) exists between the target and predicted results. Moreover, the error between them was also found to be at its lowest. This shows the higher precision and prediction accuracy of proposed model. Conscientiously assessing the results of performance evaluation and model validation, the proposed model is highly recommended to be used for determining the remnant flexural capacity or strength of fire imperilled RC beams for future real-world scenarios or applications.

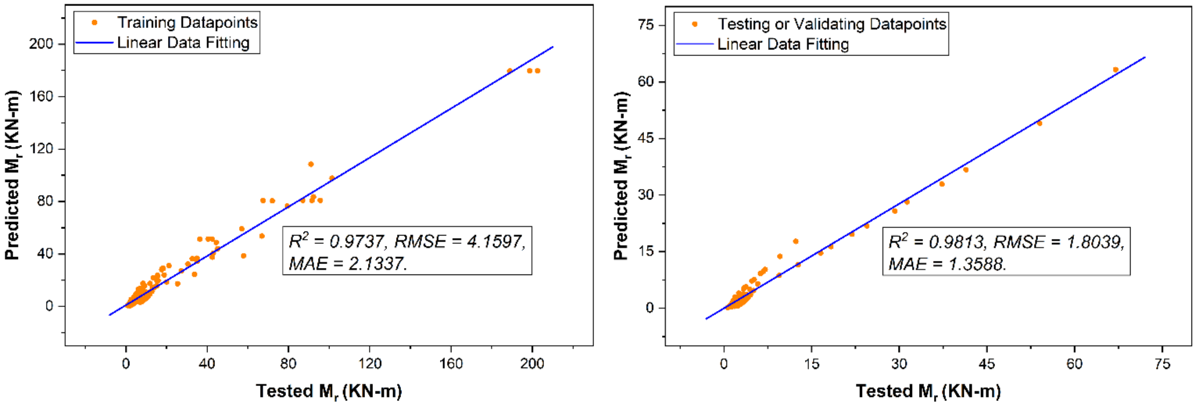

Figure 4: Performance Evaluation Results of Proposed Model

4 Conclusions

This article presented a novel gene expression programming (GEP) based research which has established the potential and practical relevance of the GEP in accurately estimating (or forecasting) the residual (or remnant) flexural strength of fire imperilled RC beams, contributing to the field of structural engineering and fire safety. On the basis of the findings of this research, the conclusions drawn are presented below.

1 The proposed model offers a unique way of computing the remaining flexural strength of RC beams after being imperilled to fire while avoiding the complex structural and mathematical calculations.
2 The model as proposed by this research was discovered to be accurate and precise in predicting the remnant flexural strength of RC beams imperilled to fire.
3 The trend of output with the input variables of the model as proposed by this research was discovered to be in consonance with the results obtained from experimental methods. This validates its ability to capture the underlying physical processes of the given phenomenon.
4 Fire exposure time was found to be the most significant input parameter of the proposed model followed by clear cover and concrete's compressive strength.

Analyzing the performance or fitness scrutinization results, the model evolved by this research can be assuredly recommended for quickly, accurately, and dependably forecasting the remnant flexural strength of RC beams after being imperilled to fire.

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