Finite Element Modeling and Statistical Analysis of Fire-Damaged Reinforced Concrete Columns Repaired Using Smart Materials and FRP Confinement

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Abstract. Practical testing for observing the failure modes is expensive, time consuming and often limits the pace of research progress. Moreover, because of the limitations of equipment, the existing structures cannot be tested at ultimate failure and scale effect is not observed on large scale experimentally. Thus, numerical modeling and statistical analysis is required for prediction of the behavior of fire damaged and fire-damaged repaired structures. This Paper explores the regression models and Finite element studies to predict the load-deformation response of bolstered concrete columns, damaged through exposure to heat at 300 °C, 500 °C and 900 °C, strengthened using smart materials and confined by carbon fiber reinforced polymers. Using software ABAQUS, a numerical model was developed, capable of predicting the axial load-deformation performance of undamaged, fire damaged and fire-damaged reinforced columns repaired by employing various confinement techniques. SPSS Software was used for Regression modeling (Linear, multiple, and Quadratic). The obtained results showed that regression equations and numerical modeling offered a better alternative to the experimental methods. High correlation coefficient r and coefficient of determination r^2, more than 90%, for all developed equations, confirmed it as an excellent fit statistical model for prediction of axial load capacity and axial deformation. Similarly, the response predicted by numerical modeling showed minor difference i-e less than 10% with that of experimental. Thus, it can be concluded that, the numerical modeling and prediction formulae agree quite with the experimental results and can be used as alternatives for prediction of loads and deformations.

Keywords: Fire-damaged columns · Smart construction materials · Numerical modeling · Regression modeling · Abaqus · SPSS

1 Introduction

Repairing and strengthening of structures is a challenging and rising current issue globally due to increasing the economic crisis. Concrete is a thermally slow structural material and incombustible in nature due to its low thermal conductivity and high thermal capacity [1]. The non-combustible behavior and low thermal conductivity of concrete limits

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the depth of penetration of fire damage which makes the concrete structurally sound material enough even after being exposed to intense fires. Although concrete structures are damaged to some extent during a fire, they can conserve residual energy due to the redistribution of the load from the damaged region to the non-damaged region even if part of the structure is severely damaged by fire [2]. Therefore, it is unusual for concrete structures damaged by fire to fall completely during or after a fire incident. It would therefore be of economic interest to asset owners and insurers to find the most cost-effective, efficient, and fast-moving solution for fire damage. The cost for demolition and rebuilding can be avoided, as the repairing of structures requires less capital cost than demolition or rebuilding. A fire damaged repaired building can be re-utilized faster, which provides a direct saving to the owners and insurers because of the earlier re-functioning of building. The residual compressive strength and stiffness of fire damaged concrete structures are affected after exposure to fire. To repair the fire damaged structures, it is essential to restore the original minimum strength, ductility, and stiffness, which they have possessed before the fire. The high cost of replacement or demolition requires remediation or reinforcement methods as an alternative to extending the service life of the damaged concrete structure. Bailey and Yaqub also saw the impact of the short-term structure and the shrinkage of the reinforced concrete columns fitted with different FRP. They tested seventeen types of columns under uniaxial compression. It was found that the FRP-wrapped columns had a significant impact on the load capacity. Similarly, column shapes have also a depressing effect on column load capacity. Fibre reinforced polymer (FRP) composite is one of the most recent advanced promising technique making a significant impact on the repair and retrofit industry in terms of time and cost. The use of this technique is particularly attractive that it is very simple and fast for the practicing engineers to wrap the fibre reinforced polymer around the damaged structural members without any escalating the cross-sectional size, weight, and interruption to the use of the structure. In the past, most of the published research work had proven that the fibre reinforced polymer (FRP) confinement can significantly enhance the strength, deformability, and ductility of the damaged structural members [3–7]. Practical testing for observing the failure modes is expensive, time consuming and often limits the pace of research progress. Thus, numerical modeling and statistical analysis is required for the prediction of the behavior of fire damaged and fire-damaged repaired structure [8–11]. FE value measurements have been used by many investigators to predict the performance of CFRP-confined concrete cylinders or columns with a variety of binding materials and bonding dimensions [12–14]. To assess the effectiveness of the RC Post heated column, a non-linear FEM was created by Mohamed Bikhiet, et al. They found that with load consumption and an increase in surface temperature the column quickly failed. ABAQUS software is a popular tool used by researchers in the analysis of FE for their research work. This tool is an indirect analysis program that is a compatible model. The two types used in ABAQUS for concrete models are "Brittle Cracking Model for Concrete" and "Concrete Damage Plasticity model" [15]. The concrete damaged plasticity model is the most widely used model based on the assumption of isotropic damage and deterioration of elasticity caused by plastic stiffness [16–18]. There is a gap in the literature on experimental, statistical, and numerical methods for recovering residual RC columns after a fire/heating. To the best of author's knowledge, very limited Statistical and FEM studies are available on the axial load capacity of Post heated reinforced columns repaired with advanced materials (CFRP Wraps, Epoxy fill Steel Wire Mesh covered with CFRP Wraps). So, an effort is made in this research to address this gap and numerical models and regression formulae are developed for reliable and fast prediction.

2 Experimental Work

The experimental work was conducted to determine the effectiveness of CFRP wrap to repair fire damaged reinforced concrete (RC) circular columns. Concrete columns were casted in laboratory at University of Engineering and Technology, Taxila. Heating of reinforced concrete columns was carried out after seven months of casting in the Car bottom Heat-Treatment Furnace A-49 (S 209) (available in the hydraulic shop of Heavy Mechanical Complex (HMC), Taxila), except those at room temperature (See Fig. 1).

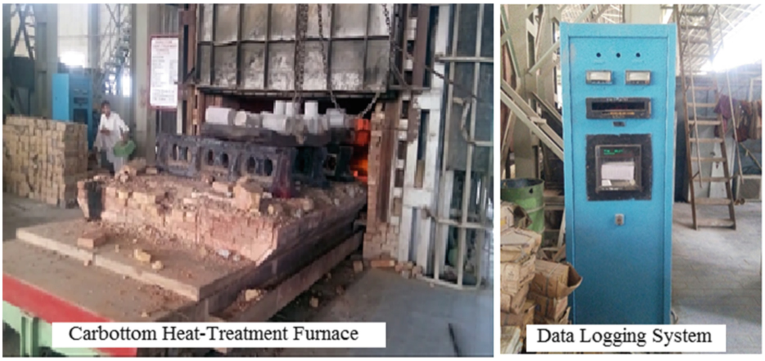

Fig. 1. Heating of specimens

After heating, the samples were cured and repaired using different techniques. After preparing the surface of the post-heated reinforced concrete columns they were wrapped in a polymer reinforced with carbon fiber. Only one layer of unidirectional carbon fiber reinforced polymer (CFRP) wrap CFW 600 (0.337 mm thick) used in this study to investigate the effect of polymer-reinforced fiber on the strength, stiffness, energy dissipation and ductility of post-heated repaired reinforced circular columns. The fabric sheet was cut according to the perimeter and the length of the types to be folded including a 200 mm circular joint according to the recommendations. The CFRP fabric was impregnated with epoxy Chemdur-300 and then wrapped around the heat damaged repaired specimens with the main fibers oriented in the transverse direction using a wet layup technique as shown in Fig. 2. The testing setup is shown in Fig. 3.

Fig. 2. a) Repairing of specimens, b) covering sample with steel wire mesh, c) sample wrapped with mesh, d) and e) Cutting and preparing CFRP, f) epoxy injected to samples, g) sample covered with cement sand mortar, h) and i) CFRP Wrap in progress, k) and L) sample repaired and ready for testing.

Fig. 3. Testing of specimens

3 Numerical Modeling

ABAQUS Standard 6.12 is used for the statistical simulation of concrete cubes. Border conditions, different geometric parameters, and materials were discussed in detail during the modeling of the variants. An equally solid 3D phase is used for concrete modeling. ACI code given by Eq. (1) was used for calculation of modulus of elasticity (Ec) of concrete.

$$Ec = 4700\sqrt{fc'} \tag{1}$$

The initial and maximum increment size of 0.01 and the minimum increase size 10^{-10} was used as input structures. In the current study, the performance of concrete materials was described using the CDP model provided by Liu et al. (Tao and Chen, 2014) describing the relationship between the type of inelastic, the strain of plastic, and compression stress and the hardness of the concrete. The CDP model in ABAQUS consists of plastic performance, compression behavior, and strong concrete behavior. A concrete object is modeled using a solid three-dimensional object to reflect a non-concrete character. The mesh that has been used for the concrete is C3D8R which stand for an 8-node linear brick with reduced integration. The linear elastic behavior can be taken up to $0.4f_{cm}$ according to P. Kmiecik et al. (Kmiecik and Kamiński) [19]. The Stress-strain curves obtained (experimentally) in tension and Compression, for controlled samples, fire damaged unconfined and heat damaged repaired concrete is given in Fig. 4 and Fig. 5. This was used as input while simulating various techniques.

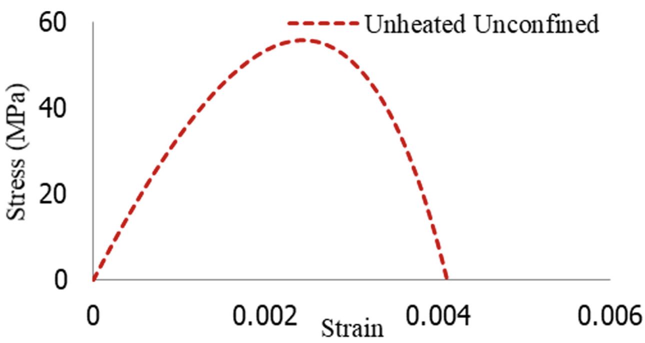

Fig. 4. Stress–strain relationship for controlled samples (experimental)

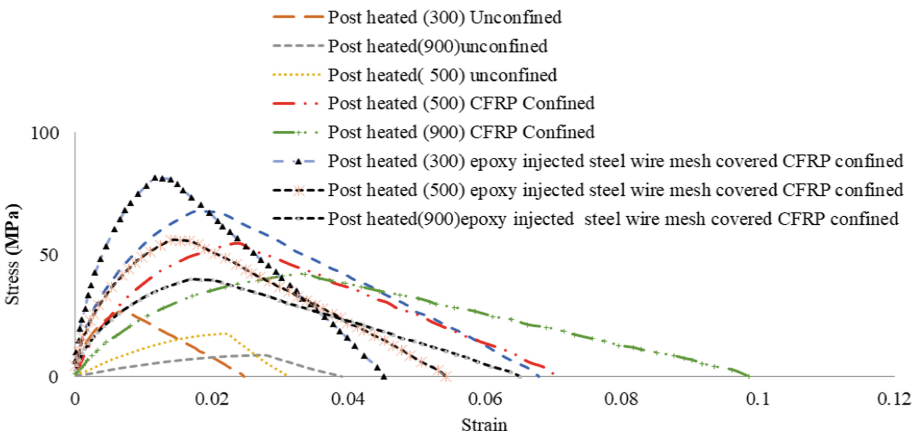

Fig. 5. Stress–strain curves for fire damaged and repaired concrete (experimental)

The concrete ultimate tensile strength was estimated by using Eq. (2) proposed by Wang and Vecchio and Genikomsou and Polak [20, 21]. The Modified Tension Stiffening curves obtained experimentally are given in Fig. 6. These are used as input in defining tensile behaviour of repaired samples in Abaqus.

$$ft' = 0.33\sqrt{fc'}\ \text{(Mpa)} \tag{2}$$

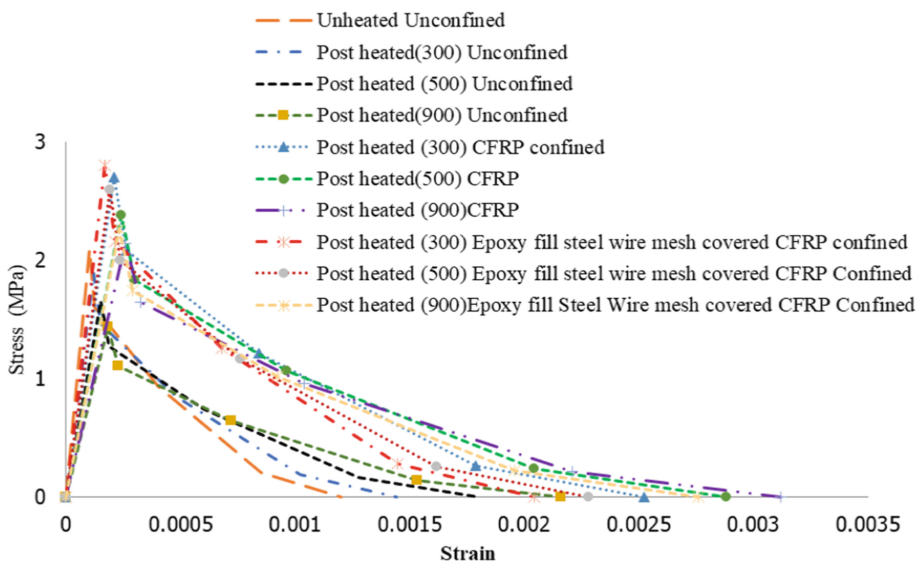

Fig. 6. Stress–strain curves for post-heated (°C) repaired concrete in tension.

4 Statistical Analysis for Strength Prediction (Regression Models)

In the text a figure Statistical models have the attraction that once combined they can be used to make predictions much faster than other modeling techniques and are correspondingly simpler to implement in software.

The dependent variable (Outcome variable) is axial load capacity while the independent variable is temperature. A simple linear regression model is developed for reduction in strength of concrete after being subjected to heating. Simple Linear regression model coefficients taken from (IBM SPSS) are used to predict residual axial capacity after heating.

$$P_{ntf\Theta} = 147.69t_f - 0.77\Theta + 1.426(0.85fc'(A_g - A_{st}) + f_yA_{st})\ (100°C \le \Theta \le 900°C) \tag{3}$$

$P_{ntf\Theta}$ shows the confined load capacity of post-heated CFRP confined reinforced circular columns in kN at values of thickness and temperature, ɵ represents temperature in degrees Celsius and t_f is the symbol used for the thickness of CFRP fiber in mm. A_g is gross area of concrete, Ast is area of steel and $f_y$fy is yield strength. A deformation equation for Carbon fiber reinforced polymer confined post heated circular columns subjected to axial loading is constituted using quadratic regression model. Due to higher value of deformation after confinement the equation has large value of Y-intercept showing that the model will predict higher deformations as best fit curve however slight variation may be noted during small values. The quadratic regression relation constituted in the form of following equations.

$$P_{ncc} = -4.64\,\text{þ}_c^{\,2} + 171.2\,\text{þ}_c + 877 \quad (100^0C < \Theta \leq 300^0\,C) \tag{4}$$

$$P_{ncc} = -1.865\,\text{þ}_c^{\,2} + 94.02\,\text{þ}_c + 1167 \quad (300^0C < \Theta \leq 500^0C) \tag{5}$$

$$P_{ncc} = -2.12\,\text{þ}_c^{\,2} + 84.72\,\text{þ}_c + 842 \quad (500^0C < \Theta \leq 900^0C) \tag{6}$$

"Pncc" is symbol used for Axial confined load capacity in kN and "þc" represent confined deformation of circular columns in mm. The appropriate model is confirmed by performance measurement parameters. Coefficient of correlation and Coefficient of determination is well above the limit specified. For the temperature of 300 °C and 500 °C more than 90% of the change in axial deformation values can be explained by model input variables. However, this percentage is slightly low for 900 °C as shown in 4th column of table above. The root means the value of the square and Sig. They also report the most appropriate model of the first two temperature sets with the highest RMSE values in the third set.

5 Results and Discussions

The effect of temperature on strength and conversion is best studied by exposing the reinforced circular columns to heat. Moreover, repairing of these damaged columns using different techniques is carried out with objectives of increase in mechanically properties particularly strength and stiffness. Post heated (300 °C) axial load capacity

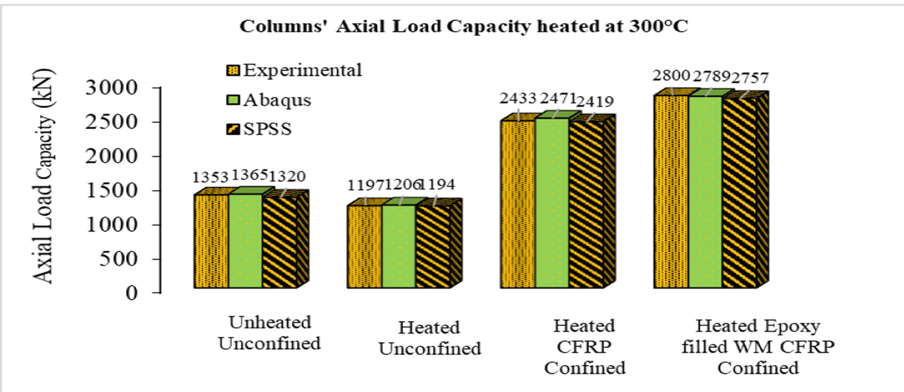

Fig. 7. Axial load capacity for heat damaged and repaired columns at 300 °C.

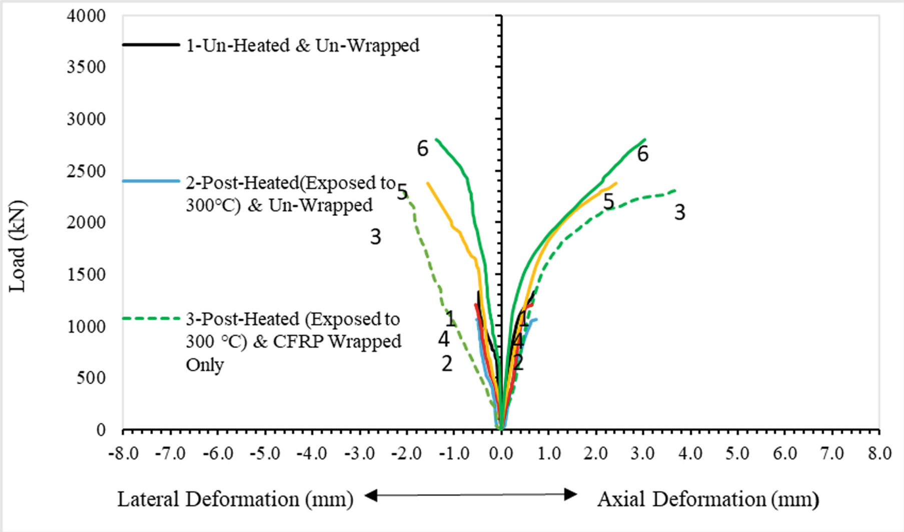

Fig. 8. Effect of repairing techniques on load-deformation curves for temperature 300 °C (experimental)

is less than unheated unconfined by 12% (See Fig. 7). To restore this reduction CFRP confinement is applied to damaged RC columns. CFRP increased the axial capacity of damaged RC column by 80% more than controlled sample. However, no significant effect was made to the value of stiffness. For the stated reason it was decided to use such a technique that not only increase axial capacity but stiffness of members also so that load can be transferred efficiently. Epoxy injected steel wire mesh covered and CFRP wrapping was used for this purpose. This not only resulted significance increase in axial capacity (100%) but also controlled deformation thus providing adequate stiffness to member to pass load safely (See Fig. 8). This procedure was repeated for 500 °C and 900 °C. The axial capacity of post-heated 500 °C unconfined reinforced circular columns was reduced by 27% after being subjected to heating. CFRP confinement used as a repair technique increased axial capacity by 60% more than that of the controlled sample. It is important to note that this increase in strength for CFRP confined samples was 120% more than the post-heated 500 °C unconfined case. However, confinement did not contribute to the stiffness which was greatly reduced by the heat. To solve this problem, epoxy wireless cover-up CFRP techniques have been used, which not only to increase power by 80% over-controlled sample capacity but also to solve the problem of stiffness. The axial deformation of column increases after being subjected to heat. Regarding the effect of repairing techniques on deformation of damaged RC column, it is noted that deformation increases with the confinement of CFRP. The use of epoxy filled wire mesh covered CFRP confinement resulted in controlled deformation. The results obtained by using regression model are very close to those of the experiment. However due to higher values of deformation, the regression model of post heated unconfined and post heated CFRP confinement has high values of Y-intercept. Because of this problem the SPSS model cannot predict good values of deformation at lower

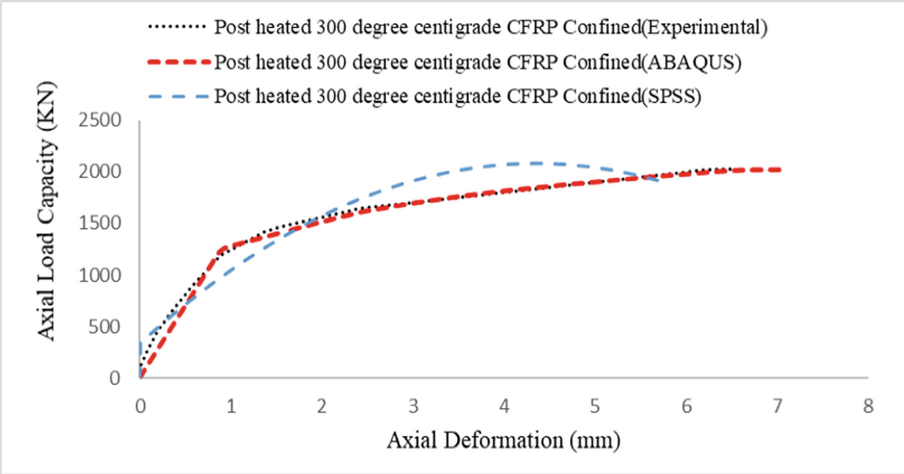

Fig. 9. Comparison of axial deformation columns

load. However excellent prediction is noted at higher values. Finite element model has resulted excellent results of deformation prediction (See Fig. 9).

6 Conclusions

This study concludes that regression equations and numerical modeling offer a best alternative to experimental methods which are expensive in terms of cost and time. Moreover, because of the limitations of equipment, the existing structures cannot be tested at ultimate failure and scale effect cannot be observed on large scale experimentally. These restraints have strongly encouraged the development of advanced Finite element modeling and statistical methods capable of representing the behavior of concrete structures reinstated by composite materials under all possible loading conditions.

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