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Application of fuzzy logic approach in predicting the lateral confinement coefficient for RC columns wrapped with CFRP

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ABSTRACT

Worldwide ageing infrastructures which are vulnerable to seismic lateral loads and located in high seismicity regions have arrested the interest of many researchers to find alternative materials and techniques to strengthen in bending and shear, for example reinforced concrete (RC) beams, slabs, columns, etc. There are several strengthening/repair techniques and materials in literature. Although the method of strengthening concrete structures with fiber reinforced polymers (FRP) is a relatively new technique, it has existed for more than two decades. In this context, several confinement models have been developed for FRP-confined concrete for the prediction of stress–strain response and several researchers have developed various constitutive models to measure the increase in the axial strength of concrete due to the confinement effect of FRP laminates. In this study, RC columns wrapped with carbon FRP (CFRP) considering some existing confinement models in the literature have been investigated. Moreover, based on the experimental data set in the literature, a new artificial intelligence-based algorithm (a Mamdani-type fuzzy inference system) was implemented to model the strength enhancement of CFRP confined RC columns using fuzzy logic methodology. Fuzzy logic predicted results were compared with the outputs of a non-linear regression analysis-based exponential model derived in the scope of the present work. The best predictive performances of the models were assessed by means of various descriptive statistical indicators. The comparison of the proposed prognostic approach with existing empirical and experimental data exhibits a very good precision of the developed artificial intelligence-based model in predicting the lateral confinement coefficient in CFRP wrapped RC columns.

1. Introduction

In earthquake prone regions all over the world, existing reinforced concrete (RC) structures have inadequate seismic resistance due to continuously updating forms of the design requirements [1–4]. Past earthquakes demonstrated that existing buildings suffered severe damages, due to the poor seismic resistance of the structural elements such as beams, slabs, columns and shear walls. Some preliminary lessons were emphasized and discussed in light of the observed buildings performance, damage statistics and patterns of various configurations of RC construction. Hence, seismic design codes have gone through major changes over the last few decades due to the lessons learned from past major earthquakes. One of the major changes in the codes was on increasing the seismic resistance of the existing RC structures through the use of Performance-Based (PB) design principles. PB design principles allow for the utilization of strength and/or displacement ductility reserve of the structure. Many researchers have attempted to find alternative materials and techniques to strengthen the capacity of the RC beams, slabs, columns, etc. in bending and shear. For the columns under seismic loading, lateral confinement with fiber-reinforced polymer (FRP) can be implemented as a substantially efficient method in order to retrofit the plastic hinge regions of the columns having inadequate confinement. FRP wrapping method is therefore an alternative easy-to-implement retrofitting method to increase the deformation capacities and compressive strengths. The use of FRP in columns for this purpose is a relatively new technique and has been extensively used for more than two decades. In this context, many experimental and analytical investigations have been conducted in last decades to evaluate the axial load capacity and stress–strain behavior of concrete confined with FRP polymers. These investigations on RC columns have demonstrated that FRP jackets prevent premature failure of cover concrete and buckling of the steel bars and lead to enhancement of

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the axial strength and energy absorption capacity of the wrapped column under both static and cyclic loading. Several confinement models have been proposed in the literature to estimate and to assess the non-linear behavior of RC columns wrapped with FRP [5–9].

In design process, the prediction of stress–strain relations for FRP confined RC columns in an accurate and rapid manner is very crucial. In this context, several proposed analytical models have been developed for design, detailing and installation of FRP wrapped RC columns as given above. However, the variety of factors reflecting constitutive behavior of concrete, material properties of composites, effect of column size, cross-sectional geometry, and variation of confinement stiffness during loading makes the proposed models complicated and difficult to implement in computer applications. In some cases, there have been quite differences between the calculated and the obtained values obtained in predicting non-linear behavior of confined columns. Therefore, researchers also produced some new alternative methods for predicting technique using artificial intelligent analysis.

In a recent work, Tanarslan et al. [10] developed an artificial neural network (ANN) model to predict the shear capacity of RC beams strengthened with FRP reinforcements. They declared that the ANN model was more accurate than the guideline equations with respect to the experimental results. In a similar work, Naser et al. [11] investigated an alternative approach in order to predict fire resistance of RC T-beams strengthened with CFRP plates. As a result, they concluded that the developed NN model could be used as a computational tool in the analysis and design of RC beams strengthened with CFRP plates under thermal fire loadings. In another study, Mashrei et al. [12] proposed a back-propagation NN (BPNN) model considering one hundred and fifty experimental data from several sources in order to predict the bond strength of FRP-to-concrete joints. Their results indicated that the BPNN model provided an efficient method for calculating the bond strength of FRP-to-concrete joints when compared to those from existing analytical models. Moreover, Koroglu et al. [13] used single and combined artificial NNs (CANNs) in order to predict the flexural capacity of rectangular RC columns wrapped with FRP. As a result, proposed CANN model had lower prediction error than those of the single ANN model. Cevik [14] studied genetic programming (GP), stepwise regression (SR), neuro-fuzzy (NF) and single NN techniques in estimating the strength enhancement of concrete cylinders confined with FRP and results were compared with 10 models existing in the literature. Furthermore, Naderpour et al. [15] proposed a new approach to obtain the compressive strength of concrete confined with FRP using a large number of experimental data by applying ANN. The comparison of the proposed approach with existing empirical and experimental data showed good precision with the ANN-based model. Finally, Elsanadedy et al. [16] developed an ANN model and regression model for predicting of compressive strength and crushing strain of concrete wrapped with FRP. They claimed that the use of ANN in evaluating the compressive strength and crushing strain of wrapped concrete was practical.

It can be noted that modeling of highly dynamic systems in the structural engineering is very difficult because their performance is complex and varies significantly with several operational and loading conditions. Although some traditional models may give a good in-sight into the mechanism, however, they require a lot of hard work before being applied to a specific structural system. Therefore, due to their capabilities of capturing the non-linear relationships existing between variables in a complex system, artificial intelligence-based models have recently been implemented for modeling of several complex systems whose behaviors are not well understood. Potential advantages and benefits of artificial intelligence-based methods have already been highlighted by many substantial studies in the relevant literature [17–19]. Among them, fuzzy and neuro-fuzzy techniques have gained more attention over the past decade and so. They have a distinctive advantage since these models provide a transparent and systematic analysis without requiring complex formulations and tedious parameter estimation procedures [20]. Hence, fuzzy logic-based methods have recently found a wide application in modeling and controlling of various structural engineering problems [14,21–29].

To the best of the authors' knowledge, there are no systematic papers in the literature specifically devoted to a study regarding an artificial intelligence-based modeling of the lateral confinement coefficient in CFRP wrapped RC rectangular columns using the fuzzy logic technique. Although much attention has been given to the structural behavior of FRP-strengthened RC elements and structures considering the geometrical and mechanical characteristics, almost no information is available in the literature regarding the fuzzy logic-based modeling of the present structural engineering problem. Therefore, without requiring a complex model structure, detailed first principles and tedious parameter estimation procedures as conducted in the conventional confinement models, implementation of a fuzzy logic methodology may be considered as an alternative contribution for modeling the mechanical response of CFRP confined RC rectangular columns.

Consequently, based on the above-mentioned facts, it is noted that a knowledge-based prognostic modeling scheme may provide a transparent and a systematic analysis for modeling of the strength enhancement in CFRP wrapped RC rectangular columns by a set of logical connections in a speedy and practical manner. Therefore, in this paper, development of a new modeling scheme using the fuzzy logic methodology was proposed and described. Considering the non-linear nature of CFRP confined RC columns, the specific objectives of this study were: (1) to develop a fuzzy-logic-based prognostic model that could be able to predict the lateral confinement coefficient in CFRP wrapped RC rectangular columns; (2) to compare the proposed artificial intelligence-based methodology against the conventional non-linear regression-based analysis for various descriptive statistical indicators, such as coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE), index of agreement (IA) and fractional variance (FV); and (3) to verify the validity of the proposed prognostic approach by several experimental data used as the testing set.

2. Experimental data

2.1. Lateral confinement coefficient

It is well known that the lateral confinement leads to an increase in the compressive strength of concrete. A well-known relation of Richart et al. [30] can be used for expressing the compressive strength of confined concrete:

$$f'_{cc} = f'_{co} + k_1 f'_l \quad \text{or} \quad K_s = \frac{f'_{cc}}{f'_{co}} = 1 + \frac{k_1 f'_l}{f'_{co}} \tag{1}$$

where f'_l is the effective lateral confining stress (Fig. 1); f'_{cc} and f'_{co} are the compressive strength of confined and unconfined concrete, and K_s may be defined as the lateral confinement coefficient respectively.

There exist several important and accurate predictive models based on this approach for the concrete confined with FRP composite jackets in the literature [31–37]. The majority of such models have focused on the analytical representation of the behavior of concrete specimens especially with circular section adopting the approach of Richart et al. [30]. On the other hand, Saadatmanesh et al. [31], Spoelstra and Monti [35], Restapol and De Vino [38],