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Shear strength prediction of steel fiber reinforced concrete beam using hybrid intelligence models: A new approach

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A R T I C L E I N F O

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A B S T R A C T

Despite modern advancements in structural engineering, the behavior and design of reinforced concrete beams in shear are still a major concern for structural engineers. In this research, a new Support Vector Regression algorithm coupled with Particle Swarm Optimization (SVR-PSO) is developed to predict the shear strength (S_s) of steel fiber-reinforced concrete beams (SFRC) using several input combinations denoting the dimensional and material properties. The experimental test data are collected from reliable literature sources. The main variables used to construct the predictive model are related to the dimensional and material properties of the beams. SVR-PSO, the objective predictive model, is validated against a classical neural network model tuned with the same metaheuristic optimizer algorithm. The findings of the modeling study provide a clear evidence of the superior capability of the SVR-PSO used to predict the SFRC shear strength relative to the benchmark model. In addition, the construction of the predictive models with a lesser number of input data attributes are attained, leading an acceptable prediction accuracy of the SVR-PSO compared to the ANN-PSO model. In summary, the proposed SVR-PSO methodology has demonstrates an effective engineering strategy that can be applied in problems of structural and construction engineering prospective, applied to predict shear strength of steel fiber reinforced concrete beam using advanced hybrid artificial intelligence models developed in this study.

1. Introduction

Steel fibers are the most prevalent types of fibers that are used for reinforcement of concretes, known as steel fiber-reinforced concretes (SFRC) [1–3]. Several mechanical advantages have been identified as the possible merits of utilizing the SFRC as the structural components [4]. However, their dominant effect is notable in enhancing the post-cracking behavior [5]. SFRCs have been extensively used in different types of construction problems, but not in buildings that are likely due to a lack of the design provisions in the respective building codes [6,7]. SFRC beams are therefore one of the common components that have been widely studied in terms of their structural performance, and especially in their shear failures because of its complex mechanisms [8,9].

The methods for modeling the SFRC beam shear strength prediction can be categorized into experimental, analytical, numerical, and soft computing (SC) based techniques. Laboratory studies are able to exactly monitor the structural behavior, but they are very costly and time consuming, including the leftover questions, such as how to set up the materials, geometries, physical and mechanical properties, and the loading conditions that are different in many isolated studies [10–17]. Analytical methods are therefore a cost-effective way to address this issue, however, these methods are significantly based on empirical and semi-empirical approaches that can yield precise results for the range of experimental data from which they were derived, but they do not fit well when applied to the other (unseen) experimental data [8,18–20]. In this regard, a limited number of studies have been performed to develop semi-empirical [5], non-empirical, and even a range of theoretical models for the shear resistance estimation of the SFRC beams [21,22]. A numerical simulation of the SFRC beams applied to predict

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their shear resistance behavior has not been addressed adequately [23,24], mainly because the RC beams are characterized by a non-stabilized manner but the SFRC behaves as a composite material.

Over the past decade, SC approaches have been successfully implemented in the field of material and structural engineering, and especially in the area of reinforced concrete engineering [25,26]. However, a survey of the literature on the popular SC-based techniques demonstrates a lack of studies in the prediction of SFRC beam's structural performance. Adhikary and Mutsuyoshi [31] developed two different ANN-based models with four and five input parameters using historical experimental beams data set. The study, followed by another attempt conducted by [27] where the authors have used the ANN model for the presumption of the shear strength of the SFRC beams considering 5 input parameters (i.e., steel fiber blend ratio, aspect ratio, reinforcement ratio, effective depth, and ratio between the shear length and depth). Recently, a set of 173 SFRC beams without stirrups, having concrete compressive strength ranging from 20.6 to 175 MPa (as medium-strength, high-strength and ultra-high-strength concrete), and steel fiber of various shapes (hooked, crimped and straight/plain), is used to develop an ANN model [28]. ANNs have also been used in some of the other studies with an emphasis on investigating the influence of some of the input parameters [29–31], and predicting the mechanical properties of SFRC [32,33].

A linear genetic programming-based model has been developed by [34] using total of 213 data sets and 9 input parameters. Several models were developed by considering different combinations of the 9 input parameters, and the best model, based on a multi-objective strategy, was presented with four parameters. Genetic programming has also been recently used by [35] for this problem. This was conducted using linear and non-linear regression analyses with a total of 5 input parameters, resulting in the development of six models after dividing a set of 222 experimental dataset into six groups [36]. The study of Kara [37] proposed an empirical equation based on the gene expression programming using a total of 101 datasets and considering their 5 different input attributes. Both multiple linear regression models and principal component regression models have also been established using a total of 222 experimental dataset [38]. Utilizing multi-expression programming [39], two new equations for normal and high strength SFRC beams proposed based on 104 data sets for each one and a new equation without categorizing the strength of concrete using all 208 data sets. Very recently a genetic-algorithm-based approach was used to simplify the proposed analytical models from existing experimental results of 222 SFRC beams without stirrups [40].

Studies in published literature has revealed that the utilization of SC-based techniques for predicting the complex systems always raises two problems: first is the transformation of all the information into numerical input parameters to feed the technique, which is a key pre-process step in any SC based modeling, and second is the need to find the best topology of the technique that can be used to address the prediction problem [41]. Based on a review of the published literature of SC-based techniques, these two problems have become quite evident.

In this study, we propose a new coupled data-intelligent model using the vector regression integrated with Particle Swarm Optimization algorithm for the prediction of shear strength of steel fiber-reinforced concrete beams. Seven input variables are used as the feature attribute combinations where the input data representing the attributes defined by reinforcement ratio ($\rho\%$), concrete compressive strength (f_c'), fiber factor (F_1), volume percentage of fiber (V_f), fiber length to diameter ratio (l_f/l_d), effective depth (d), and shear span-to-strength ratio (a/d) are applied and the shear strength (S_s) is the output (target) matrix. The defined variables are demonstrated on the free-body diagram as shown in Fig. 1. An input approximation technique is applied to firstly reduce the most suitable input matrix to generate a computationally efficient and an accurate artificial intelligence model trained with a small number of input variables. The models based on the proposed SVR-PSO method is then validated in respect to a hybrid

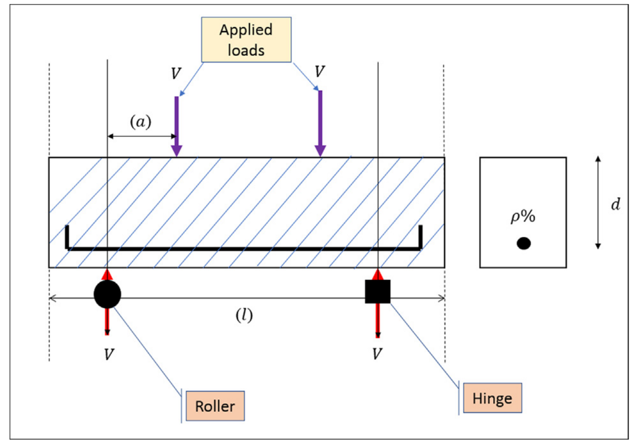

Fig. 1. The general description of physical properties of steel fiber reinforced concrete beam.

Artificial Neural Network model integrated with the Particle Swarm Optimization algorithm (ANN-PSO) to create a comparative framework with the hybrid SVR-PSO model. By extensive analysis of predicted and measured dataset in the independent testing phase, the work therefore, aims to generate a robust and a reliable soft computing tool that can be used for predicting the *Ss* with a high level of accuracy to support key engineering decisions made in structural design engineering.

In the next section, a brief overview of the mathematical framework and the methodology is presented, while the third section present the investigated experimental dataset. The application, analysis and discussion of the proposed hybrid SVR-PSO model is presented in Section 4 and the last section presents the conclusions and closing remarks of this study.

2. Methodology overview and model development

2.1. Support Vector Regression (SVR)

Among the several artificial intelligences, soft computing models used in the field of engineering and science, the SVM model is the most popular version of all data-driven models due to its ability to solve classification and regression problems and its ability to attain a global-optima rather than getting trapped in a local maxima/minima issue [25]. Relevant to the investigated problem in this study, the regression problem was formulated by a dataset of the form $\{x_i, y_i\}$. The SVR regression formulation can therefore be expressed as [42]:

$$f(x) = w\varphi(x) + b \quad (1)$$

The optimization of this regression function [43] can be obtained using:

$$Minimum \quad 0.5\,\|w\|^2 + C\sum_{i=1}^{n}(\xi_i + \xi_i^*) \quad (2)$$

and is subjected to the following conditions [42]:

$$\left\{\begin{matrix} y_i - w\varphi(x_i) - b \le \varepsilon + \xi_i \\ -y_i - w\varphi(x_i) + b \le \varepsilon + \xi_i^*, \quad i = 1, 2, \cdots, n \\ \xi_i,\ \xi_i^* \ge 0 \end{matrix}\right\} \quad (3)$$

where w and b = the undetermined paraments, φ = the non-linear transfer function, ε = the loss function, C = regularization parameter, ξ_i, ξ_i^*: slack parameters.

In this paper, a Radial Basis Function (RBF) has been used as a kernel equation to transform the non-linear problem to a linear problem as described below [44]: