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Evolutionary multivariate adaptive regression splines for estimating shear strength in reinforced-concrete deep beams

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ABSTRACT

This study proposes a novel artificial intelligence (AI) model to estimate the shear strength of reinforced-concrete (RC) deep beams. The proposed evolutionary multivariate adaptive regression splines (EMARS) model is a hybrid of multivariate adaptive regression splines (MARS) and artificial bee colony (ABC). In EMARS, MARS addresses learning and curve fitting and ABC implements optimization to determine the optimal parameter settings with minimal estimation errors. The proposed model was constructed using 106 experimental datasets from the literature. EMARS performance was compared with three other data-mining techniques, including back-propagation neural network (BPNN), radial basis function neural network (RBFNN), and support vector machine (SVM). EMARS estimation accuracy was benchmarked against four prevalent mathematical methods, including ACI-318 (2011), CSA, CEB-FIP MC90, and Tang's Method. Benchmark results identified EMARS as the best model and, thus, an efficient alternative approach to estimating RC deep beam shear strength.

1. Introduction

Because shear stress is the primary failure mode of reinforce-concrete (RC) deep beams (Mansour et al., 2004), the behavior and design of these beams in shear mechanism is an area of concern for structural engineers. Furthermore, because concrete structures are fragile, shear failure in the plain concrete members of these structures may cause sudden structural collapse. Avoiding high-risk failure modes is thus a priority objective for civil engineers (Amani and Moeini, 2012). Based on the above, the ability to accurately estimate the shear strength of RC deep beams is critical to the safe and widespread application of these beams in construction projects.

Technical manuals published by the American Concrete Institute (ACI) (ACI-318, 2008), Canadian Standard Association (CSA) (CSA, 1994), and Construction Institute Research and Information Association (CIRIA Guide 2) (CIRIA-Guide2, 1977) provide standardized methods for calculating the ultimate shear strength of RC deep beams. However, calculated values are conservative in light of experimental tests (Pal and Deswal, 2011; Tan et al., 1997; Teng et al., 1998) due to the large number of influencing parameters and the potentially nonlinear relationships between these parameters and shear strength. The inherent complexity of these relationships limits designer ability to assess shear strength and has made it difficult to establish a mathematical model able to accurately estimate shear strength (Amani and Moeini, 2012). Thus, there is no analytical model that accurately estimates RC deep beam shear strength (Appa and Sundaresan, 2012).

The artificial intelligence (AI) inference model is a potentially advantageous alternative approach to RC deep beam shear strength estimation. AI simulates the human inference processes, inferring new facts from previously acquired information and changing adaptively in response to changes in historical data. Tsai (2011) stated that AI technique delivered a high level of strength estimation accuracy. The present study thus employs multivariate adaptive regression spline (MARS) to construct a proposed model able to accurately estimate the shear strength of RC deep beams and account for the effects of many of the parameters deemed by researchers to impact on RC deep beam shear strength (Mansour et al., 2004).

MARS is a nonlinear, non-parametric regression methodology (Friedman, 1991). MARS' greatest advantage is its ability to explore the complex nonlinear relationships between a response variable and predictor variables. Additionally, MARS has the ability to determine the input parameters that impact significantly on the response. MARS has been demonstrated particularly effective in handling prediction problems and successfully employed in credit scoring (Lee et al., 2006), computer wholesaling (Lu et al., 2012), paper manufacturing (García et al., 2012), public water supply issues (Vidoli, 2011), and engineering software (Zhou and Leung, 2007). Many studies have further demonstrated the superiority of MARS over other data techniques (Leathwick et al., 2006; Samui, 2012).

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However, it is surprising that MARS has not yet been applied to problems in the field of structural engineering.

Building a MARS model requires users select tuning parameters that include maximum number of basis functions M_{max}, penalty (i.e., smooth parameter) d and maximum interaction between variables I_{max}. These parameters are considered as important features in controlling MARS model complexity and generalization (Andalib and Atry, 2009). Therefore, obtaining an optimal MARS parameter set is crucial to achieving MARS prediction accuracy. Friedman's prior parameter selection suggestions have large value ranges, with actual selected values dependent on the dataset at hand (Friedman, 1991).

To overcome this drawback of MARS, our paper used the ABC (Karaboga, 2005) algorithm as a search engine to determine optimal MARS parameter values. ABC was introduced by Karaboga in 2005 and is a swarm intelligence-based optimization algorithm inspired by honeybee foraging behavior. Its relatively small number of control parameters makes ABC flexible and easy to execute for novice users (Li et al., 2011). Various works have demonstrated the comparative superiority of ABC over other algorithms in identifying optimal solutions (Karaboga and Akay, 2009; Li et al., 2010). ABC is also a reliable tool when paired with other data mining techniques (Hong, 2011). ABC is thus a potentially suitable search engine for identifying suitable MARS parameters such as M_{max}, d and I_{max}.

The objective of this research was to develop and test the evolutionary multivariate adaptive regression splines (EMARS). The authors created EMARS by fusing MARS and ABC in a manner that incorporated the strengths and avoided the weaknesses of each technique. This newly proposed model operates automatically without human intervention and accurately estimates the shear strength of RC deep beams under various parameter settings. This study then compared the performance of EMARS against three other benchmark data mining techniques, including back-propagation neural network (BPNN), radial basis function neural network (RBFNN), and support vector machine (SVM).

The remainder of this paper is organized as follows: the second section reviews related research works; the third introduces the EMARS model; the fourth describes the data collection process; the fifth validates the EMARS model and compares simulations results; and the last presents conclusions.

2. Literature review

2.1. Previous works

There is increasing research interest in applying AI techniques to problems related to RC deep beam shear strength. Numerous studies have proposed approaches to modeling the shear strength of RC deep beams and analyzing the influence of input parameters. Goh (1995) first used ANN to predict the ultimate shear strength of RC deep beams with six input parameters. The author stated that ANN could provide predicted values close to test values. Sanad and Saka (2001) tested ANN's effectiveness in predicting the ultimate shear strength of RC deep beams with output response derived using nine input parameters. The study demonstrated that ANN outperformed several mathematical approaches, including ACI (ACI-318, 1995), Strut-and-Tie (Siao, 1993), and Mau and Hsu's method (Mau and Hsu, 1989).

Yang et al. (2007) also studied ANN's ability to predict RC deep beam shear capacity. Ashour et al. (2003) used genetic programming to model RC deep beam shear strength and derived mathematical formulae that indicated the shear-span-to-effective-beam-depth ratio and main-longitudinal-bottom-reinforcement ratio as the most significant parameters. Pal and Deswal (2011) recently applied the SVM to model RC deep beam shear strength using nine input parameters. Study results found SVM superior to ANN and ACI (ACI-318, 2004).

Previous studies have generally applied similar ANN and GP techniques with only minor modifications and the inclusion of some traditional techniques. This may represent a shortcoming of applying AI to the shear strength problem. The significant disadvantage of ANN is the need to select a large number of controlling parameters to construct the network, e.g., number of hidden layers, number of neurons in hidden layers, learning rate, and momentum (Samarasinghe, 2006).

This means that the ANN training process must be obtained via a gradient descent algorithm on the error space, which may be very complex and contain many local solutions that may prevent an ANN model from converging on an optimal solution (Kiranyaz et al., 2009). Additionally, ANN does not represent an explicit relationship between input and output parameters or even indicate the relative importance of each input variable.

Although Pal and Deswal (2011) assessed SVM as superior to ANN in estimating RC deep beam shear strength, SVM does not help construct a mathematical formulae for shear strength. In other words, SVM cannot indicate the relative importance of each input variable either. As for GP, this method does not perform a proper numerical estimation of model parameters (constants/coefficients). This tends to yield functions that grow in length during the evolutionary search phase (Davidson et al., 2003), potentially creating a final model that is impractically large and difficult to interpret. Similar to ANN and SVM, GP also does not indicate the relative importance of variables.

2.2. Multivariate adaptive regression splines

MARS was first proposed by Friedman (1991) as a flexible procedure to organize relationships that are nearly additive or involve interactions with fewer variables. MARS makes no assumptions about the underlying functional relationship between dependent and independent variables in order to estimate the general functions of high-dimensional arguments given sparse data (Friedman, 1991; Samui, 2012). One further advantage of MARS is its ability to estimate the contributions of basis functions so that the additive and interactive effects of predictors are allowed to determine the response variable.

MARS is established by fitting a basis function (term) to distinct independent variable intervals. In general, splines (also called piecewise polynomials) have pieces that connect smoothly together. The interface points between pieces are called knots, denoted as t. MARS uses two-sided truncated power functions as spline basis functions, described in Eqs. (1) and (2). Fig. 1 ($q=1$; $t=0.5$) provides an illustration

$$[-(x_v - t)]_+^q = \begin{cases} (t-x_v)^q & \text{if} \quad x_v < t \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

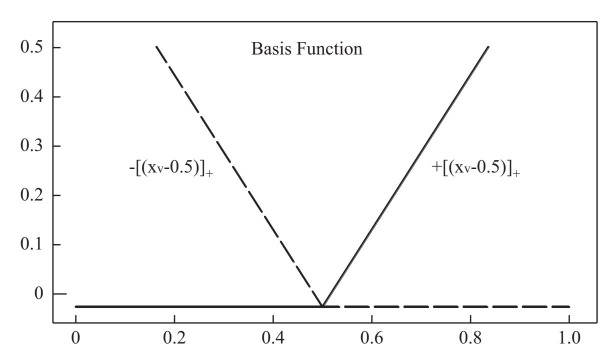

Fig. 1. Basis function.