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Moment-rotation prediction of precast beam-to-column connections using extreme learning machine

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Abstract. The performance of precast concrete structures is greatly influenced by the behaviour of beam-to-column connections. A single connection may be required to transfer several loads simultaneously so each one of those loads must be considered in the design. A good connection combines practicality and economy, which requires an understanding of several factors; including strength, serviceability, erection and economics. This research work focuses on the performance aspect of a specific type of beam-to-column connection using partly hidden corbel in precast concrete structures. In this study, the results of experimental assessment of the proposed beam-to-column connection in precast concrete frames was used. The purpose of this research is to develop and apply the Extreme Learning Machine (ELM) for moment-rotation prediction of precast beam-to-column connections. The ELM results are compared with genetic programming (GP) and artificial neural network (ANN). The reliability of the computational models was accessed based on simulation results and using several statistical indicators.

Keywords: moment-rotation; forecasting; extreme learning machine; precast beam-to-column connection; partly hidden corbel

1. Introduction

1.1 General

Precast concrete construction method is being widely applied in construction industry. Improvement of the design for these connections are of interest for their better performance. Many researchers have been conducted recently by the authors in order to improve the design of structural members for their better performance like connections with composite beams (Shariati *et al.* 2010, Shariati *et al.* 2011a, Shariati *et al.* 2011b, Shariati *et al.* 2012a, Shariati *et al.* 2012b, Shariati *et al.* 2012c, Khorramian *et al.* 2015, Shariati *et al.* 2015, Vo-Duy *et al.* 2015, Shahabi *et al.* 2016a, Shahabi *et al.* 2016b, Shariati *et al.* 2016, Tahmasbi *et al.* 2016, Khorramian *et al.* 2017, Mansouri *et al.* 2017, Shariati *et al.* 2017, Vo-Duy *et al.* 2017, Ho-Huu *et al.* 2018, Hosseinpour *et al.* 2018, Nasrollahi *et al.* 2018, Paknahad *et al.* 2018, Sedghi *et al.* 2018, Vo-Duy *et al.* 2018, Wei *et al.* 2018, Davoodnabi *et al.* 2019), steel rack connections (Shah *et al.* 2015, Shah *et al.* 2016a, Shah *et al.* 2016b, Shah *et al.* 2016c, Shariati *et al.* 2018, Chen *et al.* 2019), through beam conneaction (Arabnejad Khanouki *et al.* 2011, Arabnejad Khanouki *et al.* 2016, Abedini *et al.* 2017, Abedini *et al.* 2019).

From a survey of available literature, precast concrete can be defined as concrete, which is cast in some location other than its position in the finished structure (Farah *et al.* 2004). In general, precast concrete can be categorized into three basic structural forms which are skeletal frame system, load bearing wall system and cell system (Mohammadhassani *et al.* 2014, Mohammadhassani *et al.* 2015). A skeletal frame system is achieved by connecting precast columns and beams together with precast flooring/roofing elements supported by the beams. While, the load bearing wall system is solid, sandwich or perforated precast concrete panels that can efficiently carry the vertical loads as well as the horizontal loads as shown in Fig.1. A cell system is the structure consists of a number of precast cell units, which are connected to build the structure (Trikha *et al.* 2004).

The design and construction of joints and connections is vital part in precast concrete structures due to their role to transmit forces between structural elements to provide

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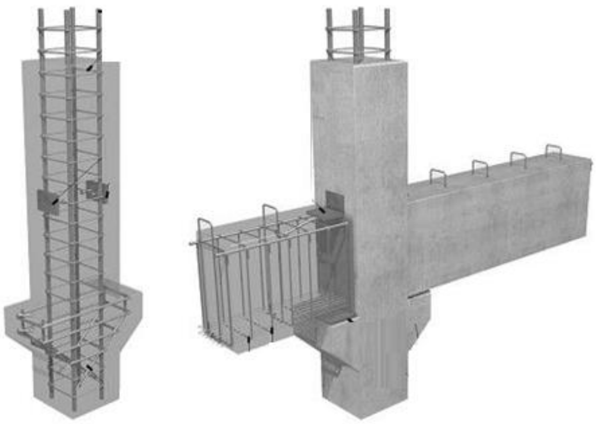

Fig. 1 General shape of proposed connection

stability and robustness (Elliott 2002, Abedini *et al.* 2017, Zhao *et al.* 2018).

The performance of precast concrete structures is greatly influenced by the behavior of beam-to-column connections (Abedini *et al.* 2019). A single connection may be required to transfer several loads simultaneously so each one of those loads must be considered in the design. A good connection combines practicality and economy, which requires an understanding of several factors; including strength, serviceability, erection and economics. This research work focuses on the performance aspect of precast beam-to-column connection. In this study application of soft computing method means Artificial Neural Network (ANN) for prediction of moment and rotation in precast beam to column connection has been used. The main objective of this study is to find out the most influential factors for moment-rotation prediction of this precast beam-to-column connections.

The main classification of connection and its behavior can be defined by moment-rotation (M-ϕ) characteristic. The ANN can be used as an alternative to the analytical approach as ANN offers advantages such as no required knowledge of internal system parameters, compact solution for multi-variable problems. The application of such analytical tools has been used by the authors in many research recently (Hamidian *et al.* 2012, Toghroli *et al.* 2014, Aghakhani *et al.* 2015, Mohammadhassani *et al.* 2015, Toghroli 2015, Mansouri *et al.* 2016, Safa *et al.* 2016a, Safa *et al.* 2016b, Toghroli *et al.* 2016, Khorami *et al.* 2017, Mansouri *et al.* 2017, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Shariat and Shariati 2018, Toghroli *et al.* 2018, Zandi *et al.* 2018, Mehrmashhadi *et al.* 2019b).

Extreme Learning Machine (ELM) as a strong tool of ANN has been introduced as a soft computing algorithm for single layer feed forward neural network (NN) (El Debs *et al.* 2005). It is capable to solve problems caused by gradient descent based algorithms like back propagation which applies in artificial neural networks (ANNs) and to decrease required time for training NN. It has been proved that by utilizing the ELM, learning becomes very fast and it produces good generalization performance (Wang *et al.* 2018). It has been widely utilized for the estimation of

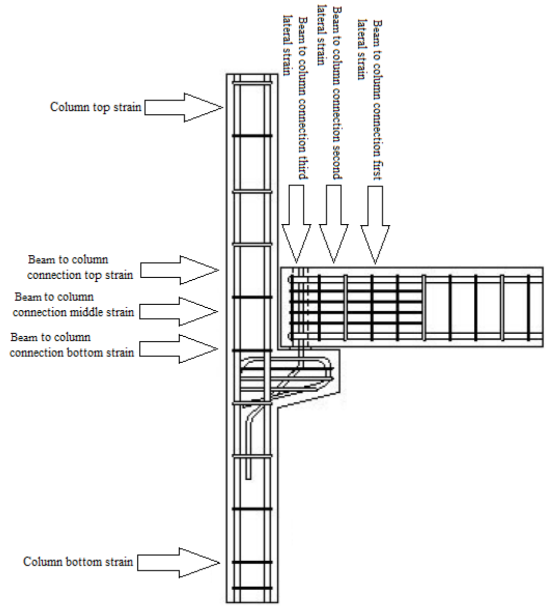

Fig. 2 Schematic diagram for location of LVDTs

problems in many different fields of water resources and has potential applications in the newly emerged metamaterial field applications where large data libraries are needed, or where using differential calculus is hindered by complicated cost functions and coupling between parameters involved, as has been shown, for instance, inpantographic metamaterials (Nejadsadeghi *et al*. 2019) and granular metamaterials (Nejadsadeghi *et al*. 2019).

In this investigation the main goal is to anticipate the moment-rotation prediction of precast beam-to-column connections using ELM approach and the primary objective is to analyze the moment-rotation based on eight LVDT values.

2. Methodology

2.1 Data collection

The main aim of the full scale test is to determine the moment-rotation of the connection (Cheok and Lew 1991, Cheok and Lew 1993, Stone *et al*. 1995) to prevent any failure (Bobaru *et al*. 2018, Mehrmashhadi *et al*. 2019a, Mehrmashhadi *et al*. 2019c). From these M-ϕ characteristics, it will be possible to abstract the hogging moment capacity, rotational stiffness and ductility of the connection. Besides, the load-displacement relationship, stress distribution and shape deformation can be obtained. The results of test on several specimens were used from the literature (Birkeland and Birkeland 1966, Cheok and Lew 1991, Cheok and Lew 1993, Stone *et al*. 1995, Alcocer *et al*. 2002, Choi *et al*. 2013). The reading of linear displacement transducers (LVDT) have been used. All signals from the sensors were automatically recorded and linked to a computer using data logger. The respective calibration factors for the various sensors were inputting into data logger to linearize the signals. The logged data was transferred and processed using Excel Software 2010.

Table 1 Input and output parameters

Inputs	Parameters description
input 1	Column top strain
input 2	Beam to column connection top strain
input 3	Beam to column connection middle strain
input 4	Beam to column connection bottom strain
input 5	Column bottom strain
input 6	Beam to column connection first lateral strain
input 7	Beam to column connection second lateral strain
input 8	Beam to column connection third lateral strain
output	Moment-rotation prediction of precast beam-to-column connections

2.2 Moment-rotation relationship

From the testing of beam-to-column connections, the value of moment is gained by multiplying the corresponding applied point load with the distance of the point load from the surface of the column. While for rotation, the value is obtained by dividing the corresponding vertical displacement with the distance of the LVDT from the surface of the column (Elliott 2002). The LVDT readings are used in this study to obtain the statistical data to be used in ELM. The location of all LVDTs are shown in Fig. 2.

2.3 Statistical data

Table 1 shows input and output parameters which are used in this investigation. All percentage numbers are converted in decimal numbers during the soft computing training procedure.

2.4 Extreme learning machine

Extreme Learning Machine (ELM) as a novel learning algorithm for single hidden layer feed forward networks (SLFNs).

This approach has some priority compared with conventional neural networks including: 1) ELM is easy to use, and its usage increment not only makes the learning extremely fast but also produces good generalization performance (Yang and Ashour 2011, Bashir and Ashour 2012, Ashour and Kara 2014); 2) in conventional neural networks all the parameters of the networks such as learning rate, learning epochs and local minima are tuned iteratively by using such learning algorithms; 3) ELM can be easily implemented and can obtain the smallest training error and the smallest norm of weights (Rahmaninezhad *et al.* 2009, Weldu *et al.* 2016, Yasrobi *et al.* August 3-6, 2009).

In Fig. 3 the schematic topological structure of ELM network is shown. For M arbitrary samples $(\mathbf{x}_i, \mathbf{t}_i)$, in which $\mathbf{x}_i = [x_{i1}, x_{i2}, \ldots, x_{in}]^T \in \mathbf{R}^n$ and $\mathbf{t}_i = [t_{i1}, t_{i2}, \ldots, t_{in}]^T \in \mathbf{R}^m$, standard single hidden layer feed forward networks (SLFNs) with N hidden nodes and activation function $g(x)$ are modeled as follows:

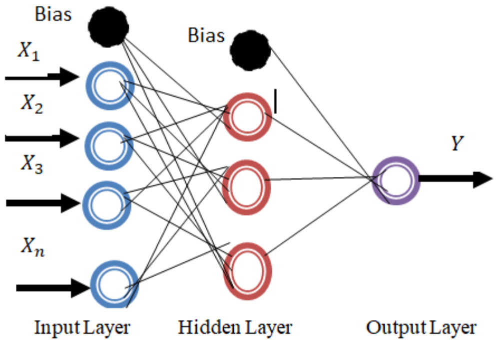

Fig. 3 The topological structure of the extreme learning machine network used in this study

$$\sum_{i=1}^{M}\beta_i g_i(\mathbf{x}_j)=\sum_{i=1}^{M}\beta_i g(w_i.x_j+b_i)=o_j,\ j=1,\ldots,N \tag{1}$$

where $w_i = [w_{i1}, w_{i2}, \ldots, w_{in}]^T$ is the weight vector between input and hidden nodes, $\beta_i = [\beta_{i1}, \beta_{i2}, \ldots, \beta_{in}]^T$ is the weight vector between output and hidden nodes, and b_i is the threshold of the ith hidden node. That standard single hidden layer feed forward networks with M hidden nodes with activation function $g(x)$ as follows:

$$\sum_{i=1}^{M}\beta_i g(w_i.\mathbf{x}_j+b_i)=\mathbf{t}_j,\ j=1,\ldots,N. \tag{2}$$

These equations can be written as follows:

$$\mathbf{H}\beta=\mathbf{T} \tag{3}$$

where

$$\mathbf{H}=\begin{bmatrix} g(w_1.\mathbf{x}_1+b_1) & \cdots & g(w_M.\mathbf{x}_1+b_M) \\ \vdots & \cdots & \vdots \\ g(w_1.\mathbf{x}_N+b_1) & \cdots & g(w_M.\mathbf{x}_N+b_M)\end{bmatrix}_{N*M}$$

$$\beta=\begin{bmatrix}\beta_1^T\\ \vdots \\ \beta_M^T\end{bmatrix}_{M*m} \text{ and } \quad T=\begin{bmatrix}t_1^T\\ \vdots \\ t_M^T\end{bmatrix}_{N*m}.$$

where $\mathbf{H}$ is the hidden layer output matrix on neural network. The output weights can be constructed by finding least square solutions mentioned equation which the result represents the following equation:

$$\beta=\mathbf{H}^{\dagger}\mathbf{T} \tag{4}$$

where $\mathbf{H}^{\dagger}$ is the Moore–Penrose generalized inverse of the hidden layer output matrix $\mathbf{H}$.

2.5 Models performance evaluation

Predictive performances of the proposed models were presented as the root means square error (RMSE), coefficient of determination (R^2) and Pearson coefficient

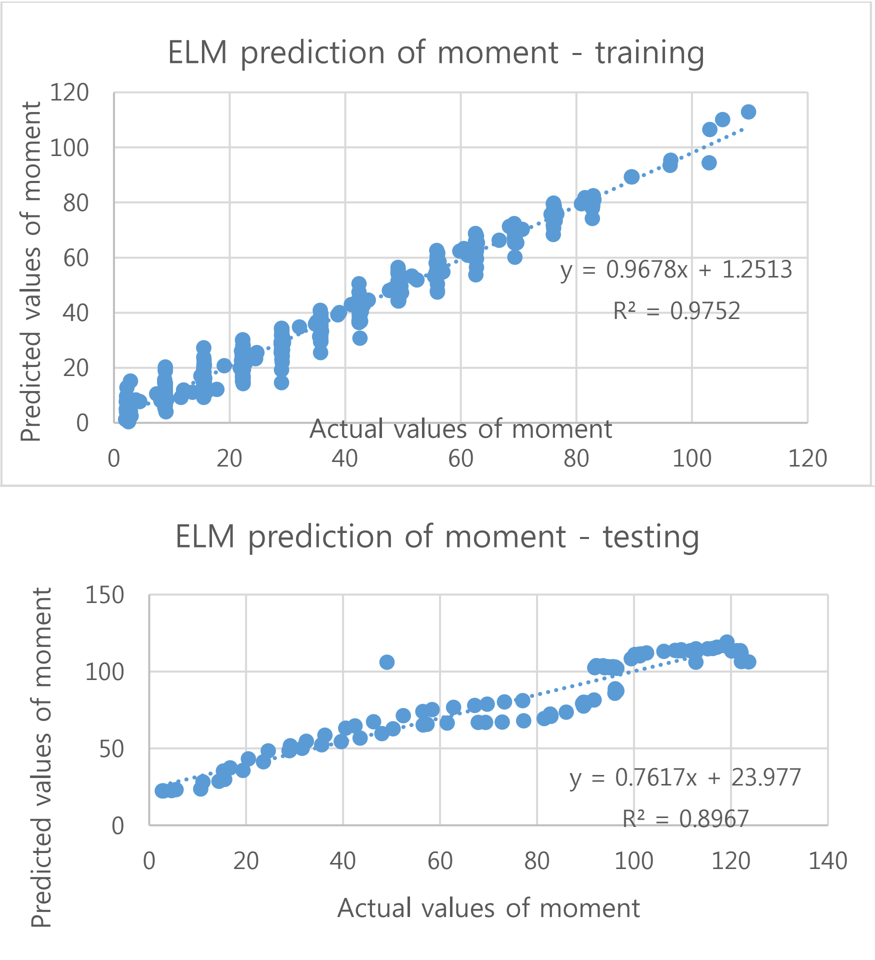

Fig. 4 Scatter plots of actual and forecasted values of moment using ELM approach

(r). These statistics are defined as follows:

1) Root-mean-square error (RMSE),
2) Pearson correlation coefficient (r),
3) Coefficient of determination (R^2)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{5}$$

$$r = \frac{n\left(\sum_{i=1}^{n} O_i \cdot P_i\right) - \left(\sum_{i=1}^{n} O_i\right)\cdot\left(\sum_{i=1}^{n} P_i\right)}{\sqrt{\left(n\sum_{i=1}^{n} O_i^2 - \left(\sum_{i=1}^{n} O_i\right)^2\right)\cdot\left(n\sum_{i=1}^{n} P_i^2 - \left(\sum_{i=1}^{n} P_i\right)^2\right)}} \tag{6}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O_i}\right)\cdot\left(P_i - \overline{P_i}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \overline{O_i}\right)\cdot\sum_{i=1}^{n}\left(P_i - \overline{P_i}\right)} \tag{7}$$

Here, O_i and P_i represent the forecast and experimental values, respectively and n denotes the sum of test data.

3. Results and discussion

3.1 Performance analysis

In this section, performance results of the ELM predictive model are reported for moment forecasting based on the given set of inputs of LVDT values. The same procedures have been used for rotation prediction as well. Fig. 4 presents the accuracy of the developed ELM predictive model for moment for training and testing data. The prediction accuracy is acceptable for this data. It can be seen that most of the points fall along the diagonal line. It follows that the prediction results are in very good agreement with the measured values for the ELM method. This observation can be confirmed with acceptable value for the coefficient of determination. The number of overestimated or underestimated values is limited. Consequently, it is obvious that the predicted values enjoy high level of precision. Fig.s 5 and 6 presents forecasting accuracy for the moment for the ANN (Petković *et al.* 2012) and GP (Jalal *et al.* 2013) methods. Based on the results one can see the better forecasting accuracy with ELM than ANN and GP results.

3.2 Performance comparison of ELM, ANN and GP

In order to demonstrate the merits of the proposed ELM approach on a more definite and tangible basis, the ELM

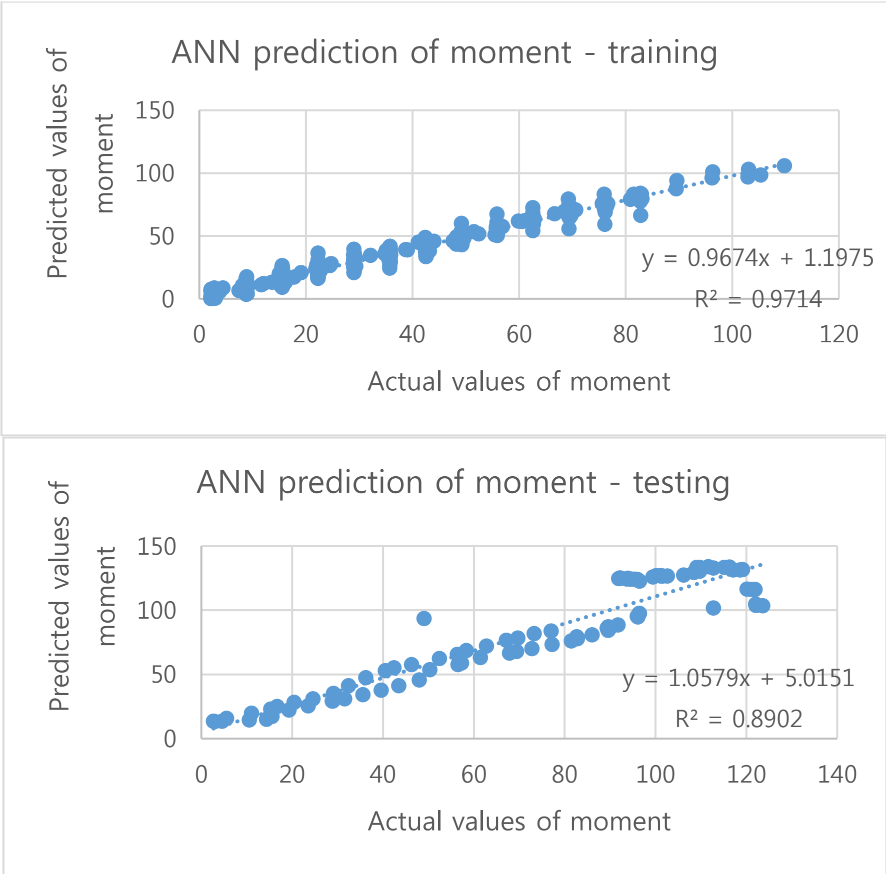

Fig. 5 Scatter plots of actual and forecasted values of moment using ANN approach

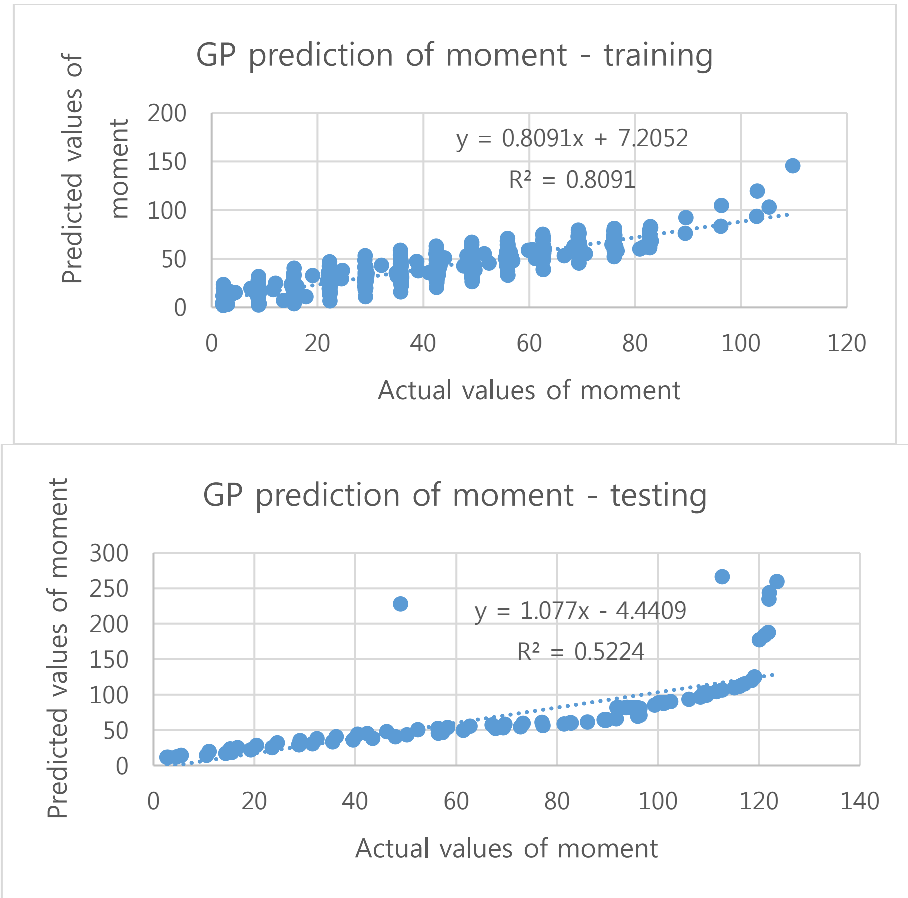

Fig. 6 Scatter plots of actual and forecasted values of moment using GP approach

Table 2 Comparative performance statistics of the ELM, ANN and GP models for moment prediction

ELM (training)			ANN (training)			GP (training)		
RMSE	R^2	r	RMSE	R^2	r	RMSE	R^2	r
3.821438	0.9752	0.987504	4.095255	0.9714	0.985611	10.58304	0.8091	0.899483
ELM (testing)			ANN (testing)			GP (testing)		
RMSE	R^2	r	RMSE	R^2	r	RMSE	R^2	r
13.95208	0.8967	0.946943	16.17926	0.8902	0.943494	36.40935	0.5224	0.722751

models' prediction accuracy was compared to the prediction accuracy of the GP and ANN methods, which were used as benchmarks. The conventional statistical error indicators (RMSE, r and R^2) were used for comparison. Table 2 summarizes the forecasting accuracy results for the dataset of the moment prediction. More relavent data is presented in the appendix A1.

4. Conclusions

In this research, connections were examined for structural performance as measured by forces and displacements from which the moment-rotations were calculated in beam-to-column connection. The size of the members and the reinforcement of the precast column and beam and their strength were chosen to simulate an actual building frame as close as possible. In present study, we describe the moment-rotation prediction of precast beam-to-column connections using the ELM method.

An efficient learning model based upon ELM was developed to estimate the moment-rotation. Accuracy level of predicted values was assessed in comparison to ANN and GP results. The simulation results revealed that ELM model is able to predict moment-rotation favorably so that it provides the most accurate predictions. The ELM algorithm can generally be effectively utilized in moment-rotation prediction of precast beam-to-column connections.

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Appendix A1: Input parameters influence on forecasting of the moment

ELM model 1: in1 in2 --> trn=12.5785, chk=13.6762
ELM model 2: in1 in3 --> trn=11.6324, chk=12.6581
ELM model 3: in1 in4 --> trn=16.3801, chk=17.4344
ELM model 4: in1 in5 --> trn=17.1769, chk=17.5111
ELM model 5: in1 in6 --> trn=16.1984, chk=15.7400
ELM model 6: in1 in7 --> trn=18.4940, chk=19.1200
ELM model 7: in1 in8 --> trn=12.2865, chk=17.2781
ELM model 8: in2 in3 --> trn=12.4943, chk=13.7291
ELM model 9: in2 in4 --> trn=12.9177, chk=13.8692
ELM model 10: in2 in5 --> trn=12.2958, chk=13.1229
ELM model 11: in2 in6 --> trn=11.1645, chk=12.0501
ELM model 12: in2 in7 --> trn=12.1043, chk=13.2405
ELM model 13: in2 in8 --> trn=13.3053, chk=13.7270
ELM model 14: in3 in4 --> trn=10.2682, chk=12.1377
ELM model 15: in3 in5 --> trn=11.2658, chk=12.6731
ELM model 16: in3 in6 --> trn=10.3824, chk=11.4004
ELM model 17: in3 in7 --> trn=11.4482, chk=12.6454
ELM model 18: in3 in8 --> trn=13.4138, chk=14.1414
ELM model 19: in4 in5 --> trn=14.0615, chk=14.9922
ELM model 20: in4 in6 --> trn=11.9752, chk=12.9596
ELM model 21: in4 in7 --> trn=18.7101, chk=20.1260
ELM model 22: in4 in8 --> trn=12.8843, chk=13.9062
ELM model 23: in5 in6 --> trn=19.7760, chk=19.8088
ELM model 24: in5 in7 --> trn=12.7790, chk=13.8123
ELM model 25: in5 in8 --> trn=10.3981, chk=11.7087
ELM model 26: in6 in7 --> trn=11.3851, chk=11.5566
ELM model 27: in6 in8 --> trn=10.7070, chk=12.1760
ELM model 28: in7 in8 --> trn=11.2776, chk=11.5497

ELM model 1: in1 in2 in3 --> trn=7.7615, chk=10.8486
ELM model 2: in1 in2 in4 --> trn=8.5257, chk=16.4160
ELM model 3: in1 in2 in5 --> trn=7.6815, chk=26.1534
ELM model 4: in1 in2 in6 --> trn=8.4540, chk=9.9442
ELM model 5: in1 in2 in7 --> trn=8.9667, chk=30.3173
ELM model 6: in1 in2 in8 --> trn=8.0014, chk=12.5318
ELM model 7: in1 in3 in4 --> trn=8.1441, chk=17.6608
ELM model 8: in1 in3 in5 --> trn=9.0970, chk=22.4466
ELM model 9: in1 in3 in6 --> trn=8.6841, chk=11.0785
ELM model 10: in1 in3 in7 --> trn=9.0009, chk=14.2191
ELM model 11: in1 in3 in8 --> trn=8.2041, chk=18.6048
ELM model 12: in1 in4 in5 --> trn=10.6454, chk=21.2779
ELM model 13: in1 in4 in6 --> trn=8.3171, chk=14.9738
ELM model 14: in1 in4 in7 --> trn=10.3563, chk=14.7847
ELM model 15: in1 in4 in8 --> trn=8.8106, chk=9.6838
ELM model 16: in1 in5 in6 --> trn=11.3169, chk=12.0196
ELM model 17: in1 in5 in7 --> trn=10.8222, chk=20.8945
ELM model 18: in1 in5 in8 --> trn=8.7800, chk=22.6351
ELM model 19: in1 in6 in7 --> trn=10.1286, chk=16.0180
ELM model 20: in1 in6 in8 --> trn=9.4155, chk=13.7086
ELM model 21: in1 in7 in8 --> trn=9.3561, chk=20.3966
ELM model 22: in2 in3 in4 --> trn=8.6823, chk=11.9726
ELM model 23: in2 in3 in5 --> trn=8.4046, chk=22.4343
ELM model 24: in2 in3 in6 --> trn=8.1556, chk=13.8159
ELM model 25: in2 in3 in7 --> trn=8.0223, chk=16.8075
ELM model 26: in2 in3 in8 --> trn=10.7009, chk=13.0352
ELM model 27: in2 in4 in5 --> trn=9.0319, chk=16.9290
ELM model 28: in2 in4 in6 --> trn=9.0924, chk=9.4151
ELM model 29: in2 in4 in7 --> trn=8.1110, chk=12.8398
ELM model 30: in2 in4 in8 --> trn=7.9588, chk=25.7814
ELM model 31: in2 in5 in6 --> trn=9.2520, chk=14.5523
ELM model 32: in2 in5 in7 --> trn=9.2734, chk=11.7064
ELM model 33: in2 in5 in8 --> trn=7.9096, chk=17.6289
ELM model 34: in2 in6 in7 --> trn=8.0191, chk=27.7637
ELM model 35: in2 in6 in8 --> trn=6.8355, chk=11.8562
ELM model 36: in2 in7 in8 --> trn=7.2347, chk=11.0409
ELM model 37: in3 in4 in5 --> trn=8.1496, chk=26.3057
ELM model 38: in3 in4 in6 --> trn=8.1349, chk=8.9678
ELM model 39: in3 in4 in7 --> trn=7.8301, chk=16.4187
ELM model 40: in3 in4 in8 --> trn=8.4264, chk=16.4583
ELM model 41: in3 in5 in6 --> trn=9.4215, chk=11.0076
ELM model 42: in3 in5 in7 --> trn=8.6681, chk=18.4692
ELM model 43: in3 in5 in8 --> trn=8.2603, chk=34.5955
ELM model 44: in3 in6 in7 --> trn=8.1737, chk=17.6163
ELM model 45: in3 in6 in8 --> trn=7.9273, chk=33.1414
ELM model 46: in3 in7 in8 --> trn=8.3303, chk=23.3551
ELM model 47: in4 in5 in6 --> trn=9.7530, chk=19.4916
ELM model 48: in4 in5 in7 --> trn=10.1478, chk=19.3079
ELM model 49: in4 in5 in8 --> trn=7.5165, chk=13.8428
ELM model 50: in4 in6 in7 --> trn=8.6110, chk=29.7884
ELM model 51: in4 in6 in8 --> trn=7.2117, chk=10.7983
ELM model 52: in4 in7 in8 --> trn=7.6738, chk=23.8478
ELM model 53: in5 in6 in7 --> trn=9.8508, chk=19.0796
ELM model 54: in5 in6 in8 --> trn=8.4909, chk=20.4296
ELM model 55: in5 in7 in8 --> trn=8.0298, chk=23.7191
ELM model 56: in6 in7 in8 --> trn=8.8925, chk=11.2619