

ORIGINAL RESEARCH

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Creating relation between bolt arrangements at bolted moment connections among cold-formed steel members using artificial neural network

Babak Ebadi Tabrizi^{1*} and Mahmood Hosseini²

Abstract

In this paper, three artificial neural networks are presented using the experimental results from bolted moment connections among cold-formed steel members and the software MATLAB in order to predict the rotation at the connections. A common neural network which has a multilayer perceptron along with back propagation learning algorithm is applied in this research. Each of the networks consists of four layers including two hidden ones. The number of neurons in the first hidden layer is changed from 1 to 10 to achieve optimal results. The best results are obtained when the networks had 10, 10, and 9 neurons in the first hidden layer for column base and beam column connections (in positive and negative rotations), and they had the performance of 0.0001371, 0.00044, and 0.00047, respectively, after being trained in the software MATLAB. Thirty percent of the data from each test series were omitted randomly in order to verify the networks. The Mann–Whitney *P* value tests are 0.9933, 0.9393, and 0.9653 for column base and beam column connections (in positive and negative rotations), respectively.

Keywords: Cold-formed steel, Artificial neural networks, Bolt arrangements, Bolted moment connections

Introduction

Cold-formed steel

Lightweight steel structures offer an interesting alternative to more traditional construction technologies, especially for low and medium rise residential and office buildings (Casafont et al. 2006) due to some considerable advantages such as high strength-to-weight ratio, reduced labor costs, fast erection, and economical transportation due to the light weight of cold-formed members (Ebadi Tabrizi and Vosoughifar 2011; Yu and LaBoube 2010; Zaharia and Dubina 2006). Cold-formed steel sections had been considered as secondary structural members such as purlins to support roof cladding (Chung and Lau 1999). Since 1990, there has been a growing tendency to utilize cold-formed steel as structural members in buildings in a variety of countries such as USA, Canada, Australia, and Japan (Ebadi Tabrizi and Vosoughifar 2011; Wong and Chung 2002). The

most common cold-formed steel sections are lipped C sections and lipped Z sections, and the thickness typically ranges from 1.2 to 3.2 mm. Common yield strengths are 280 and 350 N/mm² (Chung and Lau 1999; Wong and Chung 2002). Moreover, there is a whole range of variants of these basic shapes, including sections with single and double lips and sections with internal stiffeners (Chung and Lau 1999). Furthermore, welds, screws, and steel bolts are used as connector for these sections (AISI 2008; Pedreschi et al. 1998).

There are various design recommendations (AISI 1996, 2008; British Standard Institution 1987; Code AS/NZ 4600 2005; Eurocode EN 1993; ECCS Committee TC7, Working Group TWG 7.2 1983) on the design of cold-formed steel structures along with complementary design guides (AISI 1995, 2007; ECCS Committee TC7, Working Group TWG 7.2 1983; Hancock 2007; LaBaube and Yu 2006; Martin and Purkiss 2011; Zaharia and Dubina 2006) and worked examples to assist practicing engineers. For bolted moment connections, the presence of bolts will introduce high localized stresses onto the connected parts of the members which may have adverse effects on the section resistances of the members.

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There is a lack of general design rules for moment connections among cold formed steel members in the literature particularly for open sections such as lipped C sections' (Chung and Lau 1999).

In this paper, it is attempted to obtain some nonlinear equations between the results achieved from Chung and Lau's investigation (Chung and Lau 1999) by means of the artificial neural networks (ANNs).

Artificial neural networks

Neural networks are learning systems based on a simplified model of the biological neuron, which can model the relation between a set of inputs and a set of outputs. In the same way as the biological neural network changes itself in order to perform some cognitive task (such as recognizing faces or learning a concept), artificial neural networks modify their internal parameters in order to perform a given computational task. The typical tasks neural networks that perform efficiently and effectively are as follows: classification (for example deciding which category a given example belongs to or the identification of a disease from some symptoms), recognizing patterns in varied data, and prediction. Artificial neural networks are usually non-parametric approaches represented by connections between a very large number of simple computing processors or elements (neurons). The ANN is trained by supplying it with a large number of numerical observations or the patterns to be learned whose corresponding classifications are known. During training, the final sum-of-squares error over the validation data for the network is calculated. The selection of the optimum number of hidden nodes is made on the basis of this error value. Once the network is trained, a new object is classified by sending its attribute values to the input nodes of the network, applying the weights to those values, and computing the values of the output units.

The multilayer perceptron is generally divided into three layers: the input layer, the hidden layer, and the output layer, where each layer in this order gives the input to the next. The extra layer gives the structure needed to recognize non-linearly separable classes. Figure 1 demonstrates a general architecture of an artificial neural network with two hidden layers.

Applying artificial neural networks for the research

In this study, three diverse ANNs are trained in order to predict the rotation of column base connections and beam column connections under different applied moments using an empirical data (Chung and Lau 1999), and in order to obtain the best possible results, the number of neurons was changed in the first hidden layer from 1 to 10. The network which had the best

performance was selected for each test series. The achieved results show the sufficient compatibility of the ANNs with experimental data.

Methods

In this investigation, the empirical data (Chung and Lau 1999) in each test series are divided into two groups as training and testing data. The first one includes 70% of the whole data and the second consists of the remaining 30%. As the names imply, they were used to train and test the networks consecutively. In addition, each group includes two sub-groups known as the input and target data. Using sigmoid function which has a range between 0 and 1, it is necessary to normalize the whole data before applying to the software.

Experimental method

Chung and Lau 1999 conducted an experimental investigation on the structural performance of cold-formed steel members with bolted moment connections utilizing lipped C sections. They experienced various specimens with different bolt arrangements to examine the effect of bolt arrangement on the structural performance of column base and beam column connections in order to obtain the optimal connection configuration and evaluate the rational amount of maximum rotational resistance. In the present research, three column base connection specimens and four beam column connection specimens which were configured based on the former results of Chung's investigation on beam column connections are proposed.

Generation of the input data

Column base connections

In order to generate the input data, an innovative method is applied based on the effective area of each bolt. That is, six general bolt positions (*a*, *b*, *c*, *d*, *e*, and *f*) are defined as shown in Figure 2 which displays all possible bolt positions in column base connections (the position of a column base connection is shown in Figure 3). This method results in six kinds of input data. Additionally, the moment resistance ratio of each specimen, which is defined as equivalent to $\frac{\text{Measured moment resistance of connection}}{\text{Design moment capacity of connected member}}$ according to the experimental research article Chung and Lau (1999), and the applied moment (the diverse moments which applied to the connections in the experimental research in any rotation) are considered as two other kinds of input data. Three different bolt arrangements which were experimented in Chung et al.'s experimental investigation are shown in Figures 4, 5, 6 and the related equations to generate the input data are shown next to each figure (Ebadi Tabrizi and Vosoughifar 2011). All lengths

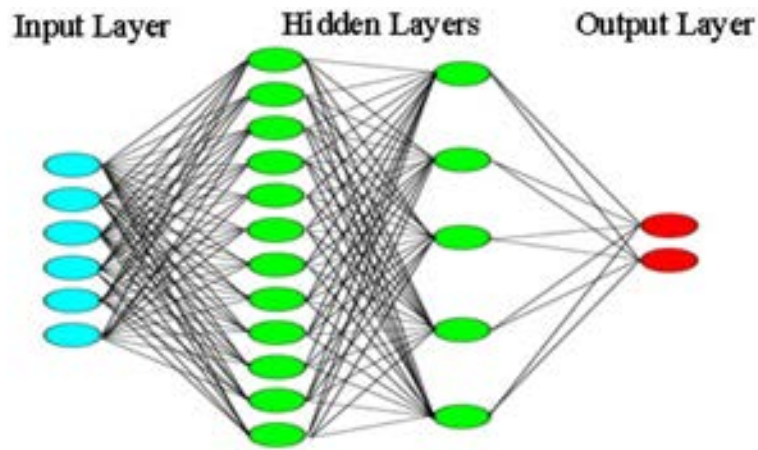


Figure 1 General multilayer perceptron architecture.

and areas in Figures 4, 5, 6 are based on millimeters and square millimeters, respectively, and the title of the specimens are the same as the empirical study (Chung and Lau 1999).

Set 1 equation is related to Figure 4:

$$a = 0, b = (n/l_1) + (A_1/A) = 0.65, c = 0, d = 0, \\ e = (n/l_1) + (A_2/A) = 0.35, f = 0$$

In Figure 4, half of the section is considered as the effective area of each bolt. In those positions which there are no bolts, the number 0 is supposed as the related input for the position.

Set 2 equation is related to Figure 5:

$$a = (m/l_1 + p/l_2) \times (A_1/A) = 0.25, b = 0, \\ c = (o/l_1 + p/l_2) \times (A_2/A) = 0.4407, d = 0, \\ e = (n/l_1 + q/l_2) \times (A_3/A) = 0.3143, f = 0$$

In Figure 5, after drawing a triangle by connecting the bolt positions a , c , and e , a perpendicular bisector of each segment was drawn. Ultimately, the effective area of each bolt was determined as shown in the figure. In those positions which there are no bolts, the number 0 is supposed as the related input for the position.

Set 3 equation is related to Figure 6:

$$a = (m/l_1 + p/l_2) \times (A_1/A) = 0.25, b = 0, \\ c = (o/l_1 + p/l_2) \times (A_2/A) = 0.4, \\ d = (m/l_1 + q/l_2) \times (A_3/A) = 0.1, e = 0, \\ f = (o/l_1 + q/l_2) \times (A_4/A) = 0.25$$

In Figure 6, one-fourth of the section is considered as the effective area of each bolt. In those positions which there are no bolts, the number 0 is supposed as the related input for the position.

Table 1 (Ebadi Tabrizi and Vosoughifar 2011) shows some random data related to the test series. The first eight columns in the table are some parts of the 70×8 input matrix and the last is a part of the 70×1 target matrix.

Beam column connections

In this test series, the innovative method is somewhat different. In these connections, the effective area of each bolt row is considered rather than that of each single bolt to generate input data as shown in Figures 7, 8, 9 and the related equations. This method results in four kinds of input data. Additionally, the moment resistance ratio of each specimen, ψ , defined above, and the moment ratio are considered as two other kinds of input data. It is important to mention that the moment ratio in the empirical study (Chung and Lau 1999) is the applied moment, defined above, divided by 178 kNm. The unit of all lengths and areas in Figures 7, 8, 9 are millimeters and square millimeters, respectively, and the title of the specimens are the same as the empirical study (Chung and Lau 1999).

Set 4 equation is related to Figure 7:

$$a = (l_1/l) \times (A_1/A) = 0.025, \\ b = (l_2/l) \times (A_2/A) = 0.1, c = (l_3/l) \times (A_3/A) = 0.15, \\ d = (l_4/l) \times (A_4/A) = 0.225$$

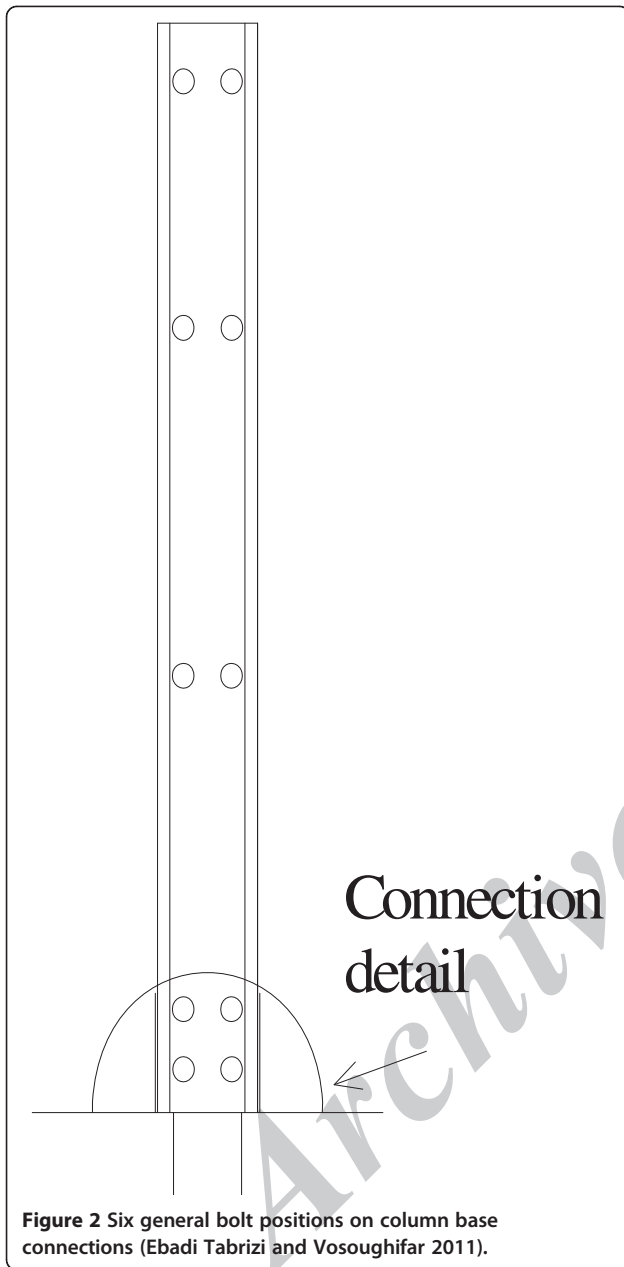


Figure 2 Six general bolt positions on column base connections (Ebadi Tabrizi and Vosoughifar 2011).

Set 5 equation is related to Figure 8:

$$a = \left(\frac{l_1}{l} \right) \times \left(\frac{A_1}{A} \right) = 0.0167,$$

$$b = \left(\frac{l_2}{l} \right) \times \left(\frac{A_2}{A} \right) = 0.0667,$$

$$c = \left(\frac{l_3}{l} \right) \times \left(\frac{A_3}{A} \right) = 0.1,$$

$$d = \left(\frac{l_4}{l} \right) \times \left(\frac{A_4}{A} \right) = 0.2333$$

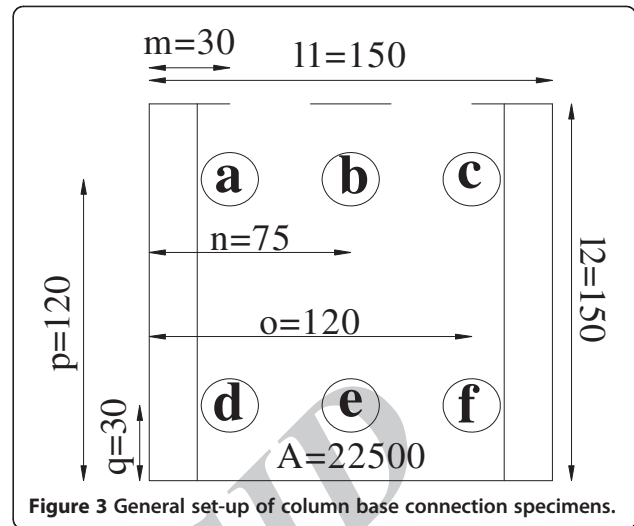


Figure 3 General set-up of column base connection specimens.

Set 6 equation is related to Figure 9:

$$a = \left(\frac{l_1}{l} \right) \times \left(\frac{A_1}{A} \right) = 0.0133,$$

$$b = \left(\frac{l_2}{l} \right) \times \left(\frac{A_2}{A} \right) = 0.0533,$$

$$c = \left(\frac{l_3}{l} \right) \times \left(\frac{A_3}{A} \right) = 0.08,$$

$$d = \left(\frac{l_4}{l} \right) \times \left(\frac{A_4}{A} \right) = 0.1867$$

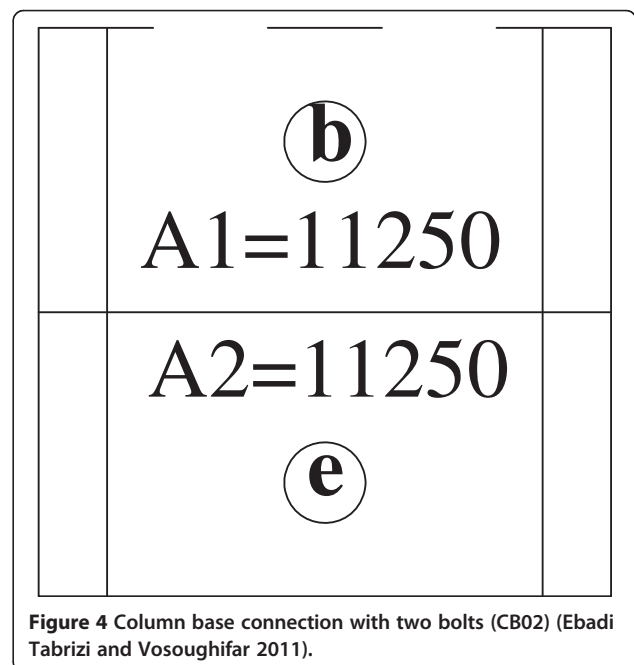


Figure 4 Column base connection with two bolts (CB02) (Ebadi Tabrizi and Vosoughifar 2011).

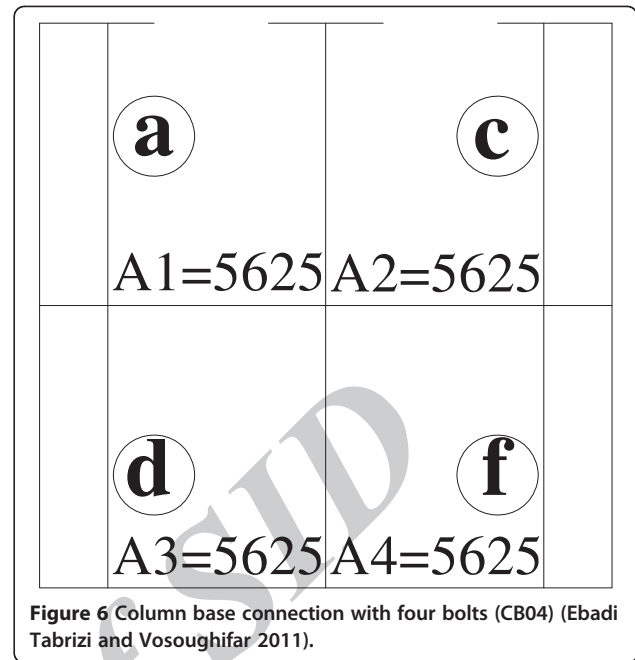
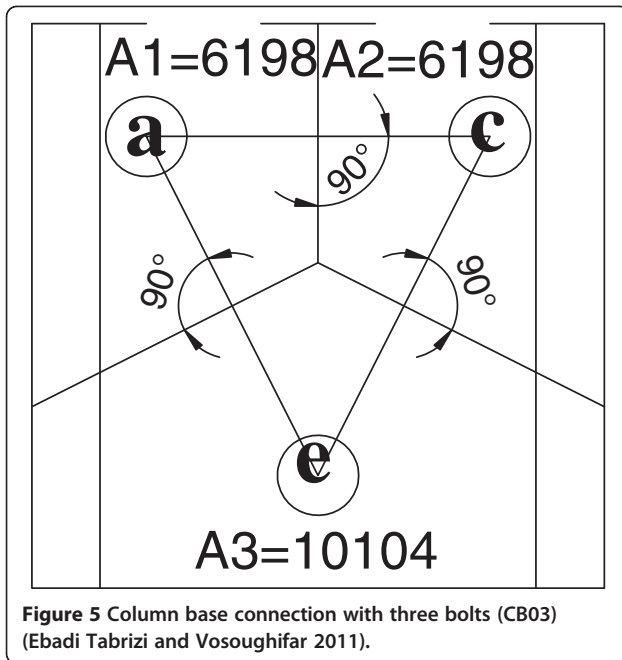


Table 2 demonstrates some random data related to the positive rotations in beam column connection experiment. The first six columns in the table are some parts of the 88×6 input matrix and the last is a part of the 88×1 target matrix. For negative rotations, all data are the same, but those related to the moment ratio and rotation are different.

Training the neural network

After generating the input and target data and training the network, a nonlinear relation between input and target data would be established. For this purpose, tansig and pureline functions are utilized as two hidden layers of the neural networks in the software MATLAB. Achieving the desired results is in accordance with the mean squared error (MSE) method which is based on reaching the minimum error (Equations 1 to 3) (Howard and Mark 2006).

$$MSE = (1/N) \sum_{i=1}^N (y_i - \bar{y})^2 \quad (1)$$

$$I = \text{pure line}(w_2 \times \text{tansig}(w_1 \times c) + b_1) + b_2 \quad (2)$$

In Equation 2, I demonstrates the target function (amount of rotation in normalization space), c represents column matrix of input data in normalization space,

w shows the amount of weight, and b exhibits the amount of bias.

In fact, the main equation would be as in Equation 3.

$$I = w_2 \left(\frac{1 - e^{-2((w_1 \times c) + b_1)}}{1 + e^{-2((w_1 \times c) + b_1)}} \right) + b_2. \quad (3)$$

Results

After generating the input and target data as explained in the 'Generation of the input data' section for all of the specimens on column base connections and randomly removing 30% of them, a matrix of 70×8 as the input and a matrix of 70×1 as the target resulted. Likewise, for positive rotations on beam column connections, a matrix of 88×6 as the input and a matrix of 88×1 as the target and for negative rotations a matrix of 97×6 and a matrix 97×1 as the input and target matrixes were obtained. In order to reach the best results, the number of neuron in the first hidden layer (tansig) were changed from 1 up to 10, and for the second one, the number remained 1 consistently. For column base connections, the best result was obtained when the first layer had 10 neurons. In the same way, for beam column connections, the best results for positive rotations were obtained when the first hidden layer had 10 neurons, and for the negative ones, when it had 9 neurons.

Obtained weights and bias

Weight and bias matrixes for column base connections

$$w_1 = \begin{bmatrix} -7.1416 & 2.1038 & -3.0152 & 15.0185 & 10.4828 & -2.9944 & -1.1978 & 6.5986 \\ -7.8375 & 3.4299 & -0.03265 & -13.776 & -0.33133 & -4.6405 & -2.4233 & 6.4385 \\ 1.1222 & -1.1127 & -2.1755 & 7.4747 & -0.92848 & -3.4598 & -1.7747 & -2.1551 \\ 7.2355 & -3.0937 & 2.0148 & -13.8911 & 11.7159 & -9.3262 & -1.3013 & -9.37 \\ 7.8439 & 9.6562 & 6.7155 & -13.2602 & 8.2061 & 7.2236 & 2.529 & -36.0712 \\ 0.23138 & 3.4017 & 1.1992 & 10.6416 & -5.3998 & 14.0822 & -3.3159 & -10.8645 \\ -0.73095 & 11.3158 & 1.8218 & 4.2301 & 1.5808 & -0.81086 & 16.4528 & -51.5236 \\ -7.3802 & 6.5347 & -8.4536 & 13.856 & 3.7442 & 6.2343 & -7.9405 & -9.7996 \\ -12.0774 & 77.6679 & -27.8645 & 12.8895 & -40.7601 & 56.8364 & 17.7938 & -208.805 \\ 13.7867 & -29.8094 & 10.1251 & 10.03 & -10.5941 & 0.5107 & 8.483 & 40.1591 \end{bmatrix}$$

$$W_2 = [-12.6684 \quad 12.9782 \quad -0.24255 \quad -0.51626 \quad -0.35149 \quad 0.11406 \quad 0.24328 \quad -0.18623 \quad -0.0355 \quad 0.025886]$$

$$b_1 = \begin{bmatrix} -2.886 \\ 0.12722 \\ 3.5444 \\ 8.7702 \\ 24.7252 \\ 6.0635 \\ 37.8571 \\ 0.75639 \\ 83.4737 \\ -8.418 \end{bmatrix} \quad b_2 = [0.87092]$$

Weight and bias matrixes for positive rotations on beam column connections

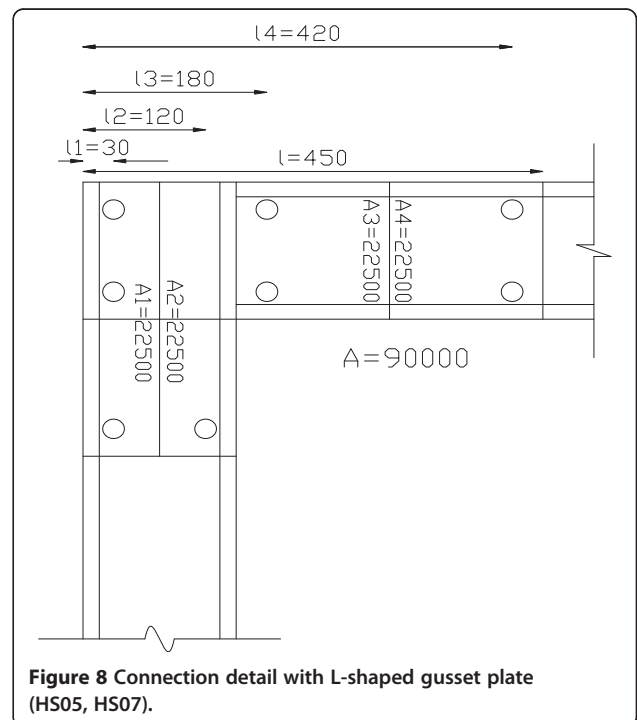
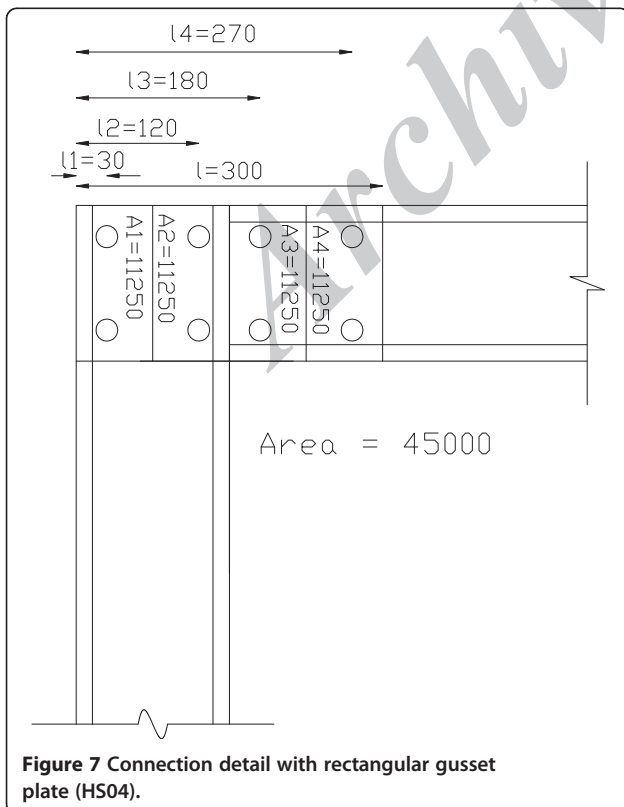
$$W_1 = \begin{bmatrix} 141.5579 & 14.185 & 104.8468 & -50.7341 & 0.71013 & 47.771 \\ 223.7558 & 223.007 & 362.3525 & 335.1485 & -48.5011 & -81.9475 \\ 181.3345 & -15.3991 & -63.48 & -2.508 & -65.8679 & -46.5518 \\ 129.2752 & 266.8782 & 355.9198 & 385.8697 & -48.3285 & -81.6669 \\ -211.7361 & 22.4239 & 20.8451 & -7.914 & 1.0991 & -3.6802 \\ -164.1526 & -68.1121 & -35.5014 & 49.7034 & -21.5111 & 3.1561 \\ 89.573 & 5.2463 & -33.5349 & 18.8298 & -4.4561 & 5.1058 \\ 68.4542 & 37.7457 & -37.5342 & 7.7943 & -1.1366 & 3.4632 \\ -182.2714 & -33.9586 & -6.8378 & 20.3452 & -10.9284 & -1.4199 \\ -185.0904 & 10.0709 & -63.2159 & 124.13 & -51.9318 & 48.3349 \end{bmatrix}$$

$$W_2 = [40.358 \quad 30.4642 \quad -41.5217 \quad -30.5145 \quad 63.132 \quad 32.1359 \quad -6.5944 \quad 76.1194 \quad 51.2953 \quad -39.9649]$$

Table 1 Random data related to the column base experiment (Ebadi Tabrizi and Vosoughifar 2011)

<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>	Moment resistance ratio	Applied moment	Rotation (target)
0	0.65	0	0	0.35	0	0.19	0.326087	0.212766
0	0.65	0	0	0.35	0	0.19	0.413043	0.297872
0.25	0	0.4407	0	0.3143	0	0.57	0.428571	0.214286
0.25	0	0.4407	0	0.3143	0	0.57	0.667954	0.438776
0.25	0	0.4	0.1	0	0.25	0.53	0.804348	0.431373

$$b_1 = \begin{bmatrix} -52.9441 \\ -54.9172 \\ 17.9205 \\ -67.7276 \\ 1.8079 \\ 12.9326 \\ -3.7002 \\ -1.6741 \\ 10.709 \\ -33.7378 \end{bmatrix} \quad b_2 = [-50.1954]$$



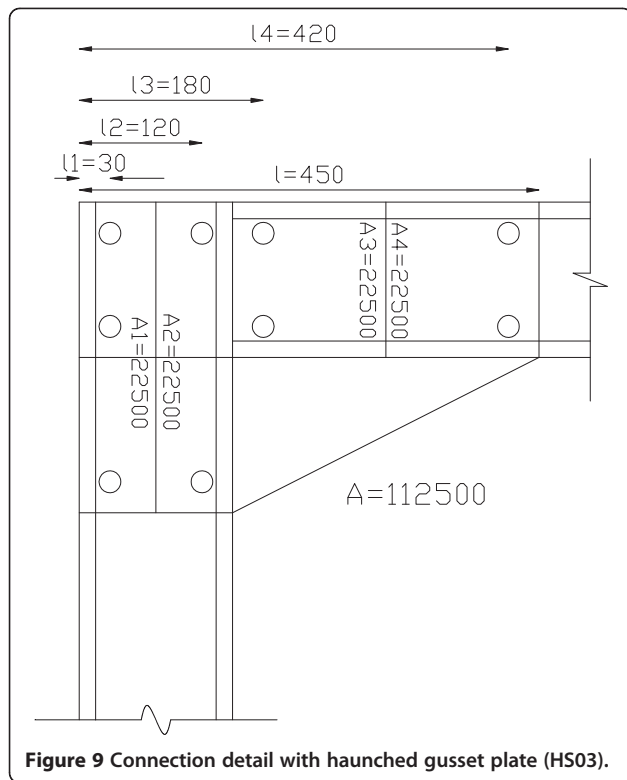


Figure 9 Connection detail with haunched gusset plate (HS03).

Ultimately, the nonlinear relation created between both groups of data will be as in Equation 4:

$$R = w_2 \left(\frac{1 - e^{-2((w_1 \times c) + b_1)}}{1 + e^{-2((w_1 \times c) + b_1)}} \right) + b_2. \quad (4)$$

In Equation 4, R represents the amount of rotation in the connection.

After training the networks for each test series and converting those data, which are in normalized amounts, to the real amounts, the inputs of training and testing data were given to the software in order to compare the amounts of real rotations with those calculated by the neural networks. Figures 10, 11, 12 provide these comparisons on the graphs for the training data and Figures 13, 14, 15 do so for the testing ones.

Discussion

In order to make a better verification, the software SPSS was used in order to attain the amounts of P value and compare the amounts of rotation resulting from the ANNs and those obtained from the empirical tests in each test series for both testing and training data. The closer amount of P value to 1 demonstrates a better

Weight and bias matrixes for negative rotations on beam column connections

$$W_1 = \begin{bmatrix} -208.807 & 2.2243 & 42.9368 & 7.2271 & 0.60938 & -2.7453 \\ 184.3424 & -26.6282 & -58.1657 & 209.7296 & 15.227 & 23.5744 \\ 39.2924 & 48.1542 & 53.6074 & 47.5165 & 13.7996 & 3.8075 \\ 67.4195 & -20.2576 & -9.2676 & -6.7806 & -0.65319 & 2.7651 \\ -190.8677 & -58.342 & -34.6957 & 233.9478 & 15.4519 & 20.7273 \\ 80.1761 & 84.5859 & 36.1588 & -247.3608 & -17.255 & -22.2189 \\ 179.9455 & -10.3429 & -95.4906 & 46.9524 & 15.1291 & 23.5115 \\ -129.8164 & -22.4931 & 30.9836 & 18.3099 & -1.9712 & 190.7024 \\ 57.9464 & -24.3555 & 7.207 & -44.7665 & -44.0481 & -23.4504 \end{bmatrix}$$

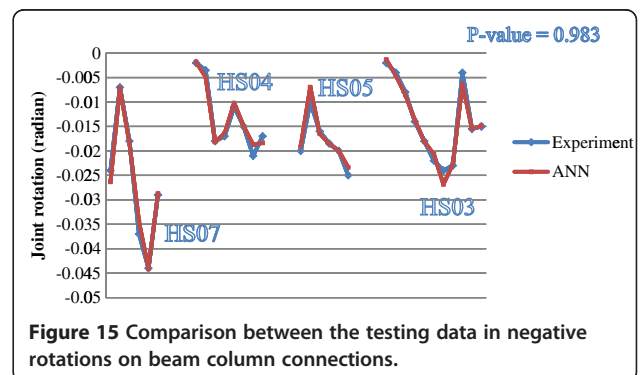
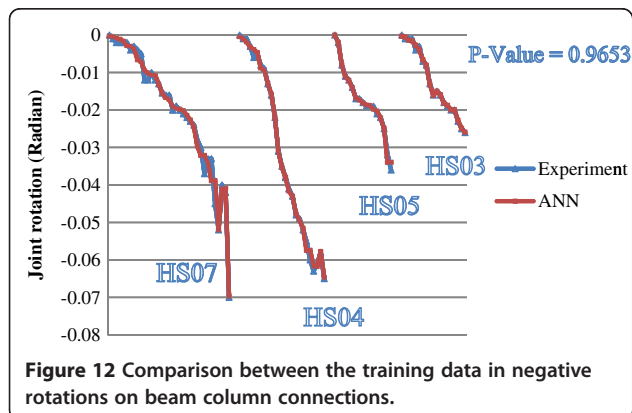
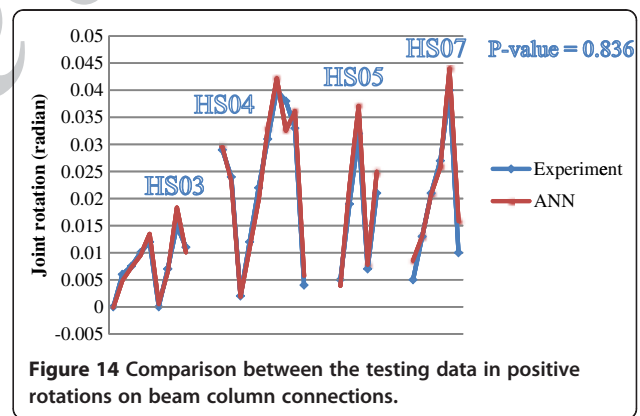
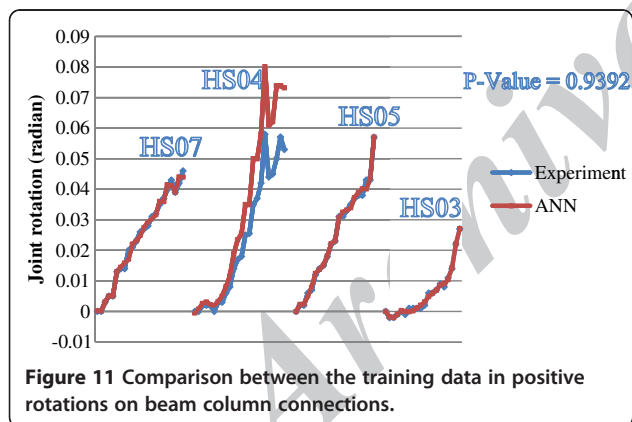
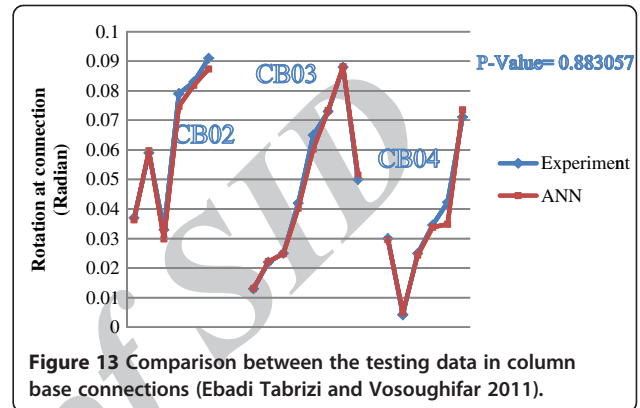
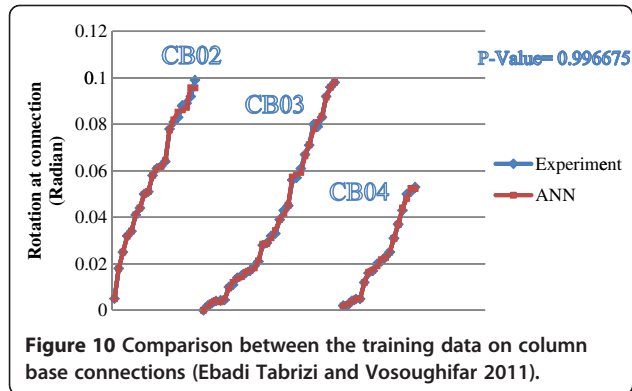
$$W_2 = [81.8024 \quad -75.8631 \quad 1.0664 \quad 81.5372 \quad -59.0674 \quad -134.85 \quad 76.1976 \quad -11.8267 \quad 76.2868]$$

$$b_1 = \begin{bmatrix} 0.26182 \\ -67.6064 \\ -34.1308 \\ -0.18845 \\ -65.0419 \\ 70.1763 \\ -26.802 \\ -195.2816 \\ 54.3714 \end{bmatrix} \quad b_2 = [-10.1791]$$

Table 2 Random data related to positive rotations in beam column connection experiment

<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	Moment resistance ratio	Moment ratio	Rotation (target)
0.0667	0.1	0.1	0.15	0 ^a	0.90625	0.695652
0.025	0.1	0.15	0.225	0.48	0.320755	0.051724
0.0667	0.1	0.1	0.15	0.76	0.423077	0.210526
0.0133	0.0533	0.08	0.1867	0.77	0.365854	0.103448

^aBecause in Chung et. al.'s paper nothing has been mentioned as the moment resistance ratio of the specimen HS07, the number 0 is used for this parameter.



agreement between the compared data. On the other hand, less than 0.05 exhibits a marked difference between them. The calculated P values, related to each comparison, are shown in Figures 10, 11, 12, 13, 14, 15.

It is worthwhile to mention that because the current research is based on a number of specimens, a numerical analysis and more empirical studies would be useful to have a better validation of the proposed ANN models.

Conclusions

Based on the study, the following points were obtained:

1. The proposed neural network models have the ability to create appropriate nonlinear relations to evaluate the amount of rotation at bolted moment connections among cold-formed structural members. As a result, using the innovative method, the amount of rotation would be calculated.
2. The achieved results prove that the innovation method applied to generate the input data for bolt arrangements suits the experimental model.
3. Evaluating the rotation at bolted moment connections in cold-formed steel members by the innovative method could be helpful in compiling design recommendation as the rotation would be computed accurately and rapidly.
4. The obtained amounts of P value prove that the achieved results match the empirical results.

Abbreviations

ANNs: Artificial neural networks; MSE: Mean squared error.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

BET introduced and promote the innovation used in this study and performed the tasks related to the utilized computer programs. MH was the supervisor of the study and the organizer of the article. Both authors read and approved the final manuscript.

Authors' information

BET graduated B.S. Civil Engineering from the Islamic Azad University, South Tehran Branch and started his scientific researches 2 years ago starting with the first part of this paper (ANN for column base connections in CFS) which was presented in the 6th International Conference on Seismology and Earthquake Engineering (SEE6). He has two other full papers. One was recently presented in 15th World Conference on Earthquake Engineering Lisbon, Portugal (15WCEE) entitled A Two-Ring Energy Dissipating Device with Similar Behaviors in Tension and Compression to Create Buckling Resistant Braces. Another full paper is regarding the evaluation of ASCE7-10 which is under review. Dr. MH is an associate professor at the Structural Engineering Research Center, board member of the Center of Excellence on Risk Management, and head of the Lifeline Engineering Department, The International Institute of Earthquake Engineering and Seismology (IIEES). He has more than 250 publications in a wide variety of local and international journals and conferences including the *Journal of Structural Design of Tall and Special Buildings*.

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