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Optimization of Bracing Systems using Neural Networks

E.M. Elkassas and S.M. Swelem
College of Engineering and Technology
AASTMT, Alexandria, Egypt

Abstract

This paper proposes a technique for the selection of optimum bracing systems and the corresponding sections for the bracing members at a minimum cost. Based on a list of criteria and design requirements, selected bracing systems and the corresponding section of the bracing members are evaluated for optimum performance and cost for a given project.

Multi-storey buildings located in Egypt are used as case studies. They consist of multi-storey frames, with different numbers of bays. Different vertical bracing systems are used in this study; V-bracing, A-bracing and X-bracing. For each case, three types of sections are used for the bracing members; a single-angle, double-angles back-to-back and star-shaped sections. The study includes six steel profiles used for the bracing members. Twenty different buildings are considered in this study. The first building consists of one storey, the second consists of two storeys \emph{etc.} The twentieth building consists of twenty storeys. These twenty buildings are studied taking into consideration one bay, three bays, five bays and finally seven bays. These bracing systems are analysed according to the allowable stress design requirements to resist lateral loads, at minimum cost, for wind pressure intensities of 70kg/m^2, 80 kg/m^2 and 90 kg/m^2. If the section succeeds in sustaining the internal forces in the bracing members, the optimum cost for the bracing members can be achieved by selecting the section with the lowest cost. That section can be a single-angle, double-angles back-to-back or star-shaped angles.

The type of artificial neural networks (ANNs) that are used in this study are a feed forward artificial multilayer perceptron (MLP) models, that map sets of input data onto sets of appropriate output. The computer program Neural Connection 2.0 is used to train the artificial neural networks; the program uses 80\% of the records for training, 10\% for validation and 10\% for testing.

The comprehensive database that was obtained from the structural analysis of all the cases that were studied was used to train five artificial neural networks to determine the three required target outputs; type of bracing system, optimum section for the bracing members and the corresponding profile of that section. The first network determines the required type of bracing system and according to this result either the second or third network in case of a V-braced building or the fourth or fifth network in the case of the X-braced building were used to determine the required section and profile of the bracing members. The (second and fourth) networks are used to determine the optimum section for the bracing members, while the (third and fifth) are used to determine the corresponding profile of that section.

The size of the training sets for each of the neural networks is about 30\% of the collected records which range from 12000 to 15000 records for each neural network. This number is the actual limit for the program used to train networks. Each neural network in the developed model was tested and validated to ensure that the output matches the actual records for different cases in the study. The final organisation of the artificial neural network model developed has been successfully trained, tested and validated to determine the target outputs with a high degree of accuracy. The degree of accuracy of the developed ANN model is 94\%, while the error rate is only 6\%.

This paper shows that artificial neural networks are very effective tools to determine the optimum type of bracing systems, the optimum required section for the bracing members and the optimum cost for each storey for different types of buildings, with a very high degree of accuracy.

Keywords: bracing systems, bracing members, multi-storey buildings, lateral loads, wind load, minimum cost, optimum bracing system, neural networks.

1 Introduction

The increase in the cost of the steel buildings has made it essential to find the most economical solutions, regarding its bracing systems. The present study proposes a technique for the selection of optimum bracing systems and the corresponding sections for the bracing members at an optimum cost. The selection of the bracing system and its corresponding member sections is often done according to design requirements, without being evaluated as it should be for optimum cost.

The proposed selection process in this study provides a methodology to choose the optimum bracing system and the corresponding bracing members sections, in order to achieve minimum cost.

Two approaches to study the optimum bracing systems of multi-story buildings were used. The first approach presented by Liang et al. [1], Wahba et al. [2] and Liang [3], used a sensitivity analysis that is based on studying the effect of element removal on the change of the strain energy of a structure. By carrying out a repeated finite-element analysis and material removal cycle, the optimal topology of bracing system for a multi-story steel frame is generated. By gradually deleting inefficient materials from a continuum design domain that is used to stiffen the frame until the performance of the bracing system is maximized. The second approach presented by

Kicinger and Arciszewski [4], Kicinger et al. [5], Kicinger [6] and Kaveh and Shahrouzi [7], studied the impact of several key parameters of cellular automata (CA) representations on the fitness of developed designs. These representations consist of an initial configuration of structural members (called design embryos) and a set of instructions based on (CA) rules (called design rules) which iteratively develop complete designs from the corresponding design embryos.

The current study proposes the use of different types of sections (i.e. optimum sections) for each storey of the building. The selection of these sections is based on optimum performance and cost.

Artificial neural network is used on the database that was obtained through the analysis of all the studied cases to obtain the three required target outputs; optimum type of bracing system, optimum section for the bracing members and the optimum corresponding profile of that section.

2 Methodology of the structural analysis

The study investigates the wind effect on buildings. Since the wind pressure increases with the height in tall buildings and causes lateral drift, minimizing lateral drift effect is an important criterion, when selecting a braced system for tall buildings. This study is a 2-D analysis of the effect of wind pressure on the selection of the type of bracing systems and their sections. This selection affects the weight and cost of the bracing systems.

The selection of the bracing system and its corresponding member sections is often done according to personal experience or perception, without being evaluated according to stability and strength requirements for optimum performance and cost. The proposed selection process in this study provides a methodology to choose the optimum bracing system and the corresponding bracing members sections.

Different multi-storey buildings located in Egypt have been investigated. The buildings consist of multi-storey frames, with different number of bays. Different vertical bracing systems are used in this study: X-bracing, V-bracing and A-bracing. For each case, three types of sections are used for the bracing members; single angle, double angles back-to-back or star-shaped. Six steel profiles are used for the bracing members. A comparison between these three cases is carried out. Twenty different buildings are studied. The first building consists of one storey, the second consists of two storeys etc. The twentieth building consists of twenty storeys. These twenty buildings are studied as one bay, three bays, five bays and finally seven bays.

These systems are analyzed according to the allowable stress design requirements to resist lateral loads, at minimum cost, for wind pressure intensities of 70kg/m^2, 80 kg/m^2 and 90 kg/m^2.Based on a list of criteria and design requirements, the selected types of bracing systems and their sections are evaluated for optimum performance and cost. When a section succeeds in sustaining the internal forces in a bracing member, the optimum cost for the bracing member can be then obtained by selecting the section with the lowest cost. This section may be a single angle (SA), back-to-back double angles (DA) or star-shaped angles (SS). The optimum sections for the bracing members for different types of bracing systems of each building are determined in each case.

Based on a list of criteria and design requirements, the selected bracing systems and the corresponding sections of the bracing members are obtained.

3 Parameters of the study

Design of the bracing systems and the selection of the bracing members sections are done according to the Egyptian code. A computer program is used to analyze these systems according to the allowable stresses design requirements to resist lateral loads at a minimum cost. Bracing members are designed as compression members.

Span of the braced frames varies from 3m to 6m with an incremental increase of 0.5m, i.e. the span of the braced frames is assumed to be (3, 3.5, 4, 4.5, 5, 5.5, 6) meters respectively, Also, the height of the braced frames varies from 3m to 4.5m with incremental increase of 0.5m, i.e. the height of the braced frames is assumed to be (3, 3.5, 4, 4.5) meters respectively. A constant spacing of 4m is considered for all the cases. The inclination angle of bracing members that lies between 35 to 55 degrees is considered while choosing the bracing system type.

Wind pressure intensities are considered; 70kg/m^2, 80kg/m^2 and 90 kg/m^2 according to the Egyptian code for Cairo, Alexandria and Marsa-Matruh cities. The buildings have different stories starting with a one storey building and ends with a twenty storey building, also the number of bays in the buildings is (1, 3, 5, and 7) respectively. All cases that are presented in this study are V-braced and X-braced buildings. The following references were used in the structural analysis [8], [9], [10] and [11].

4 Method used for training of the artificial neural networks

The database that was obtained from the structural analysis is used to train the artificial neural networks. The type of artificial neural networks (ANN's) that are used in this study are a feed forward artificial multilayer perceptron (MLP) models, that map sets of input data onto sets of appropriate output. The following references were used in the selection of the ANN's model [12] and [13].

The computer program *Neural Connection 2.0* [14] is used to train the artificial neural networks; the program uses 80% of the records for training, 10% for validation and 10% for testing.

4.1 Building the artificial neural networks model

The aspects that are considered in designing the ANN's model for this study are as follows:

1. The type of neural networks that is used in this study is a feed forward multilayer perceptron (MLP) model.
2. The task required by the network is classification.
3. The number of hidden layers is one.
4. The number of nodes in the hidden layer is (5, 10, 15, ----, 55), each time a network is trained we increase the number of nodes till we achieve the best topology for the network.
5. The transfer function is a sigmoid function.
6. The size of the training set for each of the neural networks is about 30% of the collected records which range from 12000 to 15000 records for each neural network. This number is the actual theoretical limit for the program used to train the networks.

4.1.1 The inputs

Six inputs are identified as the main variables affecting the outputs of these neural networks. These inputs are as follows:

1. Input 1: the span of the bay in meters (3, 3.5, 4, 4.5, 5, 5.5, 6 m)
2. Input 2: the height of the bay in meters (3, 3.5, 4, 4.5m)
3. Input 3: the number of bays (1, 3, 5 or 7)
4. Input 4: the total number of storeys in each building (1, 2, 3, ----, 20)
5. Input 5: the storey number under consideration (1, 2, 3, ----, 20)
6. Input 6: the wind pressure intensity (70, 80 or 90 kg/m^2)

4.1.2 The outputs

The outputs which represent the required target to be determined by the artificial neural networks are as follows:

1. Output 1: the type of bracing system, whether it is A-bracing, V-bracing or X-bracing.
2. Output 2: the type of optimum section of the bracing members for each storey in a V-braced building, whether it is single-angled, double-angled back-to-back or star-shaped angles.
3. Output 3: the type of steel profile used for the optimum section in a V-braced building. The steel profiles considered are equal angles with dimensions 70x70x7, 80x80x8, 90x90x9, 100x100x10, 110x110x10 or 120x120x11mm.
4. Output 4: the type of optimum section of the bracing members for each storey in an X-braced building, whether it is single angled, double angled back-to-back or star-shaped angles.

5. Output 5: the type of steel profile used for the optimum section in an X-braced building. The steel profiles considered are equal angles with dimensions 70x70x7, 80x80x8, 90x90x9, 100x100x10, 110x110x10 or 120x120x11mm.

From the previous structural analysis a database consisting of 51028 records were obtained for each storey in all the studied buildings, 15120 of these records are for V-braced buildings and 35910 of these records are for X-braced buildings as given in Table 1.

Neural network	Total number of records collected	Number of records used to train the network
1	51028	15000
2	15120	5000
3	15120	5000
4	35910	12000
5	35910	12000

Table 1: Records collected to train the ANN's

4.1.3 Selecting the topology of the ANN's model

Initially a single neural network, consisting of the six inputs, a hidden layer consisting of a number of nodes and the three following outputs; type of bracing system V or X, optimum section and profile of optimum section is considered. However after training the network, the resulting degree of accuracy for the three outputs proved to be poor as it is well known that the results (output) of accuracy less than 90% is classified as poor results; its degree of accuracy was 98.2%, 76.2% and 61.2% respectively as given in Table 2; so it was decided to abandon this single network and split it into two neural networks.

Output number	Output degree of accuracy
1	98.20%
2	76.20%
3	61.20%

Table 2: Results of the initial single ANN

The first neural network was trained to determine the first output, which proved to be successful. The second neural network was trained to determine the second and third outputs in the case of a V-braced building. However the degree of accuracy for this network proved to be poor, about 85.8% and 74.6% respectively as given in Table 3; so it was decided to abandon the network and split it into four networks.

Output number	Output degree of accuracy
2	85.80%
3	74.60%

Table 3: Results of the initial secondary ANN

4.1.4 Topology of the developed ANN's model

The final organization of the developed model consists of five networks as shown in Figure 1; the first network determines the required type of bracing system and according to this result we use either network (second and third) in case of V-braced building or network (fourth and fifth) in case of X-braced building to determine the required section and profile of the bracing members.

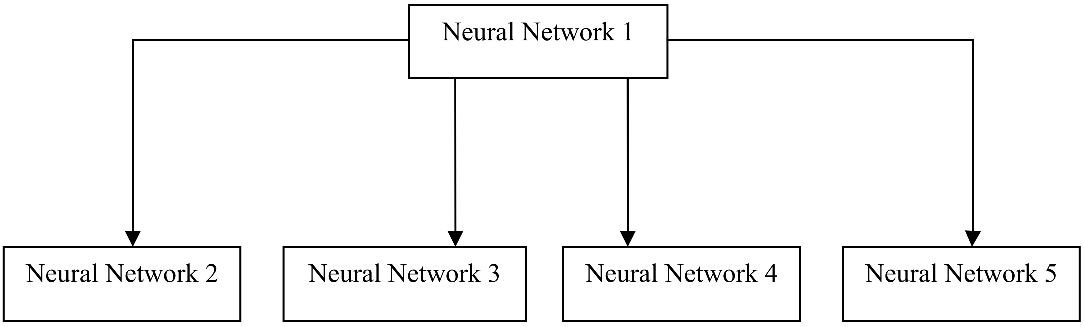


Figure 1: Organizational flowchart for Artificial Neural Networks model

Each of the following five neural networks were used to determine a single output of the five required outputs; each neural network was trained eleven times using a different number of nodes (5, 10, 15, ----, 55) in a single hidden layer. Each neural network was trained several times using a different number of nodes in the hidden layer each time, a total of eleven networks were trained to determine the neural network with the best accuracy, as given in Table 4. The input number is the number of inputs used for each network. Each network has only one single output of the five required outputs.

Neural network	Input number	Number of nodes in the hidden layer	Output number
1	1 & 2	5, 10, 15, -------, 55	1
2	1, 2, 3, 4, 5 & 6	5, 10, 15, -------, 55	2
3	1, 2, 3, 4, 5 & 6	5, 10, 15, -------, 55	3
4	1, 2, 3, 4, 5 & 6	5, 10, 15, -------, 55	4
5	1, 2, 3, 4, 5 & 6	5, 10, 15, -------, 55	5

Table 4: Training parameters for the neural networks

The topology of the first network consists of an input layer containing two inputs (input 1 and input 2) which are the span of the bay and the height of the storey. A hidden layer that uses a different number of nodes for each training starting with 5 nodes in the first training and ending with 55 nodes for last training, an output layer containing a single output (output 1) which is the type of bracing system, whether it is A-bracing, V-bracing or X-bracing.

The topology of the second network consists of an input layer containing six inputs (Input 1 to Input 6) which are the span of the bay, the height of the storey, the number of bays, the total number of storeys in each building, the storey number under consideration, the wind pressure intensity. A hidden layer that uses a different number of nodes for each training starting with 5 nodes in the first training and ending with 55 nodes for last training, an output layer containing a single output (output 2) which is the type of optimum section of the bracing members for each storey in a V-braced building, whether it is single-angled, double-angled back-to-back or star-shaped angles.

The topology of the third network consists of an input layer containing six inputs (Input 1 to Input 6) which are the span of the bay, the height of the storey, the number of bays, the total number of storeys in each building, the storey number under consideration, the wind pressure intensity. A hidden layer that uses a different number of nodes for each training starting with 5 nodes in the first training and ending with 55 nodes for last training. An output layer containing a single output (output 3) which is the type of steel profile used for the optimum section in a V-braced building.

The topology of the fourth network consists of an input layer containing six inputs (Input 1 to Input 6) which are the span of the bay, the height of the storey, the number of bays, the total number of storeys in each building, the storey number under consideration, the wind pressure intensity. A hidden layer that uses a different number of nodes for each training starting with 5 nodes in the first training and ending with 55 nodes for last training, an output layer containing a single output (output 4) which is the type of optimum section of the bracing members for each storey in an X-braced building, whether it is single-angled, double-angled back-to-back or star-shaped angles.

The topology of the fifth network consists of an input layer containing six inputs (Input 1 to Input 6) which are the span of the bay, the height of the storey, the number of bays, the total number of storeys in each building, the storey number under consideration, the wind pressure intensity. A hidden layer that uses a different number of nodes for each training starting with 5 nodes in the first training and ending with 55 nodes for last training. An output layer containing a single output (output 5) which is the type of steel profile used for the optimum section in an X-braced building.

5 Training the ANN's and results

The first neural network was trained to determine the required type of bracing system, whether it is A-bracing, V-bracing or X-bracing. As shown in Figure 2, the network achieved a degree of accuracy of 100% when it was trained using (5, 10, 20, 25, 40, 45 & 50) nodes, while a lesser degree of accuracy of 96% was achieved when the network was trained using (15, 30, 35 & 55) nodes. Therefore the best solution for this network is achieved when the network is trained using 5 nodes in the hidden layer and the output degree of accuracy is 100%, the output degree of error is 0.0%. Using more number of nodes to train the network is unnecessary as the network has already achieved the highest degree of accuracy that is possible.

The second neural network was trained to determine the optimum type of section for the bracing members in each storey for a V-braced or A-braced building, whether it is single-angle, double- angle back-to-back or star-shaped angles. As shown in Figure 3, the best result for this neural network is achieved when the network is trained using 15 nodes in the hidden layer and the output degree of accuracy is 95.4%, the output degree of error is 4.6%.

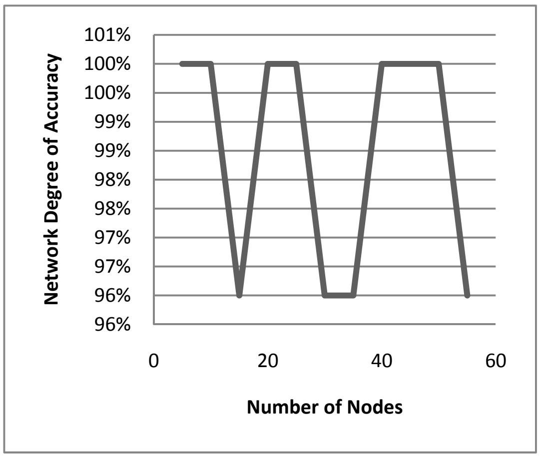


Figure 2: Results of the First Network

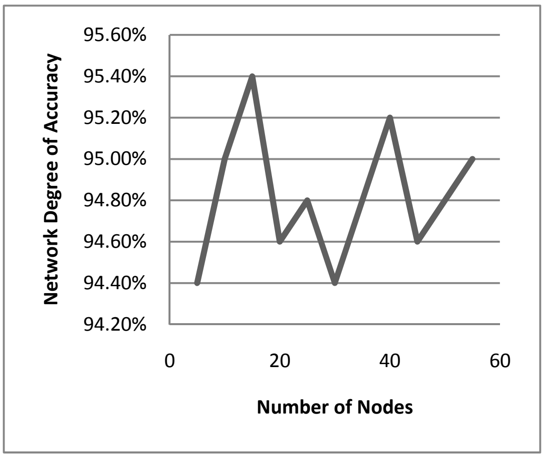
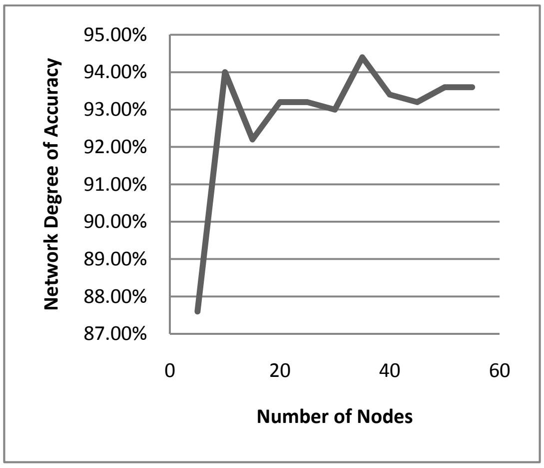


Figure 3: Results of the Second Network

The third neural network was trained to determine the type of steel equal angle profile used in the optimum section of the bracing members for each storey in a V-braced or A-braced building. As shown in Figure 4, the best result for this neural network is achieved when the network is trained using 35 nodes in the hidden layer and the output degree of accuracy is 94.4%, the output degree of error is 5.6%.

The fourth neural network was trained to determine the optimum type of section for the bracing members for each storey in an X-braced building, whether it is single-angle, double-angle back-to-back or star-shaped angles. As shown in Figure 5, the best result for this neural network is achieved when the network is trained using 45 nodes in the hidden layer and the output degree of accuracy is 95.75%, the output degree of error is 4.25%.



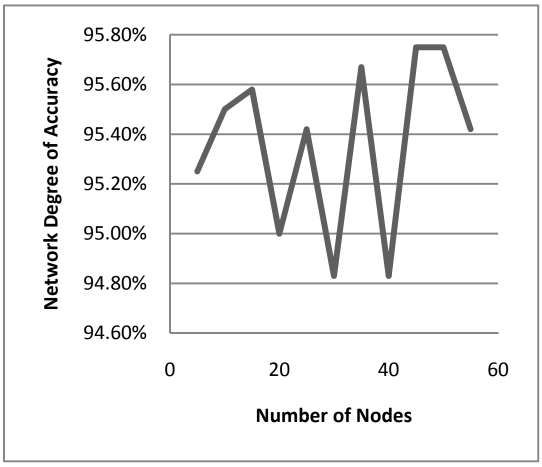


Figure 4: Results of the Third Network   Figure 5: Results of the Fourth Network

The fifth neural network was trained to determine the type of steel equal angle profile used in the optimum section of the bracing members for each storey in an X-braced building. As shown in Figure 6, the best result for this neural network is achieved when the network is trained using 40 nodes in the hidden layer and the output degree of accuracy is 93.75%, the output degree of error is 6.25%.

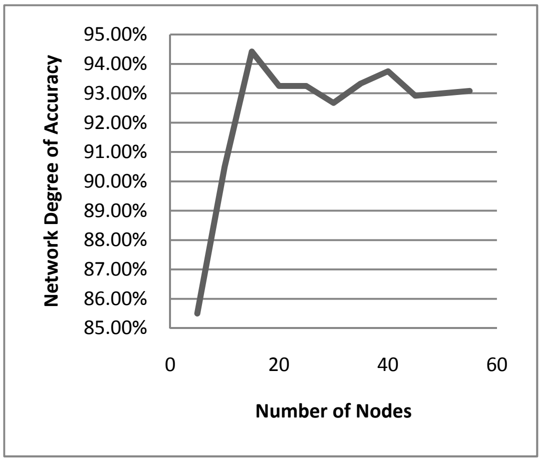


Figure 6: Results of the Fifth Network

5.1 The best degree of accuracy for each ANN

The first neural network output determines the optimum type of bracing system in each case with 100% degree of accuracy. The second neural network output determines the optimum section of the bracing members in each individual storey in a V-braced building with 95.4% degree of accuracy. The third neural network output determines the profile needed for the optimum section of the bracing members in each individual storey in a V-braced building with 94.4% degree of accuracy. The fourth neural network output determines the optimum section of the bracing members in each individual storey in an X-braced building with 95.75% degree of accuracy. The fifth neural network output determines the profile needed for the optimum section of the bracing members in each individual storey in an X-braced building with 93.75% degree of accuracy. Figure 7 shows the best degree of accuracy obtained for each of the trained Artificial Neural Networks.

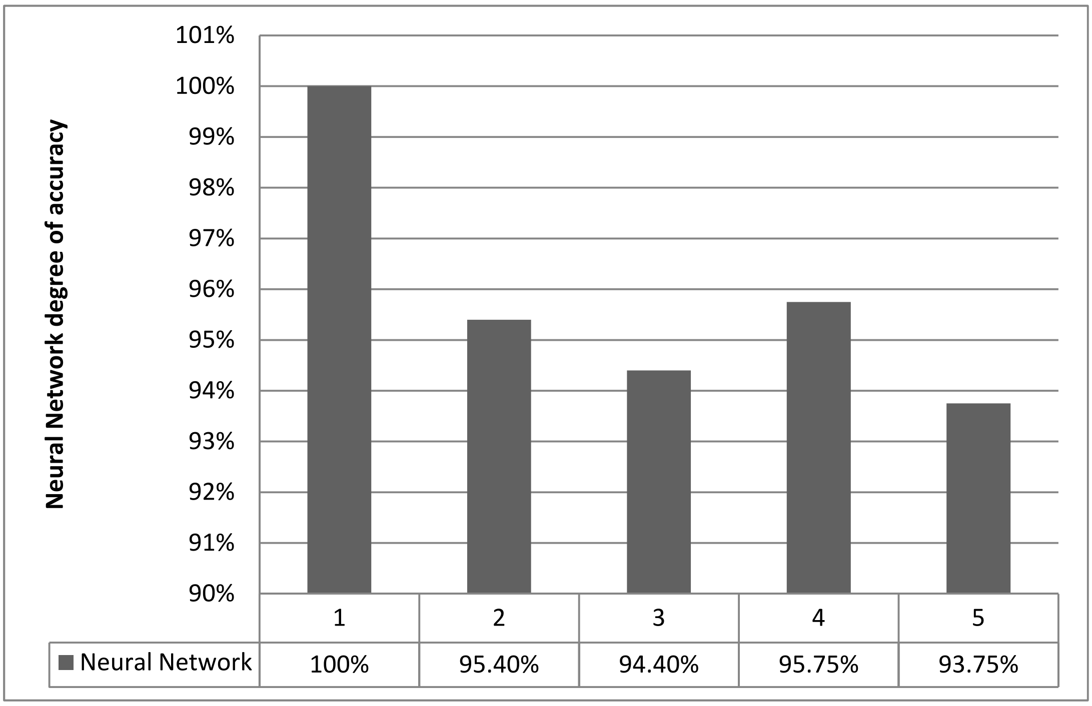


Figure 7: Best degree of accuracy achieved by each of the trained networks

5.2 Testing and validation of the ANN's model

Each neural network in the developed model was tested and validated to insure that the output matches the actual records for different cases in the study. The following examples are a comparison between the cases of buildings using actual data collected from the records and the output of the Artificial Neural Network's model to validate the ANN's model.

A multi-storey V-braced building with the data listed in Table 4 is analyzed to compare between the actual records and the model output as given in Table 5.

Number of bays	Building height	Span of the bay	Height of the bay	Wind pressure	Bracing system
5	15 storey	6.0 m	4.0 m	80 kg/m^2	V

Table 4: The data of a V-braced building

	ANN's Model output				Actual records			
Storey number	Bracing system	Optimum section	Optimum profile in mm	Cost	Type of bracing	Optimum section	Optimum profile in mm	Cost
1	V	SS	90x9	7.9%	V	SS	90x9	7.9%
2	V	DA/SS	90x9	7.9%	V	DA/SS	90x9	7.9%
3	V	DA/SS	90x9	7.9%	V	DA/SS	90x9	7.9%
4	V	DA/SS	90x9	7.9%	V	DA/SS	90x9	7.9%
5	V	DA/SS	90x9	7.9%	V	DA/SS	90x9	7.9%
6	V	DA/SS	90x9	7.9%	V	DA/SS	90x9	7.9%
7	V	DA/SS	90x9	7.9%	V	DA/SS	90x9	7.9%
8	V	DA/SS	80x8	6.3%	V	DA/SS	80x8	6.3%
9	V	DA/SS	80x8	6.3%	V	DA/SS	80x8	6.3%
10	V	DA/SS	80x8	6.3%	V	DA/SS	80x8	6.3%
11	V	DA/SS	80x8	6.3%	V	DA/SS	80x8	6.3%
12	V	DA/SS	80x8	6.3%	V	DA/SS	70x7	4.8%
13	V	DA/SS	70x7	4.8%	V	DA/SS	70x7	4.8%
14	V	DA/SS	70x7	4.8%	V	DA/SS	70x7	4.8%
15	V	DA/SS	70x7	4.8%	V	DA/SS	70x7	4.8%
Total cost				101.5%				100.0%

Table 5: Comparison between the actual records and model output in a V-braced building

In this case the ANN's model determined correctly the output for the type of bracing system, optimum section, profile and cost for each storey in the building, with the exception of the 12th storey where it determined the profile of the section differently as angle 80x8 instead of angle 70x7. This error increased the total cost by 1.5%. The error here is small and is within the acceptable accuracy of the model.

A multi-storey X-braced building with the data listed in Table 6 is analyzed to compare between the actual records and the model output as given in Table 7.

Number of bays	Building height	Span of the bay	Height of the bay	Wind pressure	Bracing system
5	15 storey	6.0 m	4.5 m	90 kg/m²	X

Table 6: The data of an X-braced building

	ANN's Model output				Actual records			
Storey number	Bracing system	Optimum section	Optimum profile in mm	Cost	Type of bracing	Optimum section	Optimum profile in mm	Cost
1	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
2	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
3	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
4	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
5	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
6	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
7	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
8	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
9	X	DA/SS	70x7	7.5%	X	DA/SS	70x7	7.5%
10	X	DA/SS	70x7	7.5%	X	SA	90x9	6.2%
11	X	SA	90x9	6.2%	X	SA	90x9	6.2%
12	X	SA	90x9	6.2%	X	SA	90x9	6.2%
13	X	SA	80x8	4.9%	X	SA	80x8	4.9%
14	X	SA	80x8	4.9%	X	SA	80x8	4.9%
15	X	SA	70x7	3.8%	X	SA	70x7	3.8%
Total cost				101.3%				100.0%

Table 7: Comparison between the actual records and model output in an X-braced building

In this case the ANN's model determined the correctly output for the type of bracing system, optimum section, profile and cost for each storey in the building, with the exaction of the 10^{th} storey where it determined the section differently as double-angle instead of single angle this error increased the total cost by 1.3%. The error here is small and is within the acceptable accuracy of the model.

The validity of the ANN's model proved to be successful in determining the target outputs with a high degree of accuracy.

6 Conclusions

By analyzing the results of the study the following points can be concluded:

- In V-bracing or A-bracing systems for all cases, the optimum section required is as follows; in 79% of the cases the optimum choice is either star-shaped or double-angles back-to-back sections, in 7% of the cases the optimum choice is star-shaped sections and in 14% of the cases the optimum choice is single angle sections.

- In X-bracing system for all cases, the optimum section required is as follows; in 73% of the cases the optimum choice is either star-shaped or double-angles back-to-back sections, in 1% of the cases the optimum choice is star-shaped sections and in 26% of the cases the optimum choice is single angle sections.

- When the section of the bracing member sustains the internal forces, the optimum cost for the bracing members can be achieved by selecting the section with the lowest cost, whether that section is a single-angled, a back-to-back double-angled or a star-shaped angles.

- All cases of X-braced buildings show that the bracing members are subjected to much smaller internal forces and thus require smaller sections, which in turn decrease the weight and the cost of the bracing members, while results of all cases of V-braced buildings show that the bracing members are subjected to higher internal forces and thus require greater sections, which in turn increase the weight and the cost of the bracing members.

The proposed optimum section in this study has proved to be successful in reducing the section and the total cost of the bracing system for all the cases in the study. Star-shaped section proved to be a better section and is used more often as an optimum section than the double-angled section, while single angle section is of limited use.

The Artificial Neural Network model has been successfully trained, tested and validated to determine the target outputs with a high degree of accuracy. The degree of accuracy of the developed ANN's model is 94%, while the error rate is only 6%.

This study shows that the artificial neural networks are very effective tools to determine the optimum type of bracing systems, the optimum section for the bracing members and the optimum cost for each storey of different types of buildings, with a very high degree of accuracy of nearly 94% of all developed networks. It is noted that there is a lack of a commercial software package which is capable of determining optimum bracing systems. Such a software program can be developed by using further studies in this field.

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