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Evaluating shear capacity of RC joints subjected to cyclic loading using ANN

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ABSTRACT: For the last few decades, many RC structures collapsed during earthquakes leading to severe losses in lives and properties. Observation of damages indicated that in many cases the main reason was the lack of the shear capacity of beam-column joints. This is usually caused by inadequate reinforcement and detailing of the joint reinforcement. The capacity of beam-column joints is influenced by various key parameters. The effect of each of these parameters has some limit of uncertainty due to the complexity of the joint behavior. Consequently, existing shear design formulae for joints produce varying results depending on the parameters accounted for in each respective formula. This paper investigates the shear behavior of interior beam-column joints subjected to cyclic loading using artificial neural networks (ANNs) based on experimental testing results collected from the literature. The paper aims to clarify the effect of some of the key parameters affecting the shear capacity of the cyclically loaded interior joints including joint shear reinforcement, concrete compressive strength, column axial stress, and joint aspect ratio. The study also evaluates the accuracy of current code formulae of the ACI-ASCE Committee 352 (2002) and Architectural Institute of Japan (1998) using experimental testing results.

1 INTRODUCTION

Beam-column joints are critical regions in reinforced concrete structures. An extensive number of studies were conducted to investigate both the behavior and design parameters of this area. Design parameters such as joint shear reinforcement, concrete compressive strength, joint aspect ratio, and column axial stress are all critical factors in the behavior of beam-column joint. In a planar frame, joint failure results in multiple reductions of redundancy of the structure, whereas a failure in beam or column results in a single reduction of redundancy (Said & Nehdi 2004). Accordingly, strength hierarchy ensures that joint failure is avoided and that a strong column weak beam will limit failure to the beam.

Through the last four decades, several studies were conducted to investigate the behavior of beam-column joints and its failure mechanisms, most of these studies focused on cyclic loading. These studies utilized both analytical techniques (Will et al. 1972; Noguchi 1981; Pantazopoulou & Bonacci 1994; Elmorsi et al. 2000) and experimental techniques (Higashi & Ohwada 1969; Durrani & Wight 1982; Otani et al. 1984; Kitayama et al. 1987; Endoh et al. 1991; Joh et al. 1991; Oka & Shiohara 1992; Teraoka et al. 1994) to investigate the shear behavior of the joint. However, despite the extensive analytical and experimental studies conducted, discrepancy still exists between these studies in accurately predicting the shear capacity of the joints and the influence of each of the design parameters on the shear strength. For the same beam-column joint specimen, each of the existing formulae predicts a different value for the shear strength. This study aims to investigate the feasibility of using artificial neural networks (ANNs) to predict the shear capacity of the monotonically loaded exterior beam-column joints. The study will also compare ANN predictions to those obtained from the following equations: ACI-ASCE Committee 352 (2002) and the Architectural Institute of Japan (1998). The parameters investigated in this study are joint volumetric reinforcement ratio, concrete compressive strength, joint aspect ratio, and column axial stress.

2 BEHAVIOR OF INTERIOR BEAM-COLUMN JOINT

Interior beam-column joints have a great importance in reinforced concrete structures. The effect of cyclic loading conditions on interior joints is much higher than the effect of monotonic loading. The reasons behind this are:

1. Larger forces can be generated on the joint for the case of cyclic loading depending on the direction of

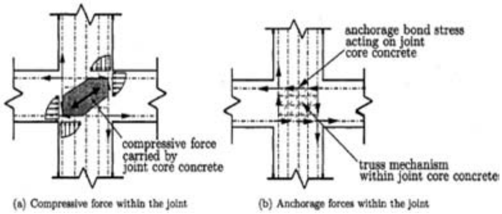


Figure 1. Strut and truss models proposed by Park and Paulay (1975) for interior beam-column joints.

forces (the ground motion) rather than the monotonic loading case.

2. According to Chopra (2007), the amount of lateral displacement of a RC structure when subjected to cyclic loading is almost twice the amount of the displacement generated by the same force value when applied monotonically to the joint.

In any reinforced concrete frame subjected to seismic loading, beams and columns experience flexure and shear forces. These forces are transformed into higher shear values acting on the joint and they might cause a shear failure in the joint. This type of failure has severe damaging results on the structure.

The strut and truss models proposed by Park and Paulay (1975) can be used for the cyclically loaded interior beam-column joints. As shown in Figure 1, two mechanisms are used for the transfer of loads through the joint. The first one is the strut mechanism which accounts for the concrete contribution to the shear strength of the joint. In this mechanism, a single concrete compression strut is used to transfer the shear forces through the joint. The second one is the truss mechanism which accounts for the contribution of joint shear reinforcement in transferring the shear forces through the joint. In this mechanism, the load is transferred through a steel tie represented by the joint shear stirrups. To ensure the presence of the tie mechanism, a strong and uniform bond stress distribution along the beam and column reinforcement should exist.

3 PREVIOUSLY PROPOSED FORMULAE AND EQUATIONS

3.1 *ACI-ASCE Committee 352 Formula (2002)*

According to the ACI-ASCE Committee 352 (2002), the cyclically loaded joints are categorized as Type 2. Type 2 joints are the ones designed to have sustained strength under deformation reversals into the plastic range (seismic loading case).

The ACI-ASCE Committee 352 (2002) proposes a general formula for the design of beam-column joints and bases on the type of joint the factors of the formula vary. The general formula is as follows:

$$V_n = 0.083\,\gamma\sqrt{f_c'}b_jh_c \tag{1}$$

where V_n is the nominal shear strength of Type 2 joints, f_c' is the concrete cylinder strength (MPa), h_c is the depth of the column in the direction of joint shear being considered (mm), b_j is the effective width of the joint (mm), it is defined as the smaller value of:

$$\frac{b_b + b_c}{2} \tag{2a}$$

$$b_b + \sum (mh_c + 2) \tag{2b}$$

$$b_c \tag{2c}$$

where $m = 0.50$ for the case of no eccentricity between the beam and column centerlines, $\gamma = 15$ for Type 2 interior planar joints (database case). Accordingly the formula becomes:

$$V_n = 1.245\sqrt{f_c'}b_jh_c \tag{3}$$

3.2 *Design equation of the Architectural Institute of Japan (1998)*

Most of the recommendations provided in the Japanese design guidelines for the cyclically loaded beam-column joints are based on studies conducted by Aoyama (1993) on the behavior of cyclically loaded beam-column joints. According to his study, it is stated that there are two earthquake design methods. The first is the strength design, in this method the structure is designed to sustain large lateral load resistance capacity. The second method is the ductility design method, where the structure is designed to have a large inelastic deformation capacity. It is very important for any structure not to suffer brittle failure by dissipating the energy of the earthquake through plastic hinges formed in the beams. This actually represents the strong column weak beam theory. This theory states that the structure should be designed to have a stronger column than the beam to increase the dissipation of energy, and to ensure the simultaneous formation of plastic hinges in the beams. Based on his study, the Architectural Institute of Japan (1998) provides the following formula for calculating of the shear capacity of cyclically loaded beam-column joints.

$$V_u = k \times \phi \times F_j \times b_j \times D \tag{4}$$

where $k = 1$, $\phi = 0.85$, $F_j = 0.80 * (f_c')^{0.70}$ (MPa), D is the column depth, b_j = effective column width. This leads the formula to be:

$$V_u = 0.68 \times (f_c')^{0.70} \times b_j \times D \tag{5}$$

3.3 *Artificial neural network approach*

Artificial Neural Networks are one of the most popular artificial intelligence techniques used in engineering applications. Multi-layer perceptron networks (MLP) have been widely used in engineering applications. They are able to map a given input (s) into desired output (s), and accordingly detect hidden and complex behavioral trends of such engineering problems by learning through the database used to train the system (Haykin 1994).

The architecture of the MLP networks consists of an input layer which represents the investigated parameters in the network, an output layer which represents the final result of the network or the behavior under investigation, and a number of hidden layers. Each layer contains a number of processing elements that are fully or partially connected to the elements in successive layers. The strength of the bond between processing elements is a numerical value called the weight of the connection. The simulation process in ANN can be expressed as the operation of detecting the optimum weights such that the network can predict an accurate value for the output within the database range.

4 EXPERIMENTAL DATABASE

The most important factor contributing to the performance of ANNs is the learning material used in the training process. Accordingly, it is imperative to train a network model on a comprehensive database to capture the actual embedded relationships between the parameters of the input and output layers. In this study, the aim is to detect the relationships between the different parameters being considered and their effect on the shear capacity of interior beam-column joints under cyclic loadings.

In this study, shear capacity of this joint type is investigated using a database consisting of 58 concrete beam-column connections collected from published literature and listed in Khalifa (2008).

The accuracy of the network was improved by imposing several limitations on specimens in the database used by the ANN model. Specimens failing due to joint shear were strictly used, with no beams in the transverse direction. Specimens with high strength concrete, and reinforcement welding into the joint were omitted. The database was formatted into groups of input vectors, each vector representing one of the investigated parameters in the study and the output vector represents the shear capacity of the joint. Table 1 represents the database range of the parameters investigated in the study.

Table 1. The parameters range for the investigated database.

Parameter	Minimum	Maximum
Joint aspect ratio	1	1.3
Concrete compressive strength MPa	21.2	70
Volumetric reinforcement ratio (%)	0	3.15
Column axial stress (MPa)	0	17.8

5 ANN MODEL

To predict the shear strength of cyclically loaded beam-column joints, an ANN was constructed with the following components: an input layer, an output layer and two hidden layers. The input layer contains four variables representing the common shear design parameters of reinforced concrete beam-column joint (volumetric reinforcement ratio, concrete compressive strength, joint aspect ratio, and column axial stress). The output layer includes one unit representing the shear capacity, V_n and the hidden layers consisted of eight and four processing units consecutively. Full bonding connections were used between the processing elements and the elements in other consecutive layers.

The software used in this model is MATLAB (2007). This software is commonly used for the simulation process of engineering problems. This software divides the given database into training and testing groups to increase the accuracy of the model and give a better understanding of the effect of each parameter in the output layer. Figure 2 represents the architecture of the proposed model.

6 RESULTS AND DISCUSSIONS

To consider an ANN successful, it must be able to accurately predict output values for input values within the range of the database used in the training and the testing process. To evaluate the accuracy of the proposed network, a comparison was held between the

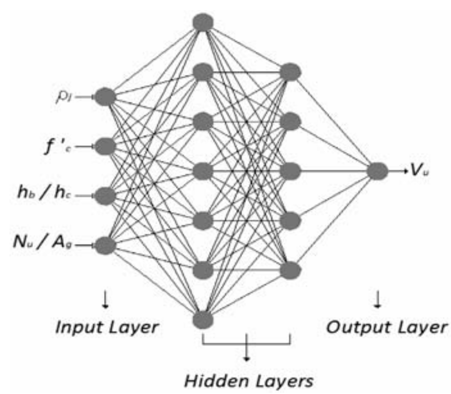


Figure 2. Architecture of artificial neural network model.

network predicted outputs which represent the shear capacity and those calculated using the formulae by ACI-ASCE 352 (2002) Architectural Institute of Japan (1998) The performance of each model was evaluated based on both the ratio of measured to predicted (or calculated) shear strength (V_m/V_p), and the average absolute error (AAE) calculated using the following equation:

$$AAE = \frac{1}{n}\sum \frac{|V_m - V_p|}{V_m} \times 100 \qquad (6)$$

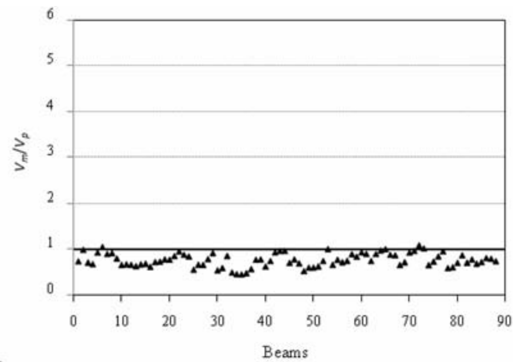
The average value, the standard deviation ($STDV$), and coefficient of variation (COV) for V_m/V_p, and the average absolute error (AAE) of the ANN model and ACI-ASCE 352 (2002) are listed in Table 2.

The shear strength of beam-column joints calculated using current shear design provisions are plotted against the experimentally measured values in Figure 3. Figure 3a indicates that the ACI shear design guidelines for reinforced concrete beam-column joints are highly inaccurate even without application of reduction factors as shown. This formula neglects the influence of the joint aspect ratio and the column axial stress, and the contribution of the joint reinforcement to the shear capacity of the joint. Using the selected data for this study and knowing the actual capacity of the specimens obtained from the experimental programs results, the average absolute error AAE for this formula is 63%, which is significantly high, and the $STDV$ for V_m/V_p of this formula is 0.29. It is recommended that this formula should not be used to estimate the shear capacity of beam-column joints due to its lack of accuracy. It should rather be used to estimate the minimum shear strength of the joint based on concrete properties and joint dimensions.

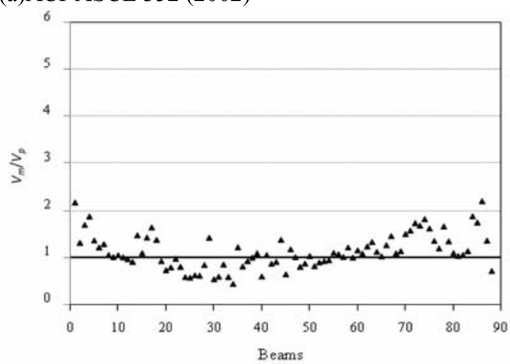
Design equations proposed by the Architectural Institute of Japan (1998) resulted in highly inaccurate prediction of the shear strength of the cyclically loaded interior bream-column joints. Figure 3a represents a plot of the actual experimental shear strength values versus the calculated ones using this formula. This formula neglects the influence of the joint aspect ratio, the column axial stress, and the contribution of joint reinforcements to the shear capacity of the joint.

Table 2. Performance of different formulae for the calculation of shear strength of RC interior beam-column joints under cyclic loading.

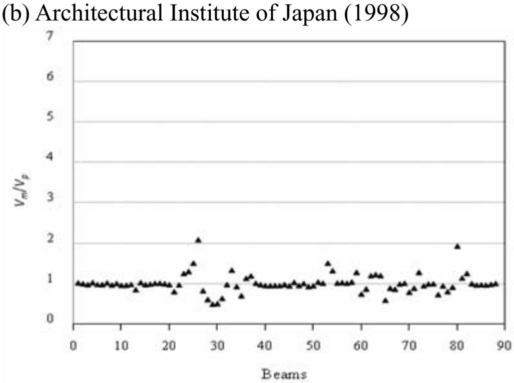
		$V_{measured}/V_{predicted}$		
Method	AAE (%)	Average	STDV	COV
ACI-ASCE 352 (2002)	63	0.77	0.29	38.7
AIJ (1998)	90	0.651	0.297	48.00
ANN	8.15	0.99	0.0988	10



(a)ACI-ASCE 352 (2002)



(b) Architectural Institute of Japan (1998)



(c) ANNs

Figure 3. Measured versus calculated shear capacity of beam-column joints.

Using the selected data for this study and knowing the actual capacity of the specimens obtained from the experimental programs results, the average absolute error AAE for this formula is 90%, which is extremely high, and the $STDV$ for V_m/V_p of this formula is 0.297. Neglecting several major factors governing the behavior of the joint refute the accuracy and the validity of this formula.

The proposed model for the ANNs produced much more accurate outputs for predicting the shear capacity of joints than the formula proposed by ACI-ASCE 352. Figure 4c shows that this model reduced the *AAE* between the actual and the predicted values to a very small value (8.15%). The model also resulted in a smaller scatter for the data with *STDV* of 0.0988. The small value of *AAE* ensures the accuracy of selecting the investigated parameters as the key factors governing the shear behavior of joints.

7 CONCLUSIONS

The purpose of this study was to study the feasibility of using artificial neural networks to predict the shear strength of monotonically loaded exterior beam-column joints. The proposed technique outperformed existing equations in the ACI code and the literature. The study also shows that ANNs are very useful tool for complex engineering problems. Further refinement to the proposed technique can be provided through incorporating new experimental research results.

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