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Shear capacity estimation of fully grouted reinforced concrete masonry walls using neural network and adaptive neuro-fuzzy inference system models

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HIGHLIGHTS

- Six full-scale reinforced concrete masonry walls under cyclic loading were tested.
- Soft computing techniques were used to predict the peak loads of masonry walls.
- The ANFIS model slightly outperforms the ANN model.
- The two proposed models performed better than the existing empirical models.

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ABSTRACT

In recent years, fully grouted reinforced concrete block masonry shear walls have been widely used as key structural elements for seismic resistance in medium- and high-rise buildings. However, accurately estimating their shear strength is truly challenging owing to the complex behavior of masonry walls under in-plane loads. This paper proposes the application of artificial neural network and adaptive neuro-fuzzy inference system models for predicting the shear strength of grouted reinforced concrete block masonry walls. To construct these models, an experiment was conducted and additional experimental data were gathered from published literature. Eleven main parameters were considered to be input parameters: compressive strength of grouted concrete block masonry, wall height, wall length, wall thickness, effective wall length, axial load, longitudinal and transverse reinforcement ratios, horizontal reinforcement spacing, and yield strength of longitudinal and transverse reinforcements. The prediction values of the well-trained artificial neural network and adaptive neuro-fuzzy inference system models agreed well with the experimental data. In addition, the comparison results showed that the two proposed models perform better than the existing empirical models. Therefore, they can be considered accurate and reliable models for estimating the shear strength of grouted reinforced concrete block masonry walls.

1. Introduction

Reinforced concrete block masonry (RCBM) structures are considered economical seismic force resisting structural systems owing to their good seismic performance compared with traditional unreinforced masonry structures as well as low cost compared with concrete structures [1]. In recent years, RCBM structures have become increasingly popular in medium-rise residential constructions, some office buildings, and business hotels [2]. For example, just in Heilongjiang Province, China, the application of this structural system has exceeded ten million square meters until 2016.

RCBM walls are the key structural elements that resist the gravity load and lateral force mainly from seismic and wind action. The shear strength of RCBM walls is considered to be one of the most important characteristics in structural design and quality control [3]. In the past few decades, numerous experimental investigations have been conducted on the seismic performance of RCBM walls

Abbreviations: RCBM, Reinforced concrete block masonry; ANN, artificial neural network; ANFIS, adaptive neuro-fuzzy inference systems; BPNN, back-propagation neural network; LMBP, Levenberg-Marquardt backpropagation; FIS, fuzzy inference systems; RMSE, root mean squared error; MAPE, mean absolute percentage error; COV, coefficient of variation.

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under in-plane lateral loads, and several theoretical and empirical formulas and masonry codes have been developed for predicting the shear strength of RCBM walls. However, owing to the complex shear mechanisms of RCBM walls and various influencing parameters, it is difficult for the theoretical models to accurately estimate the shear strength of RCBM walls. Moreover, the empirical expressions were constructed primarily based on a limited number of experimental tests. As more experimental results are available, it is necessary to re-evaluate the predictive accuracy and reliability of these empirical expressions.

In recent years, two soft computing techniques—artificial neural networks (ANNs) and adaptive neuro-fuzzy inference systems (ANFIS)—have become popular and have been successfully applied to solve different engineering problems. A previous study utilized ANNs for predicting the moment capacity of reinforced concrete slabs in fire [4]. The long-term compressive strength of silica fume concrete was estimated using ANNs and ANFIS [5]. In addition, ANFIS were used to predict the deflection and cracking behavior of near surface mounted strengthened reinforced concrete beams [6]. Mansouri et al. [7] modeled the debonding behavior of masonry elements retrofitted with fiber reinforced polymer composites using ANNs and ANFIS. Asteris et al. applied ANNs to predict self-compacting concrete strength [8,9] and the fundamental period of infilled RC frame structures [10].

Moreover, a few studies have been conducted on the application of artificial intelligence techniques to the prediction of masonry behavior. Mathew et al. [11] explored the ability of ANNs to solve complex nonlinear problems for the analysis of masonry panels under biaxial bending. Asteris et al. [12,13] modeled an anisotropic masonry failure criterion under biaxial compressive stress using ANNs. Theodossopoulos and Sinha [14] concluded that ANNs can be used to arrive at a solution with great savings in computational time. The results of these studies show that ANN and ANFIS approaches are feasible for establishing a relationship between critical parameters and complex behavior systems. However, the shear strength of fully grouted RCBM walls has rarely been estimated using ANN and ANFIS approaches.

The primary objective of this study is to develop ANN and ANFIS models to predict the shear strength of RCBM walls. This paper is organized as follows. Section 2 summarizes the common empirical formulas developed in the literature and the international masonry design codes. Section 3 describes an experimental test and lists existing experimental databases. Section 4 develops the ANN and ANFIS models. The performance of the developed ANN and ANFIS models is evaluated in Section 5, and their accuracy is evaluated in comparison with the empirical formulas. Finally, Section 6 concludes the paper.

2. Existing shear strength models

The failure mechanism of a shear wall subjected to in-plane lateral loads can be divided into flexural failure and shear failure in terms of the load conditions—aspect (height-to-width) ratio and vertical and horizontal reinforcement ratios. This paper mainly focuses on the seismic shear response of RCBM walls dominated by shear failure rather than flexure failure. According to Shing et al. flexural strength can be accurately determined using a simple flexural theory [15]. Nevertheless, no effective theory has been developed to estimate the bearing capacity dominated by shear failure. Most models available for evaluating the shear strength of RCBM walls are empirical expressions. They usually consider that shear strength is contributed by masonry, axial load, and horizontal reinforcement [16]. The shear resistance of RCBM walls is given as follows:

$$V_n = V_m + V_p + V_s \tag{1}$$

here, V_m, V_p, and V_s represent the shear resistance offered by the masonry, axial load, and shear reinforcement, respectively. Table 1 summarizes the commonly used shear strength models for RCBM walls. The formulas of five international masonry codes are also presented: Eurocode 6 [17], MSJC [18], SANZ 2004 [19], CSA S304.1 [20], and GB50003 [21]. Moreover, the equations proposed by Shing [15] and Matsumura [22] are included. For convenience, these predictive equations have been modified using common notations and consistent units.

3. Experimental program and data collection

3.1. Experimental program

3.1.1. Test specimen

To demonstrate the proposed analysis approach, six grouted concrete block masonry walls were constructed in the laboratory.

Table 1
Existing equations for calculating the shear strength of RCBM walls.

Model	Masonry contribution V_m	Axial load contribution V_p	Steel contribution V_s
Eurocode 6 [17]	$V_m = 0.3A_n$	$V_p = 0.4\sigma_n A_n$	$V_s = 0.9A_h f_{yh} d_v/s_h$
MSJC [18]	$V_m = 0.083(4.0 - 1.75h_w/l_w)A_n\sqrt{f_m}$ $V_{n(\max)} = \begin{cases} 0.5A_n\sqrt{f_m} & h_w/l_w \leqslant 0.25 \\ (0.56 - 0.22(h_w/l_w))A_n\sqrt{f_m} & 0.25 < h_w/l_w \leqslant 1.00 \\ 0.33A_n\sqrt{f_m} & h_w/l_w > 1.00 \end{cases}$	$V_p = 0.25\sigma_n A_n$	$V_s = 0.5A_h f_{yh} l_w/s_h$
SANZ [19]	$V_m = (C_1 + C_2)0.15\sqrt{f_m} l_w d_v$ $C_2 = \begin{cases} 1.5 & h_w/l_w < 0.25 \\ 0.42(4 - 1.75(h_w/l_w)) & 0.25 \leqslant h_w/l_w \leqslant 1.0 \\ 1.0 & h_w/l_w > 1.0 \end{cases}$	$V_p = 0.9\sigma_n A_n \tan\alpha$	$V_s = C_3 A_h f_{yh} d_v/s_h$
CSA S304.1 [20]	$V_m = 0.16(2 - h/d_v)\sqrt{f_m} t_w d_v \gamma$ $V_{n(\max)} = 0.4\sqrt{f_m} t_w d_v (2 - h_w/l_w) 0.5 \leqslant h_w/l_w \leqslant 1.0$	$V_p = 0.25\sigma_n A_n \gamma$	$V_s = 0.6A_h f_{yh} d_v/s_h$
GB50003 [21]	$V_m = \frac{1.5}{h_w/l_w + 0.5} 0.143\sqrt{f_m} t_w d_v$	$V_p = \frac{1.5}{(h_w/l_w) + 0.5} 0.246\sigma_n A_n$	$V_s = f_{yh} A_{sh} d_v/s_h$
Shing [15]	$V_m = (0.166 + 0.0217\rho_v f_{yv})\sqrt{f_m} A_n$	$V_p = 0.0217\sigma_n A_n\sqrt{f_m}$	$V_s = (\frac{l_w - 2d_v}{s_h} - 1)A_h f_{yh}$
Matsumura [22]	$V_m = 0.875k_u k_p\left(\frac{0.76}{(h_w/d_v) + 0.7} + 0.012\right)\sqrt{f_m} t_w d_v$	$V_p = 0.175\sigma_n t d_v$	$V_s = 0.1575\gamma\delta\sqrt{\rho_h f_{yh} f_m} t_w d_v$

* f_m = masonry compressive strength, h_w = wall height, l_w = wall length, t_w = wall thickness, A_n = net cross-sectional area, σ_n = vertical normal stress on the wall, d_v = effective length of the wall, s_h = horizontal reinforcement spacing, f_{yh} and f_{yv} are yield strength of horizontal and vertical rebar, respectively. ρ_h and ρ_v are the ratio of horizontal and vertical reinforcement, respectively. C_1 = constant taken as $33\rho_w f_{yv}/300$, C_3 = constant taken as 0.8 for masonry wall, ρ_w = the area of vertical reinforcement as a percent of effective wall area, α = the angle between the axial load and the center of the compression zone of the wall, k_u = constant taken as 1.0 for fully grouted masonry, k_p = factor affected by flexural reinforcement taken as $1.16{\rho_{ve}}^{0.3}$, ρ_{ve} = ratio of outmost wall vertical reinforcement, γ = constant taken as 1.0 for fully grouted masonry, δ = factor concerning loading method taken as 1.0 and 0.6 for double bending and single bending, respectively.