



Analysis of Shear Capacity and Deformation of Reinforced Masonry Block Shear Walls

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Abstract. This research aims to study the shear resistance and deformation capacity of reinforced masonry shear walls. By using the method of nonlinear regression analysis, the maximum shear resistance and deformation characteristics of the 295 reinforced masonry shear wall specimens in the quasi-static test database were analyzed, and corresponding prediction formulas were provided. A comparative analysis was also conducted with the existing shear resistance calculation formula for reinforced masonry shear walls in the current masonry code. The results indicate that the current code's calculation formula underestimates the contribution of grouted masonry to the shear resistance of the wall, and overestimates the influence of horizontal steel reinforcement. The significance of this study lies in its potential to impact building codes and design practices to enhance the seismic performance of reinforced masonry shear walls.

Keywords: Reinforced masonry, Regression analysis, Shear resistance capacity, Deformation prediction

1 Introduction

The reinforced masonry shear wall structure has the characteristics of low cost and high construction efficiency, and is a low-carbon and environmentally friendly building structure form. In the context of the country's strong advocacy for the construction industry to adopt prefabricated construction methods, the reinforced masonry shear wall is gradually transformed into a prefabricated component for use^{[1][2]}. However, under seismic action, the load-bearing capacity and deformation capacity of the wall will be challenged, so it is necessary to conduct in-depth research on its seismic performance.

During the investigation of seismic damage, it was found that the damaged buildings often experienced shear failure in vertical load-bearing members. Due to inadequate deformation capacity, the buildings collapsed rapidly during earthquakes, resulting in a large number of casualties and property losses. Therefore, it is necessary to study the shear bearing capacity and deformation capacity of reinforced masonry shear walls.

The reinforced masonry shear wall has complex stress mechanisms and deformation conditions. Experiments by Ghasemina^[3] have shown that simply increasing the reinforcement cannot improve the shear bearing capacity of the wall. In order to study the seismic performance of the reinforced masonry shear wall, this paper collected test data from 295 reinforced masonry shear wall specimens under low-cycle reversed horizontal force, focusing on their maximum shear resistance and deformation characteristics. Based on the failure mode of the wall panels, the panels were divided into shear failure (S group), flexural-shear failure (FS group), and flexural failure (F group). The main parameters extracted from the wall panels included yield strength of reinforcement, average compressive strength of grouted masonry blocks, shear span ratio, reinforcement ratio, and maximum carrying capacity, analyzing their probability distributions. Comparing with experimental values of the reinforced masonry block shear walls, it was found that the use of existing formulas to calculate the maximum shear carrying capacity of the wall panels tends to be conservative. To address this issue, an improved formula was proposed after regression analysis. Compared to the original formula, the improved formula suggests that grouted masonry blocks have a higher contribution to the shear carrying capacity of the wall panels. For wall panels experiencing shear failure, deformation calculation formulas under maximum carrying capacity and ultimate load were fitted based on deformation coordination assumptions and the principle of displacement superposition using parameters such as wall height-to-width ratio, axial compression ratio, and reinforcement ratio.

2 Materials and Methods

2.1 Outline of Experimental Database

This study collected quasi-static test data of 295 reinforced masonry shear walls from the literature of scholars in China, Japan, the United States and other countries, and conducted a regression analysis on the calculation formula of shear bearing capacity of reinforced masonry shear walls based on a large amount of basic data. The inclusion criteria for the test walls are as follows: 1) the wall has a grouting rate of more than 100%, 2) the overall reinforcement rate is greater than 0.15%, 3) there are no door and window openings or end constraints. horizontal loads were applied to the test wall using either asymmetric loading or cantilever loading, as shown in Figure 1. The walls had rectangular or T-shaped cross-sections, and the range of vertical pressure, width, effective height, thickness, and shear span ratios and other parameters of the walls are shown in Table 1.

Due to differences in wall construction and vertical pressure, the walls exhibited three types of failure modes under the combined action of vertical pressure and horizontal loads, including shear failure (S) in 135 walls, flexural-shear failure (F-S) in 50 walls, and flexural failure (F) in 110 walls. To conduct regression analysis on the strength and deformation of the test data, the database recorded the following parameters: 1) test settings and wall construction, 2) material strength, 3) cracking strength, maximum strength, and ultimate strength of the walls, as well as the corresponding displacements.

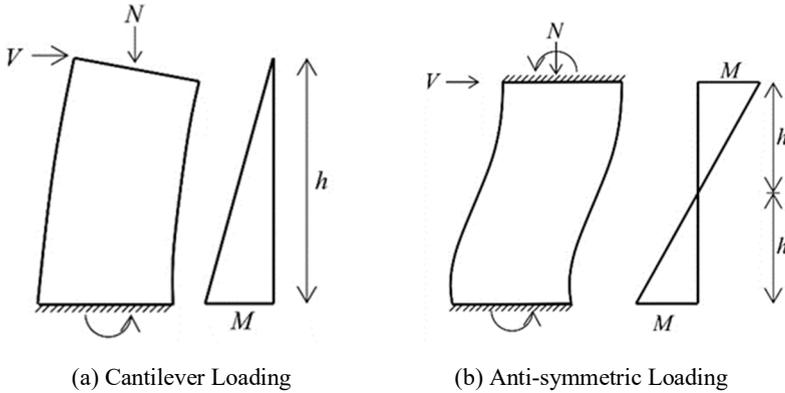


Fig. 1. Schematic diagram of stress on wall under different loading modes

The maximum carrying capacity and displacement range of the 295 test wall panels under vertical pressure and cyclic reciprocating horizontal loads are shown in Table 2. These data are derived from the hysteresis curves of the test wall panels. The reinforced masonry block shear walls demonstrate high strength and deformation capacities in all three failure modes. Among them, walls show the largest deformation when experiencing flexural failure, and the ultimate deformations of all three groups exceed the deformations at maximum load by more than 50%.

Table 1. Outline of test wall

Parameter	Max	Min	Parameter	Max	Min
Axial stress σ_y (N/mm ²)	0	5.88	Ratio of lateral reinforcements of wall ρ_w (%)	0	1.4
Length of wall L(mm)	900	2390	Average compressive strength of the grouted masonry blocks F_m (N/mm ²)	10	34.6
Thickness of wall panel t(mm)	90	290	Yield strength of tensile reinforcements σ_t (N/mm ²)	300	789
Effective height h_0 (mm)	405	3990	Yield strength of vertical reinforcements of wall σ_{vy} (N/mm ²)	0	789
Shear span ratio λ	0.41	2.3	Yield strength of lateral reinforcements of wall σ_{vyx} (N/mm ²)	0	624
Ratio of vertical reinforcements of wall ρ_h (%)	0.152	1.228			

Table 2. Summary of Measured Strengths and Deformations

Group	Maximum Strength				Deformation				
	τ_{Max}		τ_{Max} / F_m		$R_{Max} * 10^3$		$R_u * 10^3$		
	min	exp	min	exp	min	exp	min	exp	R_u / R_{Max}
	max		max		max		max		
S	0.56	1.63	0.03	0.1	1.2	6.79	3.32	10.71	1.58
	3.19		0.28		21.72		38.44		
F	0.39	1.26	0.02	0.06	2.00	10.06	3.33	18.41	1.83
	2.17		0.18		30.25		34.52		
FS	0.64	1.99	0.04	0.08	1.72	5.01	3.89	9.83	1.96
	3.06		0.17		17.88		36.07		

2.2 Design Formula for Shear Capacity According to Current Masonry Specifications

The formula (1) for the design of the shear capacity of reinforced masonry block shear walls in the sloping section, as per the current ‘‘Code for Masonry Structures Design’’^[4], is derived from the generalized shear friction theory and spatial variable angle truss model. It was obtained through regression analysis based on the test results of 41 reinforced masonry block shear walls in the sloping section by Yang Weijun^[5]. The regression equation is presented as formula (2).

$$V \leq \frac{1}{\lambda - 0.5} \left(0.6 f_{vg} b h_0 + 0.12 N \frac{A_w}{A} \right) + 0.9 f_{yh} \frac{A_{sh}}{s} h_0 \quad (1)$$

$$V_{g,m} = \frac{1.5}{\lambda + 0.5} \left(0.143 \sqrt{f_{g,m}} + 0.246 N_k \right) + f_{yh,m} \frac{A_{sh}}{s} h_0 \quad (2)$$

In the equations: f_{vg} represents the shear strength design value of grouted masonry; M , N , and V denote the design values of bending moment, axial force, and shear force for the calculated section; A stands for the cross-sectional area of the shear wall; A_w is the cross-sectional area of the web plate for T-shaped or inverted L-shaped sections, with A_w being equal to A for rectangular sections; λ refers to the shear span ratio of the calculated section; h_0 is the effective height of the shear wall section; A_{sh} represents the total cross-sectional area of horizontally distributed reinforcement or mesh placed in the same section; s is the vertical spacing of horizontally distributed reinforcement; f_{yh} is the design value of tensile strength for horizontal reinforcement. $f_{g,m}$ is the measured compressive strength of grouted masonry; N_k is the measured axial force on the wall section; $f_{yh,m}$ is the measured yield strength of horizontal reinforcement; $V_{g,m}$ is the calculated shear strength carrying capacity of the wall section.

By substituting the relevant parameters of each test wall from the database into formula (2), the calculated shear capacity $V_{g,m}$ of the wall can be determined. Then, the experimental values of shear capacity of the test wall are divided by the calculated value

$V_{g,m}$ from formula (2), reflecting the deviation of the formula (1) wall's shear capacity calculation results from the test results. The average value of the ratio of all the test wall's shear capacity calculation values to the test values is taken, and the coefficient of variation of the average ratio is determined, which provides a macroscopic analysis of the accuracy of formula (1).

2.3 Improvement of the Existing Shear Capacity Design Formula for Sloping Sections

Asad et al^[6] have indicated that the shear capacity of fully grouted reinforced masonry block shear walls differs significantly from that of partially grouted walls. Due to the higher strength of grouted concrete compared to mortar, the strength of mortar has a minimal impact on the shear capacity of the walls. Therefore, the shear performance of these walls is closer to that of reinforced concrete shear walls. The research of Sebastián^[7] have shown that, apart from material strength, the factors influencing the shear capacity of reinforced masonry shear walls are primarily associated with vertical normal stress, wall height-to-width ratio or shear span ratio, as well as horizontal and vertical reinforcement ratios^[7]. Formula (2) effectively reflects the principal factors influencing the shear capacity of reinforced masonry block shear walls and provides an ideal systematic expression. However, after a deviation analysis of the test values and V , it was found that Formula (2) is slightly conservative in calculating the shear capacity of walls.

Utilizing collected test results from reinforced masonry block walls subjected to low-cycle reciprocal horizontal forces and considering the contribution of vertical reinforcement anchorage, a nonlinear fitting analysis was carried out on the maximum shear capacity of walls to study the contributions of various components of reinforced masonry block shear walls to their shear capacity. The formulated equation is as follows, with α , β , γ , and δ representing undetermined coefficients.

$$V_{g,m} = \frac{1.5}{\lambda + 0.5} \left(\alpha \sqrt{f_{g,m}} b h_0 + \beta N_k \right) + \gamma f_{yh,m} \frac{A_{sh}}{s} h_0 + \delta f_y A_{sv} \quad (3)$$

Using parameters such as vertical normal stress, wall height-to-width ratio or shear span ratio from the database, a regression analysis was conducted on the maximum shear capacity of reinforced masonry block shear walls, and the least squares method was employed for solving.

2.4 Prediction of Deformation in Reinforced Masonry Shear Walls

In order to study the deformation of reinforced masonry block shear walls, it is necessary to identify the factors that significantly impact their hysteresis curves. Abdulelah et al^[8] have shown that axial load ratio, average compressive strength of masonry, shear span ratio, horizontal reinforcement ratio, and edge reinforcement ratio of vertical reinforcement have a significant influence on the deformation of walls. Utilizing the collected data from walls to obtain parameters such as axial load ratio, shear span ratio,

horizontal reinforcement ratio, and strength, regression analysis was conducted on the deformation and ultimate deformation of the walls under maximum lateral load.

3 Results & Discussion

3.1 Result of Deviation Analysis on Design Formula of Current Masonry Code

When the S group wall panels and FS group wall panels bear the maximum loads, they have the same stress mechanism. When comparing their values with the calculation value from Equation (2), they are classified as one category. The distribution of $(V_{Max}/V_{g,m})$ for this category of walls is shown in Figure 2a, with the average MV, standard deviation SD, and coefficient of variation CV seen in Table 3.

Observing Figure 2a, it can be noted that the current code for the shear capacity calculation of the reinforced masonry block shear walls tends to be conservative. For the F group walls, when they fail, the horizontal reinforcements do not yield, and the flexural capacity is less than their shear capacity. Figure 2b presents the distribution of $(V_{Max}/V_{g,m})$ for the walls that failed due to flexural behavior. Compared to the walls that failed due to shear, the distribution is more scattered, but most are still located above the red line. Based on the table, the average value of $(V_{Max}/V_{g,m})$ is 1.3, which is inconsistent with the result of walls failing due to flexure, indicating that the current code's design formula is unable to reflect the actual failure mode of the walls.

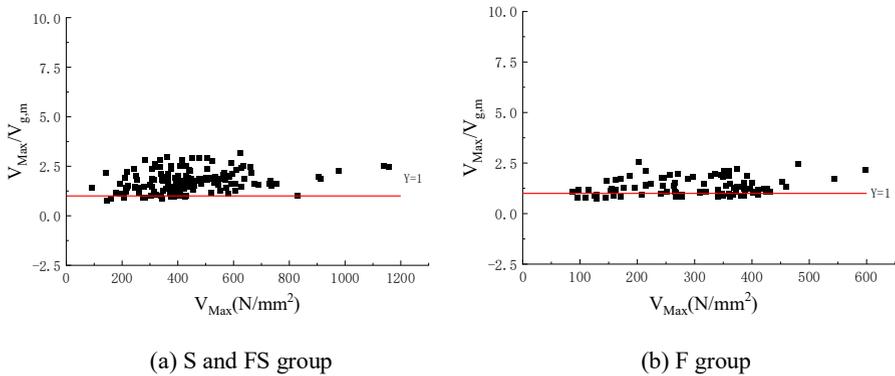


Fig. 2. Comparison Chart of Maximum Load Test Values and Calculated Values from Design Formulas

3.2 Improved Formula for Calculating Shear Capacity of Reinforced Masonry Shear Wall

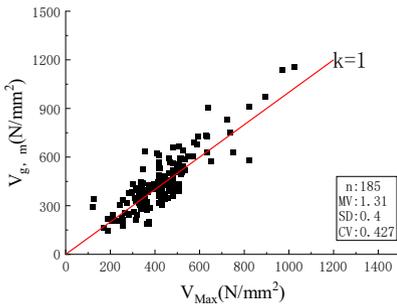
The values obtained from the regression analysis for α , β , γ , and δ are 0.24, 0.29, 0.9, and 0.052 respectively, with a coefficient of determination $R=0.9164$. The resulting formula (4) is as follows. Figure 3a shows the comparison between the maximum load

test values and the calculated values from formula (4) for the S and FS groups, with parameters such as the average value of the ratio ($V_{Max}/V_{g,m}$) shown in Table 3. Figure 3b illustrates the ratio of the maximum bending load test values for the F group walls to the values calculated using the improved formula. From the figure, it can be observed that the scattered points are evenly distributed below $Y=1$, indicating that the improved formula can effectively reflect the actual failure mode of the test walls.

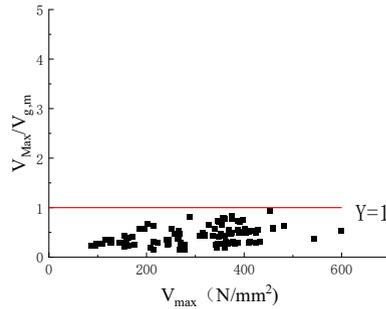
$$V_{g,m} = \frac{1.5}{\lambda + 0.5} \left(0.24\sqrt{f_{g,m}}bh_0 + 0.29N_k \right) + 0.9f_{yh,m} \frac{A_{sh}}{s} h_0 + 0.052f_y A_{sv} \quad (4)$$

Table 3. Ratios of Maximum Load Test Values to Calculated Values for Walls

Formula	Group	MV	SD	CV
(2)	S, FS	0.74	0.5	0.29
	F	1.3	0.45	0.35
(4)	S, FS	1.31	0.47	0.37



(a) S and FS group



(b) F group

Fig. 3. Comparison Chart of Maximum Load Test Values and Calculated Values from Formulas (4)

Compared to Formula (2), Formula (4) is derived from a regression analysis with more experimental data, leading to higher reliability in calculating the maximum shear capacity of reinforced masonry block shear walls. By comparing the coefficients of the two formulas, it is found that the current code's formula for slant shear capacity design may underestimate the contribution of grouted masonry blocks to the shear capacity of the walls and overestimate the influence of horizontal reinforcements. This result may also explain why in some cases, when shear tests are conducted on masonry walls without horizontal reinforcement, the design shear capacity values are much lower than the test values. The coefficient for the vertical reinforcement term is 0.052, indicating a minor contribution to the shear capacity of reinforced masonry block walls, and can be neglected in calculations.

The above analysis shows that when the reinforced masonry shear wall is under maximum load, the horizontal steel bars do not contribute their full tensile strength. The steel bars improve the overall integrity of the masonry block wall, allowing it to withstand more shear stress compared to unreinforced walls. Therefore, when designing the wall, the viewpoint that increasing the quantity of steel bars can improve the shear capacity of the wall should be carefully considered. It should be approached from the perspective of overall design, choosing appropriate section dimensions and reinforcement ratios.

3.3 Prediction Formula for Deformation of Reinforced Masonry Block Shear Walls

For shear failure:

$$R_{Max} = 3.87 \frac{H}{L} + 53.5 \frac{\rho_w \sigma_{wy}}{f_m} + 13.9 \frac{\sigma_y}{f_m} \quad (5)$$

$$R_u = 7.9 \frac{H}{L} + 146.5 \frac{\rho_w \sigma_{wy}}{f_m} + 7.15 \frac{\sigma_0}{f_m} - 66.3 \frac{\rho_h \sigma_{vy}}{f_m} \quad (6)$$

Where R_{Max} is the rotational deformation of the wall at maximum shear stress; R_u is the ultimate rotational displacement when the wall fails;

For walls tending to fail in flexure:

$$R_{Max} = 0.56 \frac{H}{L} - 36 \frac{\rho_h \sigma_{vy}}{f_m} + 6.2 \frac{\sigma_y}{f_m} \quad (7)$$

$$R_u = 1.7 \frac{H}{L} - 57 \frac{\rho_h \sigma_{vy}}{f_m} - 10.7 \frac{\sigma_y}{f_m} - 28 \frac{\rho_w \sigma_{wy}}{f_m} \quad (8)$$

Table 4. Prediction Formula for Deformation of Reinforced Masonry Block Shear Walls

Group	Formula	Multiple R	MV	SD	CV
S, FS	(4)	0.878	0.953	0.548	0.576
	(5)	0.903	1.083	0.628	0.579
F	(6)	0.24	1	0.34	0.34
	(7)	0.27	0.99	0.46	0.47

Table 4 shows the coefficient of determination of the regression equation and its comparison with test values. Through equations (4) and (5), it can be observed that for shear and flexural-shear failure, the variables selected in the regression equation exhibit a strong correlation trend with the actual deformation, with a coefficient of determination R of around 0.9. The deformation of the walls is closely related to the shear span ratio, axial load ratio, and the stress ratios of horizontal and vertical reinforcements to masonry blocks. However, for flexural deformation, the selected parameters show a

much lower correlation coefficient, of around 0.2, indicating that the selected parameters are of minor relevance to the actual deformation or cannot reflect the real deformation. The specific mechanism of flexural deformation needs further research.

4 Conclusions

In this study, a comprehensive database of experimental data for 295 reinforced masonry block shear walls, under combined vertical pressure and low-cycle reciprocating horizontal loads, was collected and established. The analysis of the data resulted in several significant conclusions

1. when comparing the maximum load test values, it was determined that the current code is overly conservative in its calculation of the shear capacity of reinforced masonry block shear walls. Additionally, it fails to accurately reflect the actual failure mode of the walls.

2. The improved formula for the shear capacity of reinforced masonry block shear walls is more accurate. A comparison with the original formula revealed that the current code's slant shear capacity design formula may underestimate the contribution of grouted masonry blocks to the shear capacity of the walls and overestimate the influence of horizontal reinforcements.

3. Deformation prediction formulas at maximum load and ultimate load have been proposed. For walls failing in shear and flexural-shear modes, the calculated values from the formulas exhibit good fit with the test values.

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