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STEPWISE REGRESSIONS FOR PREDICTING THE IN-PLANE SHEAR STRENGTH OF PARTIALLY GROUTED MASONRY WALLS

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ABSTRACT

The behaviour of partially grouted masonry shear walls is complex due to their anisotropic nature and the nonlinear interactions between blocks, mortar, grouted cells, ungrouted cells and steel reinforcement. It is crucial to develop a greater understanding in this area, as sudden shear failures of masonry walls can lead to catastrophic losses of human life and property.

This study presents the development of several new in-plane shear strength models for partially grouted masonry walls using stepwise regression. Stepwise regression identifies the most significant input variables from a pool of candidates, eliminating interdependencies and reducing the pool to an appropriate subset for predicting the output variable.

The models were generated using data compiled from 292 experimentally tested partially grouted masonry shear walls. The stepwise regressions were found to significantly outperform other existing shear strength models. It was found that, of the variables studied, the most significant ones for estimating the shear strength of partially grouted masonry walls are the axial load, wall geometry, compressive strength of mortar, and area of interior vertical reinforcement.

KEYWORDS: *partially grouted, prediction models, shear strength, stepwise regression*

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INTRODUCTION

The in-plane shear strength of masonry walls has been the subject of many studies over the past 50 years; however, the in-plane shear behavior of masonry is still not well understood. International standards have vastly different methods for predicting the in-plane shear strength of masonry, showing a lack of consensus on the matter of analytical prediction [1]. Recent studies have shown that current design equations give highly variable results in terms of accuracy when predicting the in-plane shear strength of Partially Grouted (PG) masonry in particular [2,3].

This study presents the development of several new prediction models for the in-plane shear strength of PG masonry walls. To be practical as a design equation, a model must give predictions that are both accurate and precise while maintaining appropriate levels of complexity and transparency. To achieve these goals, the current study presents models generated using stepwise regression. The performance of these models is then compared with that of the current CSA equation. Model trees are also discussed briefly, but no model trees are presented in this study.

EXISTING CSA SHEAR STRENGTH EQUATION

The in-plane shear strength equation for masonry walls is given in section 10.10.2.1 of CSA S304-14, and here as Equation 1.

$$V_n=(v_m t d_v+0.25P)\gamma_g+\left(0.6A_h f_y \frac{d_v}{s}\right)\leq 0.4\sqrt{f'_m}\, t d_v \gamma_g \quad (1)$$

where V_n is the unfactored shear resistance attributed to the masonry (N), t is the wall thickness (mm), and d_v is the effective depth of the wall (mm). P is the axial compressive load on the section under consideration (N), γ_g is a factor that accounts for partial grouting, A_h is the cross-sectional area of horizontal reinforcement (mm^2), f_{yh} is the yield strength of horizontal reinforcement (MPa), s_h is the spacing of horizontal reinforcement (mm), and f'_m is the compressive strength of masonry normal to the bed joint at 28 days (MPa). Note that some of the variable symbols have been changed to maintain consistency in this study, and strength reducing factors have been omitted.

For PG masonry, $\gamma_g=A_{net}/Lt\leq 0.5$ and A_{net} is the net area of the wall. The shear strength of the masonry, v_m, is given by Equation 2.

$$v_m=0.16\left(2-\frac{M_f}{V_f d_v}\right)\sqrt{f'_m} \quad (2)$$

where $M_f/(V_f d_v)$ is the shear span to depth ratio, taken as not more than 1 and not less than 0.25. For squat walls with H/L<1, the upper limit may be increased (CSA S304-14 section 10.10.2.2).

BACKGROUND ON STATISTICAL METHODS

Stepwise Regression

The main challenge of developing a prediction model is selecting an appropriate input variable set [4]. If too few input variables are selected, the model will be unable to capture the patterns in the data, but if too many input variables are selected, the model complexity and prediction error will both be high [5,6]. In the latter case, the model begins to fit itself to the noise in the training data in addition to fitting itself to the underlying patterns of the data (overfitting) [5].

Variable selection methods, such as stepwise regression, allow the number of input variables to be reduced to an appropriate subset [4]. They identify significant input variables while eliminating interdependencies between variables, meaning that cases where an input variable does not need to be included in the model because it could be explained by other input variables are avoided [4,7].

Stepwise regression separates candidate input variables into two sets: a selected set, and an ignored set [4]. In the first step, all the variables are in the ignored set. Variables are added one at a time to the selected set, starting with the variable which is most correlated with the output variable. The selected set is used to formulate the regression model and a partial F-test is performed to assess the significance of the variables in the resulting regression model [4]. If the p-value of any variable exceeds a predetermined value, indicating that the variable is not significant, it is removed from the regression model and returned to the ignored set [4]. The procedure ends when none of the variables in the ignored set exceed the required threshold for inclusion in the selected set.

Model Trees

MTs split data so that similar samples are clustered together and can be approximated by the same linear regression, allowing for non-linear data trends to be modeled using piecewise linear functions [4].

One study used MTs to cluster samples while implementing a modified stepwise regression at each of the resulting leaves to eliminate redundant input variables [4]. The methodology was then validated on a concrete slump dataset, as well as a large building information model dataset from the structural steel fabrication industry [4]. A similar methodology was used to develop MTs capable of predicting the in-plane shear strength of PG masonry walls [8].

METHODOLOGY

Dataset Assembly, Synthesization and Scrutinization

The models from this study were generated using a database of 292 partially grouted masonry walls compiled from 27 independent studies [8]. Following compilation, data synthesization and scrutinization were performed to ensure that the data were consistent and compatible with each other. Full details of the scrutinization and synthesization performed are available in [8].

Data synthesization is defined as "converting data to minimize variation between studies and synthesizing or predicting missing information" [9]. To this end, variations in how the compressive strength of masonry prisms was determined, as well as differences in reported shear strength, loading patterns and rates, were addressed using the correction factors proposed by Dillon [2]. For walls which had varying axial loads applied, the value of the peak axial load was estimated. Properties of reduced-scale walls were converted to those of equivalent full-scale walls using simple model scaling factors of S_L for geometric properties, S_L^2 for areas and forces, and 1 for material strengths, where S_L is the ratio of reduced-scale to equivalent full-scale wall size [8].

Data scrutinization is described as "using a set of selection/inclusion criteria" to determine which specimens should be included or excluded from a given dataset [9]. Thus, 3 walls that did not experience typical shear failures, 17 unreinforced walls, 2 double pier walls and 61 walls with missing information were removed from the complete database.

Datasets Used in this Study

Prior to commencing the data analysis, it was necessary to identify a basic set of inputs, or raw variables, that may influence the shear strength of PG masonry walls. A raw variable is one that can be measured directly, without any mathematical operations or transformations being applied. Based on the available data, a total of 34 raw variables were selected (Table 1).

Table 1: Raw variables used in this study

Variable	Definition
H	Wall height (mm)
H_{eff}	Effective wall height, dependent on support conditions (mm)
L	Wall length in the direction of applied shear force (mm)
t	Wall thickness (mm)
H_b	Actual height of CMU blocks (mm)
L_b	Actual length of CMU blocks (mm)
t_{fs}	Face shell thickness of CMU blocks (mm)
n_g	Number of grouted cells
n_t	Total number of grouted and ungrouted cells
d	Distance from extreme compression fibre to the centroid of tension reinforcement (mm)
f_{block}	Compressive strength of CMU blocks (MPa)
f_{mortar}	Compressive strength of mortar (MPa)
f_{grout}	Compressive strength of grout (MPa)
f'_{mg}	Compressive strength of grouted masonry prism with h/t=5 (MPa)
f'_{mu}	Compressive strength of ungrouted masonry prism with h/t=5 (MPa)
A_{vi}	Total area of confinement (interior vertical) reinforcement (mm^2)
A_{vf}	Total area of flexural (outer vertical) reinforcement (mm^2)
$A_{vi,bar}$	Cross-sectional area of one interior vertical reinforcement bar (mm^2)
$A_{vf,bar}$	Cross-sectional area of one flexural reinforcement bar (mm^2)
f_{yvi}	Yield strength of interior vertical reinforcement (MPa)
f_{yvf}	Yield strength of flexural reinforcement (MPa)
$s_{v,max}$	Maximum spacing between interior vertical reinforcement (mm)
$s_{v,ave}$	Average spacing between interior vertical reinforcement (mm)
A_{hbb}	Total area of bond beam reinforcement
$A_{h,bb,m}$	Total area of bond beam reinforcement, modified to ignore bars in the bottom course (mm^2)
$A_{h,bb,m2}$	Total area of bond beam reinforcement, modified to ignore bars in the top course (mm^2)
A_{hj}	Total area of joint reinforcement (mm^2)
$A_{hbb,bar}$	Cross-sectional area of one bond beam reinforcement bar (mm^2)
$A_{hj,bar}$	Cross-sectional area of one joint reinforcement ladder (mm^2)
f_{yhbb}	Yield strength of bond beam reinforcement (MPa)
f_{yhj}	Yield strength of joint reinforcement (MPa)
$s_{h,max}$	Maximum spacing between horizontal reinforcement (mm)
$s_{h,ave}$	Average spacing between horizontal reinforcement (mm)
P	Axial compressive load

Because the variables f_{block}, f_{mortar} and f_{grout} were frequently not reported by researchers, specimens missing this information would have been removed from the database as part of data scrutinization, but these variables do not appear in conventional shear strength equations. Since designers may not always have access to these values, it could be argued that they should not be included in any new shear strength equations. Consequently, two main datasets were used in this study: one which contains all of the raw variables listed in Table 2 as well as corresponding transformations (Dataset VA), and one which includes only conventional raw variables and corresponding transformations (Dataset VC). Dataset VA consists of 176 walls while Dataset VC consists of 205 walls.

Various transformations were applied by combining the raw variables through multiplication and division, to allow for non-linearities to be considered and potentially included in the generated models. Details on all the transformations that were tested as candidate variables are found in [8].

Model Generation Procedure

For each dataset, 25% of the wall specimens were randomly selected and reserved for testing. Stepwise regression models were generated in MATLAB using the function "stepwiselm". In this study, model names indicate which dataset was used for training (VA or VC) and whether the model consists of raw variables (RS) or transformed variables (TS). Variable inclusion/exclusion thresholds were adjusted between iterations of models to achieve varying levels of complexity.

Several stepwise regression models were generated, of which 27 models that contained no more than 6 terms were presented in [8]. From this set of models, those with illogical relationships, such as a negative coefficient in front of a variable which should have a positive effect on shear strength, were discarded. The remaining models were compared to each other to identify those which maximized both accuracy and precision while minimizing complexity.

RESULTS

Proposed Stepwise Regressions

Five models—three stepwise regressions and two MTs—were selected as proposed models in [8]. Although the MTs showed potential in accurately predicting the shear strength of PG masonry walls, they were outperformed by the proposed stepwise regressions. As a result, only the proposed stepwise regressions are discussed here. The first is VA-RS2 (Equation 3).

$$V_n = -0.0205H + 0.0337L + 6.00f_{mortar} + 0.0917A_{vi} + 0.289P \quad (3)$$

Because this equation only contains raw variables, the variable units are not consistent. For example, the variables H and L are measured in mm while the output variable, V_n, has units of kN. The appearance of f_{mortar}, the compressive strength of the mortar, is notable because no prior shear strength equation has included a contribution related to the strength of the mortar.

The next proposed model is VA-TS5 (Equation 4).

$$V_n=0.296P+0.255f_{mortar}t_{fs}L_b+0.291\sqrt{f_{mortar}}t_{fs}L+0.209A_{vi}f_{yvi} \quad (4)$$

This model was generated using transformed variables, resulting in an equation with consistent units, except for the presence of the square root over f_{mortar}. This inclusion is similar to including the square root of masonry prism strength in conventional shear strength equations.

The final stepwise regression that was selected as a proposed model is VC-RS3 (Equation 5).

$$V_n=0.0568L+5.18f'_m+0.175A_{vf,bar}-0.0657s_{v,ave}+0.23P \quad (5)$$

Like VA-RS2, this model contains only raw variables, meaning that the units are not consistent throughout the equation. The variable f_{mortar} does not appear in this model because it was not included in Dataset VC. Notably, f'_{mg}, the corrected grouted prism strength, appears in this equation. This variable has a positive correlation with f_{mortar} (correlation coefficient of 0.630). The appearance of $A_{vf,bar}$ is somewhat problematic, as will be discussed later on.

Each of these proposed models passed checks for homoscedasticity and multicollinearity [8].

Investigation on the Influence of Horizontal Reinforcement

It is widely accepted that horizontal reinforcement contributes to shear strength [10–12]. Almost all shear strength equations investigated in this study contain a term to account for this contribution [8]. However, none of the models initially generated in this study included any contribution to shear strength from either joint or bond beam reinforcement. An additional analysis was undertaken to investigate this issue. Full details are given in [8].

Three methods were used to generate models that included horizontal reinforcement terms: adjusting inclusion/exclusion thresholds, manually adding in horizontal reinforcement terms, and combining horizontal reinforcement terms with interior vertical reinforcement terms. Many of the resulting models did include horizontal reinforcement terms, but the models were either illogical, or only included horizontal reinforcement terms because they were effectively forced to include them. As forcing a model to include a specific variable defeats the purpose of stepwise regression, none of these models were investigated further.

Revised Model for Design Purposes

The appearance of $A_{vf,bar}$ is somewhat problematic. $A_{vf,bar}$ is the cross-sectional area of a single flexural reinforcing bar and holds little meaning as a raw variable unless it is multiplied by the number of flexural bars in the wall. Correlation analysis shows that the variable $A_{vf,bar}$ is positively correlated with A_{vf} (correlation coefficient of 0.855), which may explain why it appears in VC-RS3. Further investigation on the database compiled by [8] reveals that the way $A_{vf,bar}$ was defined in the database was inconsistent in some cases. The inconsistencies occurred in data on walls that had multiple flexural reinforcement bars of different bar sizes. Because of this inconsistency, and the fact that the variable $A_{vf,bar}$ holds very little meaning on its own, additional analysis was done to obtain an equivalent model that omits this variable.

The additional analysis used a reduced version of Dataset VC, with the only change being the removal of the variable $A_{vf,bar}$. This reduced dataset is termed Dataset VCr. Six new stepwise regressions were generated using Dataset VCr, and those with illogical relationships were eliminated. Of the remaining 3 models, the most accurate and precise was VCr-RS4 (Equation 6).

$$V_n = 0.0538L + 4.83f'_{mg} + 0.067A_{vf} - 0.0553s_{v,ave} + 0.245P \quad (6)$$

This model was generated using inclusion and exclusion threshold values of $1*10^{-5}$ and $2*10^{-5}$, respectively. The models VC-RS3 and VCr-RS4 are similar, with both containing the same variables, except that A_{vf} appears in VCr-RS4 in place of $A_{vf,bar}$. VCr-RS4 was tested for homoscedasticity (Figure 1).

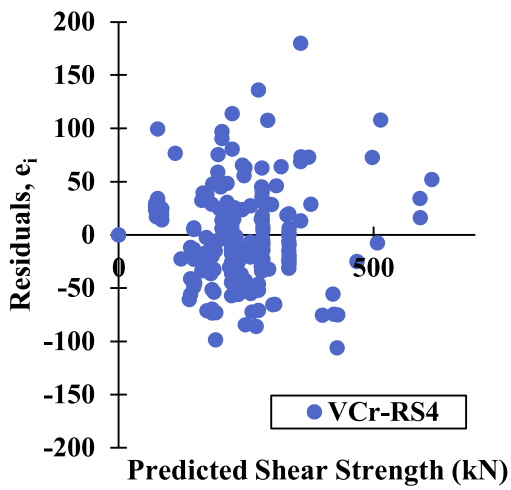

Figure 1: Residual plot for VCr-RS4

This plot shows that the variance of the error is more or less constant along the x-axis, meaning that VCr-RS4 displays appropriate levels of heteroscedasticity. VCr-RS4 also underwent the same multicollinearity test as the other proposed models (Table 2).

Table 2: VIF test results for VCr-RS4

Variable	L	f'_{mg}	A_{vf}	$s_{v,ave}$	P
VFI	1.97	1.40	2.51	2.05	1.77

Because none of the VIF values are in excess of 10, there is no significant multicollinearity in this model.

The performance of all the proposed models and the CSA equation is given in Table 2.

Table 2: Performance indicators of generated models compared to CSA equation

		VA-RS2		VA-TS5		VC-RS3		VCr-RS4		CSA
		Train	Test	Train	Test	Train	Test	Train	Test	
RMSE (kN)		36.5	37.6	35.8	38.9	43.0	41.1	44.4	43.5	129
ME (kN)		0.293	-10.6	0.105	-9.83	-2.23	-6.10	-1.80	-6.07	107
V_{exp}/V_n	Ave.	1.00	0.953	1.01	0.970	0.992	1.00	1.00	1.01	2.27
	Min	0.478	0.598	0.539	0.645	0.514	0.576	0.482	0.602	0.748
	Max	1.54	1.46	2.03	1.58	1.66	2.10	1.69	2.30	9.34
	St. Dev.	0.160	0.179	0.169	0.187	0.193	0.231	0.209	0.265	1.23

Based on these results, VCr-RS4 is a suitable replacement for VC-RS3. Because the other proposed models (VA-RS2 and VA-TS5) include an unconventional variable, f_{mortar}, VCr-RS4 is the recommended model for design purposes.

The performance of VCr-RS4 and the CSA equation is illustrated in Figure 2.

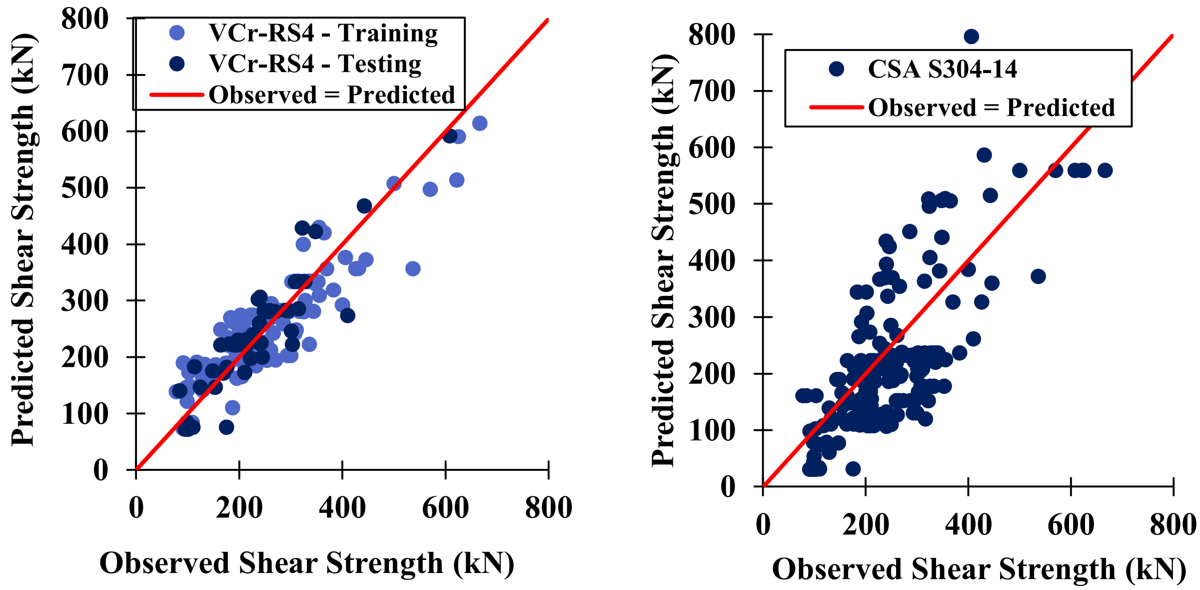

Figure 2: a) Performance of recommended model VCr-RS4 and b) Performance of current CSA equation

DISCUSSION

Significance of variables included in the models

The models generated using Dataset VA generally performed better than the models generated using Dataset VC [8]. All the models generated using Dataset VA included some form of the variable f_{mortar}, which suggests that including the contribution of mortar improves the model fit. Many of the models generated using Dataset VC, including VC-RS3 and VCr-RS4, included the variable f'_{mg}. This may be because f'_{mg} is positively correlated to f_{mortar}.

All of the proposed models included the variable P. This is consistent with the findings of numerous researchers that increasing axial load increases shear resistance [10,12,13]. All of the proposed models include a geometry related variable (H or L). This reflects the importance of aspect ratio in determining shear strength, which has been observed by many researchers [2,10,12]. Both of the VA models include terms related to the interior vertical reinforcement. This is consistent with the findings of several experimental and analytical studies that showed that interior vertical reinforcement has a positive influence on shear strength [2,14–16].

No terms related to the horizontal reinforcement appeared in any of the stepwise regressions unless they were forcefully included. This suggests that the form of the generated models is such that the contribution of the horizontal reinforcement is less significant than that of the variables that were consistently included in the stepwise regression models.

Compressive strength of the mortar

The inclusion of f_{mortar} is ground-breaking in that it has not been done in any of the existing shear strength expressions that were investigated in [8]. This could be partly because many of those expressions were developed using Fully Grouted (FG) wall data exclusively. In FG masonry, cracks pass through the blocks more than the joints, and thus the mortar joints have little influence on the shear strength of FG walls [16]. In PG walls, however, cracks pass through the mortar joints more frequently because the mortar typically plays the role of weak layers [17]. It has been observed that at high axial stress, increasing the compressive strength of mortar leads to increased shear strength [18].

One study identified mortar bond strength as one of the material properties of mortar that influences the structural performance of masonry, stating that the compressive strength of mortar is less important [19]. Another study attributed lower shear strengths of PG walls to a reduced bond between mortar and masonry units [13]. Although the compressive strength of mortar may not be the best variable to quantify the contribution of mortar to shear strength, it is possible that there is a correlation between f_{mortar} and the bond strength of mortar, which would explain the consistent appearance of f_{mortar} in the generated models.

Absence of horizontal reinforcement term

The absence of the horizontal reinforcement term in the generated models is unexpected, as almost all existing shear strength equations include a contribution from the horizontal reinforcement [8]. However, the additional analysis that was done in this area confirmed that the horizontal reinforcement terms were omitted because, for the range of available data, they were less statistically significant than the other variables considered.

Several researchers have observed that horizontal reinforcement has inconsistent or negligeable effects on the shear strength of masonry walls. It was noted in one study that increasing horizontal joint reinforcement from 0.056 to 0.11% led to increases in ultimate shear stress of 20% and 7% for PG walls with aspect ratios of 1 and 0.7, respectively, and a 7% decrease in shear strength for walls with aspect ratios of 0.5 [20]. In another study, researchers developed a macro Finite Element Model (FEM) of several lightweight concrete block masonry walls reinforced horizontally with joint reinforcement that had also been experimentally tested [21]. Both the experimental results and the FEM showed that the horizontal reinforcement did not have a noticeable contribution to the lateral peak load [21]. Researchers who studied a macro FEM of a two-storey PG wall found that varying the level of reinforcement in the middle horizontal bond beam of the wall from 0.03% to 0.48% led to a negligible increase in shear strength [22]. They concluded that the shear strength contribution from the horizontal reinforcement was negligible [22].

One possible explanation for the apparent lack of a contribution from the horizontal reinforcement is that the horizontal reinforcement may not be engaged before the shear failure occurs. However, it is important to note that horizontal reinforcement is crucial in providing ductility to masonry walls failing in shear. A design equation that ignores this fact could lead to designers neglecting to reinforce shear walls appropriately if minimum requirements are not specified. To ensure that these models do not lead to unsafe designs, their limitations must be acknowledged.

Limitations

It should be noted that the principle reason that one model outperforms another on a given set of data may be that it was generated from the same dataset used to test the models [2]. Although 25% of the collected data were reserved purely for testing purposes, these testing sets were still relatively small due to the limited amount of data available.

Additionally, these models are only dependable within the range of data used to train them, and thus cannot be used with confidence for extrapolation purposes.

CONCLUSIONS AND RECOMMENDATIONS

The stepwise regression models presented in this study achieve high accuracy and precision in predicting the in-plane shear strength of PG masonry walls without sacrificing simplicity and transparency. The presented models all outperform the current CSA shear strength equation. The amount of data synthesization and scrutinization required in this study highlight the need for researchers to be thorough in their reporting on experimental studies. In particular, variables such as f_{mortar}, f_{block} and f_{grout} are frequently not reported. This makes it difficult to determine the influence of these variables on the behaviour of masonry walls. Care should be taken in future testing to ensure that all of the raw variables listed in Table 1 are either reported or can be easily determined from the reported data. In particular, the strength of mortar, blocks, and grout should be reported and the methods used to test these materials should be clearly noted.

The generated models suggest that mortar plays an important role in contributing to the in-plane shear strength of PG masonry walls. The effects of the compressive strength of mortar, and other mortar qualities such as bond strength, should be studied further to validate this conclusion. The inclusion of the interior vertical reinforcement in several of the generated models agrees with the findings of researchers who have concluded that interior vertical reinforcement has a positive influence on shear strength [2,14–16].

No terms related to the horizontal reinforcement appeared in any of the selected stepwise regressions until steps were taken to force the inclusion of the horizontal reinforcement terms. This suggests that the contribution of the horizontal reinforcement is less significant than that of the variables that appear in the stepwise regression models. Although the absence of the horizontal reinforcement term in the majority of the generated models is unexpected, it is not altogether inconsistent with findings of other researchers. Some researchers have found that increases to the amount of horizontal reinforcement lead to inconsistent or negligeable effects on the shear strength of masonry walls [20–22]. More testing is needed to obtain conclusive evidence on this matter.

The models presented in this study are subject to certain limitations. These models are only dependable within the range of variables in the data that were used to train them. Due to the limited amount of data that were available, datasets reserved for testing were relatively small. Validation of the models using additional data is recommended. Reliability analysis is required prior to adopting any new equation for design purposes.

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