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Spatial variability and stochastic strength prediction of unreinforced masonry walls in vertical bending

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ABSTRACT

The flexural bond strength of unreinforced masonry (URM) is a key material property affecting wall out-of-plane lateral load capacity. It is well known that the unit flexural bond strength (defined here as the flexural strength of the bond between the brick and lower mortar bed joint associated with any given masonry unit (brick)) varies considerably between units, and that this spatial variability might significantly affect the structural performance and reliability of URM walls in flexure. The paper develops a computational method to predict the strength for non-load bearing single skin URM walls subject to one-way vertical bending considering unit-to-unit spatial variability of flexural bond strength. We characterise the probability distributions of wall strength and examine how spatial variability in unit flexural bond strength affects the variability of base cracking load, mid-height cracking load, peak load and behaviour of clay brick URM walls. This is done using 3-D non-linear Finite Element Analyses (FEA) and stochastic analysis in the form of Monte Carlo simulations. Varying COVs (0.1, 0.3 and 0.5) of unit flexural bond strength are considered. The mean and variance of wall strength are estimated to show the effect of spatial variability of flexural bond strength on wall strength. The failure modes of the wall are compared to show the significant differences between non-spatial and spatial analyses.

1. Introduction

The Australian masonry design code (AS3700-2011) [1] has been in a limit states format since 1988. Although it is commonly believed that current design models are conservative, the actual level of safety of masonry structures is not known. It is unclear how to compare the structures designed according to the masonry design code with the structures designed using other materials in terms of reliability (or safety) and whether different masonry walls and other structural elements have similar levels of reliability. The problem is compounded by the fact that the strength properties of masonry are highly variable, particularly the unit-to-unit flexural bond strength, due to variations in the quality of workmanship, the weather during construction, and the materials from location to location, all within one structure.

The random fields and probabilistic analyses of structures have been studied in the past few decades [2–8], however, many existing analyses of structures assume uniform flexural bond strength in the masonry wall, rather than considering the unit-to-unit spatial variability of flexural bond strength, the latter being a more realistic approach in examining material variability. In fact, the existence and importance of spatial variability of strength properties in the masonry wall has been observed in past studies. For instance, Baker and Franken [9] discussed the effects of random variation in the flexural bond strength of brick work as early as 1976. Then Baker [10] and Lawrence [11] stressed the importance of considering this factor and used Monte Carlo techniques to model its effects in analysis. Somewhat differently, the present paper explains the progression of failure, from the first crack to the post peak. Lawrence [12] suggested that assuming statistical independence of individual unit strengths provides wall capacities consistent with experimental results for vertical one-way bending. The unit-to-unit spatial variability in flexural bond strength was considered in the masonry reliability analysis by Stewart and Lawrence [13] by means of three highly idealised hypotheses. [13] also investigated the impact of wall width, workmanship and discretising of masonry unit thickness on the reliability index. By contrast, the present paper compares wall failure progression between non-spatial and spatial simulations using stochastic Finite Element Analyses (FEA), which was considered more realistic in solving a wide range of structural engineering problems relating to random fields, such as loads and material properties [14]. Stewart and Lawrence [15] estimated the characteristic masonry compressive strength by taking into account the unit compressive strength when performing the masonry analysis calculations, but only in

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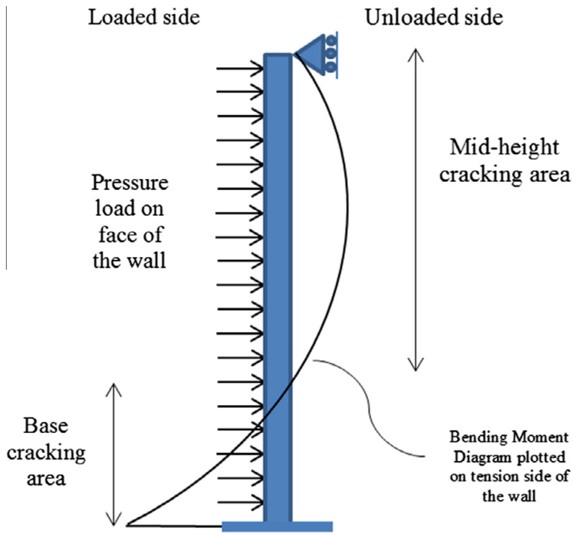

Fig. 1. Diagram for illustrating base cracking and mid-height cracking.

the form of the measured mean and standard deviation of unit strength rather than unit-to-unit spatial variability. In recent studies (e.g., [16]), the extent of spatial correlation between unit flexural bond strengths within clay brick walls was examined experimentally, for which it was recommended that each unit has a flexural bond strength that is statistically independent of its neighbours. This, perhaps unexpected, result was attributed by [16] to the significant influence of workmanship during construction on the unit flexural bond strength and the fact that the way each masonry unit is placed in the fresh mortar bed by the mason is no more closely related to the immediately adjacent units in the wall than to units elsewhere in the wall and indeed the building.

While there has been a number of studies of the effects of variability and workmanship on the strength of structural masonry [9,17–20], very few studies have considered computational methods to calculate the structural reliability of masonry structures. However, Stewart and Lawrence [13,15] developed preliminary 'proof-of-concept' techniques to estimate the structural reliability of masonry walls for vertical one-way bending, compression and shear loading (e.g., [21–23]). Stewart and Lawrence [13] developed a structural reliability model to calculate the probability of failure for masonry walls in flexure, considering the unit-to-unit variability of flexural bond strength, and showed the important effect that the unit-to-unit spatial variability could have on strength prediction and structural reliability.

The current paper presents a computational method, using 3-D non-linear Finite Element Analyses and stochastic analysis in the form of Monte Carlo simulations, to calculate the mean and variance of strength prediction for URM walls subjected to one-way vertical bending. This allows the progression of failure to be modelled from first cracking to peak load. It provides statistical evidence to illustrate the significant importance of considering the unit-to-unit spatial variability of flexural bond strength by comparing the probability distributions obtained from non-spatial and spatial analyses, for the base cracking load (the load at which tensile cracking first occurs in the base region of the wall on the loaded side, see Fig. 1), the mid-height cracking load (the load at which tensile cracking appears in the mid-height region of the wall on the unloaded side) and the peak load. Finally, the failure modes obtained from non-spatial and spatial analysis models are compared.

2. Probabilistic models

A deterministic model is generated before the establishment of non-spatial and spatial probabilistic analysis models. In this section, a 3-D non-linear FEA model of a full sized, single leaf clay

Table 2
Summary of 3-D FEA element type and mesh selection for the full sized wall.

Brick/mortar bodies	Element types	Mesh density
Masonry units (Bricks)	HE20 CHX60	$2 \times 4 \times 1$
Mortar joints	IS88 CQ48I	$2 \times 4 \times 1$
Mid-length brick interface element	IS88 CQ48I	$1 \times 4 \times 1$

Table 1
Summary of material parameters to be used in the 3-D FEA model.

Brick/mortar	Property	Value
Horizontal and vertical mortar joint interface elements	Linear normal stiffness modulus	353 N/mm^3
	Linear tangential stiffness modulus	146 N/mm^3
	Direct tensile strength	Variable
	Tensile fracture energy	Variable
	Cohesion	0.65 N/mm^2
	Tangent friction angle	0.75
	Tangent dilatancy angle	0.6
	Tangent residual friction angle	0.75
	Confining normal stress	−1.2 N/mm^2
	Exponential degradation coefficient	5
	Capped critical compressive strength	20 (25)[a] N/mm^2
	Shear traction control factor	9
	Compressive fracture energy	15 N mm/mm^2
	Equivalent plastic relative displacement	0.12
	Shear fracture energy factor	0.15
Expanded brick elements	Brick Young's modulus	20,000 N/mm^2
	Brick's Poisson's ratio	0.15
	Brick density	1800 kg/m^3
Potential brick cracks (all values are artificially high to force cracking in mortar joints and not bricks)	Linear normal stiffness modulus	1000 N/mm^3
	Linear tangential stiffness modulus	1000 N/mm^3
	Direct tensile strength	2 N/mm^2
	Fracture energy	0.5 N mm/mm^2

[a] 25 N/mm^2 is used in the FEA model with f_t = 1.4 MPa for the parameter consistency in the analysis.