IV–37. Stress-Strain Behaviour of Masonry Walls

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ABSTRACT

The stress-strain behaviour of clay masonry walls built from giant hollow load-bearing units bonded by type N mortar of both masonry cement and lime is reported. Walls were 2 units long and 10 courses high. Loading was applied centrally, and at eccentricities of approximately t/6 and approximately t/3, until failure.

The effect of eccentricity on the strength and stress-strain behaviour of masonry is discussed. Previously developed models are used to predict the elastic modulus of the masonry from the elastic moduli of the component materials. These models are found to be reasonably accurate.

For comparative purposes, results are also presented for concrete block walls of the same overall dimensions and subject to the same load conditions. Previously published methods for determining the elastic modulus of masonry are considered.

Le comportement contrainte/déformation de murs de maçonnerie d'argile construits à l'aide de grosses briques partiellement vide relieés par deux genres de mortier de type N, soit le ciment de maçonnerie et la chaux, est présenté. Les murs avaient 2 unités en longueur et 10 unités en hauteur. Les charges étaient appliquées au centre et à des excentricités approximativement de t/6 et t/3 jusqu'à affondrement.

L'effect de l'excentricité sur la force et le comportement contrainte/déformation de maçonneries est discuté. De précédents modèles sont employés pour prédire le module d'élasticité de la maçonnerie à l'aide des modules d'élasticité des composantes. Ces modèles se sont avérés être raisonnablement précis.

Pour comparaison, des résultats sont aussi présentés pour des murs de ciment de mêmes dimensions et soumis aux mêmes charges. Précédentes méthodes pour déterminer les modules d'élasticité des maçonneries sont considéreés.

Der vorliegende Report behandelt das Spannungs-dehnungsverhalten von Mauerwerkswänden aus konstruktiven Großhohlblocksteinen und "type N"-Mörtel, hergestellt mit Mauerwerkszement oder Kalk.Die Wände wurden 2 Einheiten lang und 10 Schichten hoch hergestellt, und mittig sowie mit etwa t/6 und t/3 Exzentrizität bis zum Bruch belastet.

Der Einfluß der Exzentrizität auf die Tragfähigkeit sowie das Spannungs-dehnungsverhalten von Mauerwerk wird diskutiert. Der Elastizitäts-modul des Mauerwerks wird unter Verwendung von früher entwickelten Modellen, basierend auf den Elastizitätsmodulen der verwendeten Materialien hergeleitet. Diese Modelle stellen sich als angemessen genau heraus. Zum Vergleich werden Ergebnisse von Betonsteinwäden der selben Aussenabmessungen und der selbel Belastung aufgeführt. Verfahren zur Bestimmung des Elastizitätsmoduls von Mauerwerk aus anderen Veröffentlichungen werden in Betracht gezogen.

Il rapporto tratta della relazione tra sforzo e tensione di muri construiti con stragrandi unitá in terracotta, vuote e portanti, cementate con un tipo di malta N di cemento da muratura e calce. I muri sono lunghi 2 unitá e alti 10 corsi. Il carico é stato applicato centralmente e ad eccentricitá approsimativamente di t/6 e di t/3, fino a crollo.

Vengono discussi gli effetti dell'eccentricitá sulla forza e sulla relazione tra sforzo e tensione della muratura. Sono stati usati modelli, sviluppati precedentemente, per predire il coefficiente di elasticitá della muratura dai coefficienti di elasticitá dei materiali componenti. Questi modelli sono di un'accuratezza ragionevole.

Allo scopo di render possibili dei paragoni, si riferiscono anche i risultati relativi a muri in blocchi di calcestruzzo delle stresse dimensioni complessive e soggetti allo stresso carico; e sono stati presi in considerazione metodi, pubblicati in precedenza, per determinare il coefficiente d'elasticitá dei materiali da costruzione.

INTRODUCTION

A number of studies have been performed on the stress-strain behaviour of masonry. Turnsek and Kacovic (1970) developed a non-linear stress-strain relationship for the walls they tested. Sahlin (1971) found that the stress-strain curve varied with different types of mortar and unit. Powell and Hodgkinson (1976) also found a variation in stress-strain behaviour and concluded that for design purposes different moduli should be used for the different types of masonry.

In the working stress range, the stress-strain relationship is essentially linear, although the modulus of elasticity may be expected to vary with both materials and geometric configuration. There is some need therefore, to be able to predict the elastic modulus of various masonry configurations and material combinations in order to improve design procedures. We will show in this paper that it is possible to predict the elastic modulus of masonry with reasonable accuracy from a knowledge of the component properties and the geometric configuration. The predicted values of elastic modulus are compared with the experimentally determined values. The problem of predicting the elastic modulus of masonry has received attention before. The methods proposed by Base and Baker (1973), Eskenazi, Ojinag and Turkstra (1975), Grimm (1975), Lenczner (1978), and Plowman (1965) are compared with the present Canadian Standard (CSA S304, 1977) and the values determined experimentally, as now described.

EXPERIMENTS

Eighteen 2 unit long (800mm) and 10 courses high (990mm) clay brick walls were tested in uniaxial compression to failure. Type N masonry cement mortar (volume proportions 1:3 (Masonry cement: masonry sand)) was used in nine of the walls. In the other nine walls, type N lime mortar was used (volume proportions 1:1:6 (portland cement: hydrated lime: masonry sand)). The units were "200 giant" brick units with nominal dimensions 400 × 200 × 100 mm, and the corresponding half units. A typical wall profile and a horizontal section of a mortar joint are shown diagrammatically in Figure 1.

Central uniaxial loading was applied to three walls in each group of nine. Eccentric loading was applied to groups of three walls at eccentricities of approximately t/6 and approximately t/3. With centrally loaded walls, strain measurements were taken on both faces and averaged, but only the compressive strains were considered on the eccentrically loaded walls.

Uniaxial compression tests were also performed on individual units and mortar cubes and cylinders. Stress-strain data were obtained from these tests.

RESULTS AND DISCUSSIONS

The mean values of the ultimate strengths for the various tests on masonry are compared in Table 1. Data from concrete block walls under similar loading conditions are also shown. The ratios of the ultimate strengths show that higher ultimate strengths are obtained under eccentric loading. However, doubling the eccentricity from approximately t/6 (e = 35mm) to approximately t/3 (e = 70mm) has negligible effect on the ultimate strength of the masonry. A non-linear strain gradient effect clearly exists.

Student t-tests were used to determine if the stress-strain relationship of the masonry was affected by the eccentricity of the load. The results showed that there was no effect for the majority of the stress-strain curve. This result is not surprising for these walls. Relatively uniform stress might be expected on the faces of the units, with the majority of the strain variation occurring in the webs.

Regression analysis was used to obtain the best-fit polynomial curves for the stress-strain data. The initial tangent moduli of elasticity were then determined. Tangent moduli for the individual units and mortars together with the resultant masonry are shown in Table 2. Concrete block values are also given for comparison.

Mathematical models for predicting the elastic modulus of masonry from the elastic moduli of the components have been described previously by Jessop, Shrive and England (1978). Repeating units within masonry are considered as combinations of parallel and series models (see Figure 2) and analyzed using conditions of equilibrium and compatibility. The models may be generalized by using the cross-sectional areas of the mortar and unit instead of edge dimensions as previously. This modification allows the mathematical models to be used for units of more general configuration and for more general mortaring schemes. The following equations are obtained.

MODEL 1

$$E_{mas} = \frac{A_j E_m (H_b + H_m)(A_b E_b + A_m E_m)}{A_{mas}(A_j E_m H_b + (A_b E_b + A_m E_m) H_m)}$$

$$\text{where } A_{mas} = \frac{A_j (A_b + A_m)(H_b + H_m)}{A_j H_b + (A_b + A_m) H_m}$$

MODEL 2

$$E_{mas} = \frac{(H_b + H_m)}{A_{mas}} \left[\frac{A_b A_j E_b E_m}{A_b E_b H_m + A_j E_m H_b} + \frac{A_m E_m}{H_b + H_m} \right]$$

$$\text{where } A_{mas} = (H_b + H_m) \left[\frac{A_b A_j}{A_b H_m + A_j H_b} + \frac{A_m}{H_b + H_m} \right]$$

MODEL 3

$$E_{mas} = \frac{E_m E_b (H_b + H_m)}{A_{mas}} \left[\frac{4A_m A_{bm}(A_{bj} E_b H_m + A_j E_m H_b) + A_j A_{bi}\,[A_{bm} E_b (H_b + 2H_m) + A_m E_m H_b]}{(A_{bj} E_b H_m + \text{-}a_j E_m H_b)(A_{bm} E_b (H_b + 2H_m) + A_m E_m H_b)} \right]$$

$$\text{where } A_{mas} = \frac{(H_b + H_m)\,[4A_m A_{bm}(A_{bj} H_m + A_j H_b) + A_j A_{bi}\,[A_{bm}(H_b + 2H_m) + A_m H_b]]}{(A_{bj} H_m + A_j H_b)(A_{bm}(H_b + 2H_m) + A_m H_b)}$$

In these equations, A is used for cross sectional areas in plan view, E for elastic moduli and H for vertical heights (in side elevation (see Figure 2)). The subscript *b* is used for the unit (brick or block), *m* for mortar and *j* for the cross sectional area of the horizontal bedding joint as needed in the models (see Figure 2). The subscript *mas* is used to denote the masonry property.

Using the appropriate geometric values for the walls tested and experimentally determined values of initial tangent elastic moduli for the various masonry components,

theoretical values for the elastic modulus of masonry were obtained. These values are shown in Table 3 and are compared with the experimentally determined values. Again concrete block values are included for comparison. It may be seen that the models give close predictions for masonry with type N masonry cement mortar. The results for the lime mortar masonries are not as satisfactory.

From the cylinder tests on the mortars, the lime mortar appeared stiffer than the masonry cement mortar. The models indicate that with a given unit, the modulus of elasticity of the masonry will increase if the modulus of elasticity of the mortar increases. Experimentally we find this trend followed with the concrete block masonry, but not with the clay brick masonry. Examination of the data in more detail (Khalil, 1979) reveals that the most flexible batches of type N lime mortar were used to construct the clay brick walls. If the mean initial tangent modulus of these batches is used in the model calculations for clay brick walls, then a more accurate prediction is obtained (see Table 2, bottom two rows). Using the mean initial tangent modulus of the mortar batches for the block masonry also improves those predictions.

Considering the variability of the component moduli, the results show that the models can be used to predict the masonry modulus of elasticity with reasonable accuracy. It is clear, however, that some care must be taken with quality control to obtain consistent mortar properties and that calculations should use the mean value for the mortar actually used in the masonry, rather than separately prepared batches.

The same input data as was used for the top four lines of Table 3 was used in Table 4 where further predictions of elastic modulus are shown. These predictions were made using equations previously published. As may be seen the errors vary conisderably. The model proposed by Base and Baker (1973) provides similar accuracy to those proposed here for the clay brick masonry but not for the concrete block masonry.

CONCLUSIONS

Theoretical models can be used to predict the elastic modulus of masonry walls with reasonable accuracy. In order for the predicted values to have meaning, careful quality control must be exercised and values of properties of materials actually used in the masonry should be used. There does not appear to be a strain gradient effect on the stress-strain behaviour of masonry although a clear strain gradient effect exists with respect to the ultimate stress.

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TABLE 1—Effect of eccentricity of loading on masonry strength

Masonry Type	e = 0		e = 35 mm			e = 70 mm		
	Strength MPa		Strength MPa			Strength MPa		
	Mean	Standard Deviation	Mean	Standard Deviation	Strength/Axial Strength	Mean	Standard Deviation	Strength/Axial Strength
Clay brick wall, type N, masonry cement mortar	9.23	1.63	11.48	0.86	1.24	10.57	0.78	1.15
Clay brick wall, type N, lime mortar	8.75	1.35	12.84	1.18	1.47	14.95	1.52	1.71
Concrete block wall, type N, masonry cement mortar	5.27	0.51	8.44	0.78	1.60	8.30	1.02	1.57
Concrete block wall, type N, lime mortar	6.46	0.51	8.93	0.63	1.38	9.03	1.97	1.40

TABLE 2—The best fitting polynomials for the stress-strain data of the different types of masonry tested, and the individual components.

Material	Stress-strain equation (with σ in MPa and ϵ in microstrain)
Clay brick wall, type N, masonry cement mortar	$\sigma = 7111.4\epsilon - 2249.3(10)^3\epsilon^2 + 2918.8(10)^5\epsilon^3$
Clay brick wall, type N, lime mortar	$\sigma = 6862.3\epsilon - 1785.1(10)^3\epsilon^2 + 2152.6(10)^5\epsilon^3$
Concrete block wall, type N, masonry cement mortar	$\sigma = 5806.9\epsilon - 1116.4(10)^3\epsilon^2$
Concrete block wall, type N, lime mortar	$\sigma = 7573\epsilon - 2902.4(10)^3\epsilon^2 + 5833.3(10)^5\epsilon^3$
Type N, masonry cement mortar	$\sigma = 7543.3\epsilon - 5125.9(10)^3\epsilon^2 + 1174.8(10)^6\epsilon^3$
Type N, lime mortar	$\sigma = 10623\epsilon - 1130.8(10)^4\epsilon^2 + 5075.1(10)^6\epsilon^3 - 8046.1(10)^8\epsilon^4$
Clay units	$\sigma = 7724.6\epsilon + 7637.3(10)^2\epsilon^2 - 1653.2(10)^5\epsilon^3$
Concrete units	$\sigma = 5978.1\epsilon - 3906.1(10)^2\epsilon^2$

TABLE 3—Elastic Modulus of Masonry predicted by theoretical models compared with experimentally determined values.
The values of elastic modulus have been rounded but the errors were calculated before rounding.

Masonry	Experimentally determined elastic modulus (GPa)	Model 1		Model 2		Model 3	
		Elastic Modulus (GPa)	% error from exptl.	Elastic Modulus (GPa)	% error from exptl.	Elastic Modulus (GPa)	% error from exptl.
Clay brick, type N, mas. cement	7.1	7.7	8.0	7.7	8.0	7.7	8.0
Clay brick, type N, lime	6.9	8.0	16.2	8.0	16.2	8.0	15.9
Concrete block, type N, mas. cement	5.8	6.1	5.3	6 .1	5.3	6.1	5.5
Concrete block, type N, lime	7.6	6.3	−17.7	6.3	−17. 7	6.3	−17.1
Clay brick, type N, lime*	6.9	7.5	8.8	7.5	8.8	7.5	8.7
Concrete block type N, lime*	7.6	6.4	−16.3	6.4	−16.3	6.4	−15.7

(Component values of Elastic Modulus were:

Type N masonry cement mortar, 7.5 GPa
Type N lime mortar, 10.6 GPa ←——→ *using for clay brick 6.4 GPa and concrete block 13.7 GPa
Clay units, 7.7 GPa
Concrete units, 6.0 GPa)

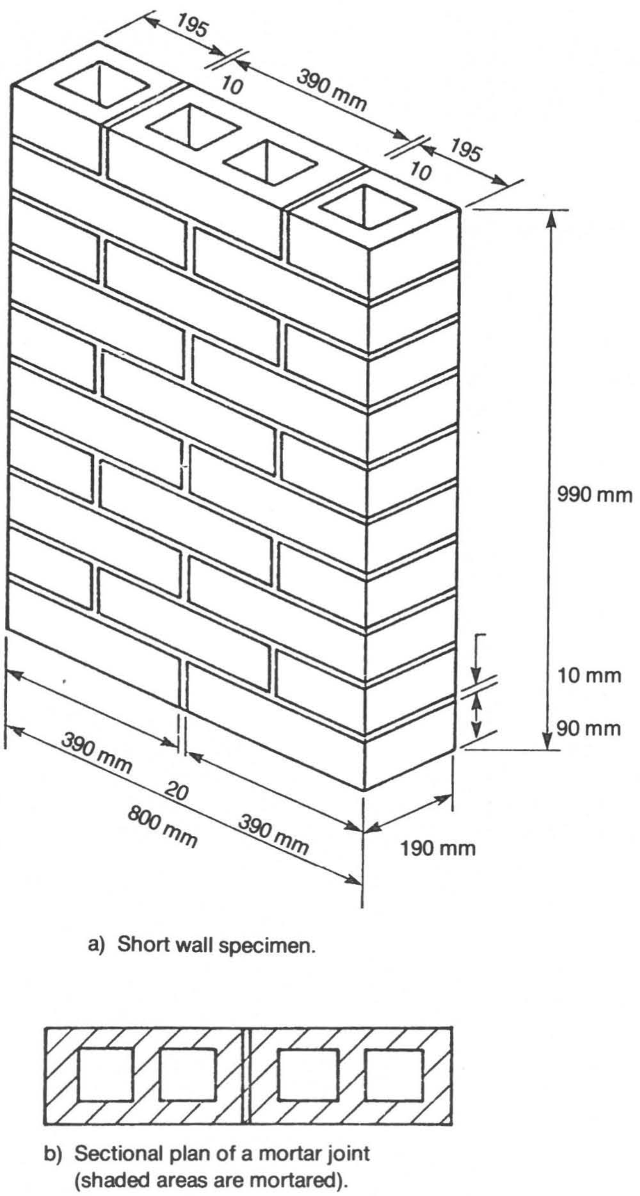
TABLE 4—Elastic Modulus of masonry predicted from previously published equations. The percentage error with respect to the experimental value is also shown.

Masonry type	C.S.A. S 304 (1977) Method A		C.S.A. S 304 (1977) Method B		Plowman (1965) from f'_m		Plowman (1965) from f'_{brick}	
	E(GPa)	% error	E(GPa)	% error	E(GPa)	% error	E(GPa)	% error
Clay brick, masonry cement mortar	11.4	*59.8*	5.5	*−22.4*	11.4	*59.8*	11.5	*61.8*
Clay brick, lime mortar	8.2	*19.5*	5.5	*−19.6*	8.2	*19.5*	4.5	*−34.4*
Concrete block, masonry cement mortar	6.9	*19.1*	5.5	*− 5.1*	—	—	—	—
Concrete block, lime mortar	7.2	*− 4.7*	5.5	*−27.2*	—	—	—	—

TABLE 4—Continued.

Masonry type	Grimm (1975) E(GPa)	Grimm (1975) % error	Eskenazi et al (1975) E(GPa)	Eskenazi et al (1975) % error	Lenczner (1978) E(GPa)	Lenczner (1978) % error	Base & Baker (1973)* E(GPa)	Base & Baker (1973)* % error
Clay brick, masonry cement mortar	6.0	*−15.1*	6.0	*−16.1*	5.0	*−29.1*	7.7	*8.0*
Clay brick, lime mortar	4.4	*−36.5*	6.0	*−13.1*	5.0	*−27.1*	7.9	*14.5*
Concrete block, masonry cement mortar	4.2	*−28.1*	8.5	*46.4*	5.0	*−13.9*	4.1	*−30.2*
Concrete block, lime mortar	4.6	*−39.3*	8.8	*16.8*	5.0	*−34.0*	4.1	*−46.0*

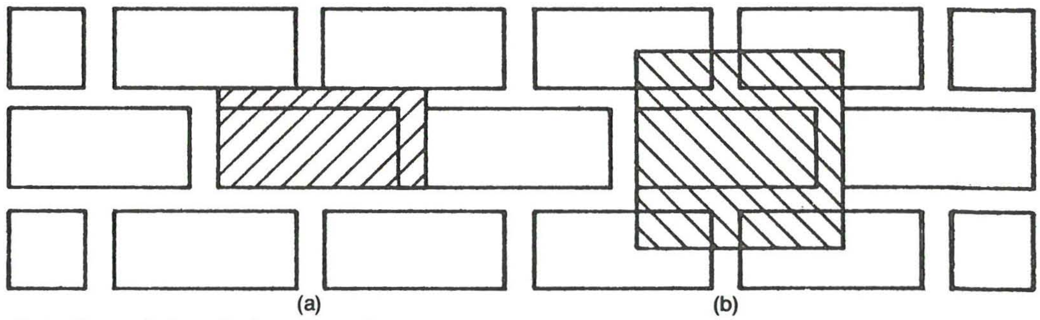
*This model is for solid units or units with small cores. In the calculations here the net and gross areas have been assumed to be those used in the calculations for Table 3.



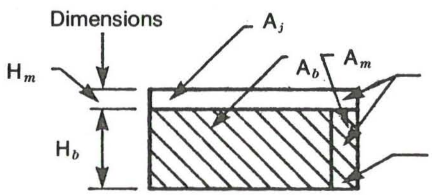
a) Short wall specimen.

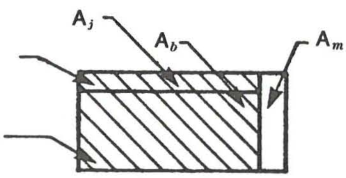
b) Sectional plan of a mortar joint (shaded areas are mortared).

Figure 1. A typical clay brick wall as used in the tests.



Repeating units in a single wythe wall.
(a) small unit (b) large unit



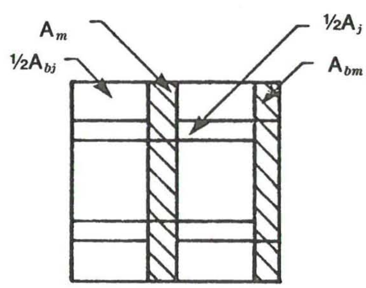


MODEL 1

(from small repeating unit)
Brick (block) in parallel with vertical mortar joint with this in series with horizontal mortar bed.

MODEL 2

(from small repeating unit)
Brick and part of horizontal bed in series, with this in parallel with vertical mortar joint.



MODEL 3

(from large repeating unit)
Two series combinations in parallel with each other.

Figure 2. Repeating units and models for a single wythe wall. The models are shown in side elevation: the cross-sectional areas (as seen in a plan view) of designated sections are labelled.