INVESTIGATION OF EFFECTIVE MODULUS OF ELASTICITY AND SHEAR MODULUS OF BRICK MASONRY WALL UNDER LATERAL LOAD

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ABSTRACT

A large number of older buildings, including a majority of heritage structures in Canada, have been constructed using unreinforced load-bearing masonry systems and construction methods. The structural integrity of these masonry buildings has been declining overtime and many of these buildings require repair and restoration.

As these buildings are restored, their compliance to current codes is being examined and their capacity to withstand seismic loads is becoming a concern. Environmental loads, such as freeze-thaw cycles, have contributed to the weakening of the infrastructure. Since masonry structures, especially unreinforced masonry structures, are weaker in tension than in compression, they are more vulnerable to lateral loads. In seismic areas, rehabilitation of masonry structures is critical in order to ensure continuous safe and satisfactory performance. Full understanding of the material properties and accurate estimation of the effective modulus of elasticity and the shear modulus of masonry structures is an essential prerequisite in the evaluation of any rehabilitation techniques.

An experimental program is currently in progress at the University of Manitoba to investigate the lateral displacement, the modulus of elasticity and the shear modulus of brick masonry walls. The first phase of the experimental program involves the testing of three unreinforced brick masonry walls with various heights under in-plane and vertical loads. Linear Variable Differential Transducers and strain gauges are used to monitor displacements and strains. The experimental data are used to evaluate the uncracked modulus of elasticity and the shear modulus of brick walls under flexure and are compared with the numerical analysis.

KEYWORDS: brick masonry, effective modulus of elasticity, shear modulus, flexure, heritage structures, lateral load.

OBJECTIVE

The objective of this research project is to estimate the effective modulus of elasticity (E) and shear modulus (G) of brick masonry walls in flexure, while ensuring the displacements of the walls are small enough to prevent cracking of the mortar.

INTRODUCTION

One of the oldest construction materials around the world is masonry. It has been used as a structural element for more than eight millennia around the world. Not only have most of the historical buildings been built of unreinforced clay brick masonry but also many nuclear power plants of the 20^{th} century. A large number of masonry buildings in Canada have been constructed in the last 200 years. The structural integrity of these old masonry buildings has been declining. One of the main reasons for this deterioration is related to the fact that these structures have not been designed to resist lateral earthquake forces but mainly to resist vertical loading. Since masonry structures are weaker in tension than they are in compression, they are more vulnerable to failure under lateral load than to vertical load. The failure of masonry walls also depends on bonding between the mortar and masonry units. The effective design, repair and strengthening of masonry buildings therefore requires sound knowledge of the behaviour of masonry materials, structural behaviour and construction methods.

SCOPE

The experimental program will investigate the lateral displacement, modulus of elasticity (E) and shear modulus (G) of brick masonry walls. A total of three unreinforced brick masonry walls will be constructed and tested under in-plane horizontal loads to study the uncracked flexural behaviour. The dimensions of the masonry walls will be as follows:

Test specimen 1: 1.0m (height) × 1m (width) × 0.21m (thickness)

Test specimen 2: 1.5m (height) × 1m (width) × 0.21m (thickness)

Test specimen 3: 2.0m (height) × 1m (width) × 0.21m (thickness)

LITERATURE REVIEW

The behaviour of masonry walls in seismic areas is influenced by several factors. One of the main factors is the performance under in-plane lateral load, which is further related to various parameters including the properties of masonry components and their performance under lateral load. Various researchers (Franklin et al. 2001; Kaushik et al. 2007) have conducted research to observe the performance of masonry under in-plane lateral load. Kaushik et al. (2007) conducted research to estimate the modulus of elasticity along with other characteristics of the clay brick masonry walls and their constituents under uniaxial compression force. Brick masonry walls were tested with incremental displacement loading at the top of each wall, which is also referred to as a stroke controlled test. The modulus of elasticity of the brick units, mortar and masonry were calculated separately from compressive tests. The modulus of elasticity of the brick masonry walls was estimated by calculating the slope of a secant between ordinates corresponding to 5 and 33% of the ultimate strength of the brick masonry walls.

According to Jaeger et al. (2008), unreinforced masonry walls (UMW) are more vulnerable to shear than flexure. According to the researchers, the modulus of elasticity and shear modulus of unreinforced brick masonry walls subjected to lateral load will be lower than the traditional values, which are estimated for masonry walls subjected to vertical load. Moreover, estimating the uncracked value of the modulus of elasticity under lateral load is an important parameter for the resistance of masonry walls to shear effects in earthquake prone areas. When unreinforced masonry walls are subjected to earthquake loads, cracks propagate through the mortar joints and sometimes through the bricks. These cracks reduce the effective modulus of elasticity and the shear modulus of elasticity of masonry walls. The proposed method of research will be significant in that it will follow a new approach to determine the effective modulus of elasticity and the shear modulus of brick masonry walls under in-plane lateral loads.

METHODOLOGY

In this research program, in-plane lateral loads was applied at the top of each masonry wall to measure the uncracked modulus of elasticity (E) and shear modulus (G) of the brick masonry walls. For this purpose, the vertical and lateral deflection under both lateral and vertical load was recorded. The stress-strain behaviour of the masonry walls was also monitored and documented. The uncracked modulus of elasticity (E) and shear modulus (G) of brick walls under flexure can be calculated using the following equations:

$$E = \frac{6Ph^3}{ba^3(\delta_2 - 2\delta_1)} \tag{1}$$

$$G = \frac{6Ph}{ba(8\delta_1 - \delta_2)} \tag{2}$$

Where P is the applied lateral load, h is the height of the masonry wall, a is the width of the masonry wall, b is the thickness of the masonry wall, δ_1 is the lateral deflection of the masonry wall of height h and δ_2 is the lateral deflection of the masonry wall of height $2h$.
For a wall of height $1.5h$, the modulus of elasticity and shear modulus can be calculated using the following equations:

$$E = \frac{1.875Ph^3}{ba^3(\delta_3 - 1.5\delta_1)} \tag{3}$$

$$G = \frac{1.875Ph}{ba(3.375\delta_1 - \delta_3)} \tag{4}$$

Where – δ_3 is the lateral deflection of the masonry wall with the height of $1.5h$.

According to Dr. Jaeger and Dr. Mufti (Jaeger et al. 2010), unreinforced masonry walls are more vulnerable to shear than to flexure. According to the researchers, the modulus of elasticity and shear modulus of unreinforced brick masonry walls subjected to lateral loads will be lower than the traditional values, which are estimated for masonry walls subjected to compressive loads. Moreover, estimating the uncracked value of the modulus of elasticity under lateral load is an important parameter for the resistance of masonry walls to shear effects in earthquake-prone areas. When unreinforced masonry walls are subjected to earthquake loads, cracks propagate through the mortar joints and sometimes through the bricks. These cracks reduce the effective modulus of elasticity and the shear modulus of elasticity of masonry walls.

Considering the above mentioned situation, Dr. Jaeger and Dr. Mufti proposed a new method to calculate the effective modulus of elasticity and the shear modulus of a brick masonry wall under in-plane lateral loads after cracking. This method is referred to as the Jaeger and Mufti method in this research paper. If a cantilever masonry wall, having the dimensions of a (length) × b (width) × h (height), is subjected to an in-plane horizontal load of magnitude P at the top, as can be seen in Figure 1, the horizontal deflection (δ) at the top of the masonry wall is given by the following equation:

$$\delta = \frac{Ph^3}{3EI} + \frac{Ph}{Gab} \tag{5}$$

$$\rightarrow \delta = \frac{Ph^3}{3E(\frac{ba^3}{12})} + \frac{Ph}{Gab} \tag{6}$$

$$\rightarrow \delta = \frac{Ph}{ab}\left\{\frac{4}{E}\left(\frac{h}{a}\right)^2 + \frac{1}{G}\right\} \tag{7}$$

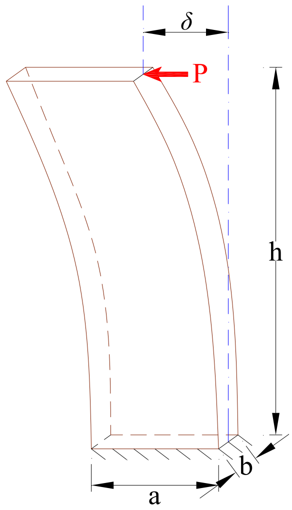


Figure 1: Deflection of Masonry Wall Under Lateral Load

Here E is the modulus of elasticity, G is the shear modulus, and I is the moment of inertia for the gross section of masonry wall. Taking the derivative of horizontal deflection (δ) with respect to horizontal load (P) yields the slope of the horizontal load versus horizontal deflection graph:

$$\rightarrow Slope = \frac{d\delta}{dP} = \frac{h}{ab}\left\{\frac{4}{E}\left(\frac{h}{a}\right)^2 + \frac{1}{G}\right\} \tag{8}$$

Replacing E= r * G, where r is the ratio of E/G and rearranging equation 8:

$$\rightarrow G = \left(\frac{d\delta}{dP}\right)\left(\frac{h}{ab}\right)\left\{1 + \frac{4}{r}\left(\frac{h}{a}\right)^2\right\} \tag{9}$$

The Jaeger and Mufti method will be validated following laboratory testing and finite element analysis of the models. The validation system is demonstrated in the flowchart presented in Chart 1.

In order to validate the model using a laboratory test, the monitoring system is to be tuned followed by monitoring the structure and evaluating the structural response. The validation through finite element analysis of the model is done by the modification of the finite element models followed by linear elastic analysis. The two validation systems are to be repeated until the results of the two methods converge and the accurate evaluation is achieved.

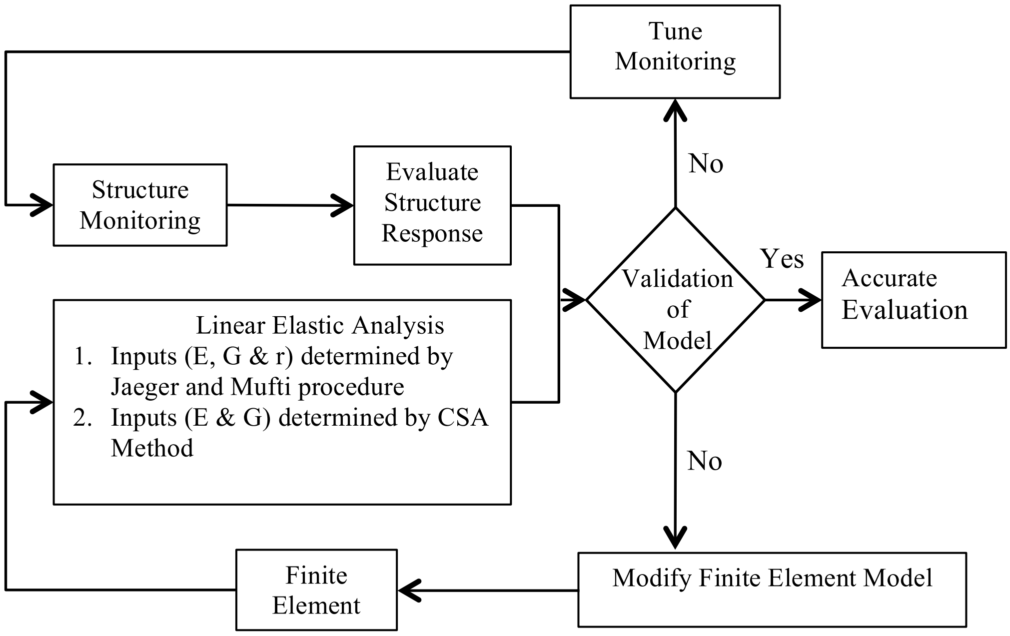


Chart 1: System Validation Using Modeling and Testing

DETAILS OF TEST SPECIMEN AND MATERIALS

Historic and old masonry structures differ from each other due to their various types of constituent materials. Old masonry bricks were collected to build the specimens so that they represent the old masonry structures. The typical soft mortar without a colour pigment was used with the ratio of 1:3:9 by volume (white Portland cement: Hydrated lime type SA: sand). When this paper was written, the first masonry wall specimen (1m × 1m × 0.21m) was being constructed in the laboratory. This wall was of two wythes thick of solid clay brick units. 10 mm thick mortar joints were provided in between the brick units. Air content for the first test specimen was 11.4%. Figure 2 shows the first test specimen being constructed. A 101.6 mm concrete beam will be casted at the top of the masonry wall to provide a level surface.

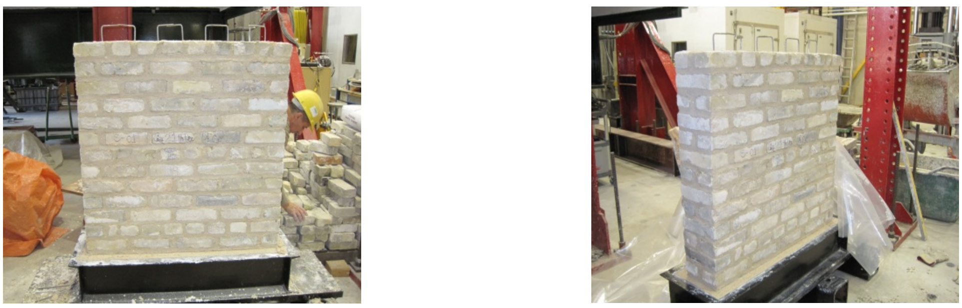


Figure 2: First Test Specimen

Three wall specimens were constructed with various heights. Table 1 presents the actual wall dimensions of the brick masonry walls after construction. The material properties of the brick units, mortar and masonry prisms are presented in Table 2.

Table 1: Actual Dimensions of Masonry Walls

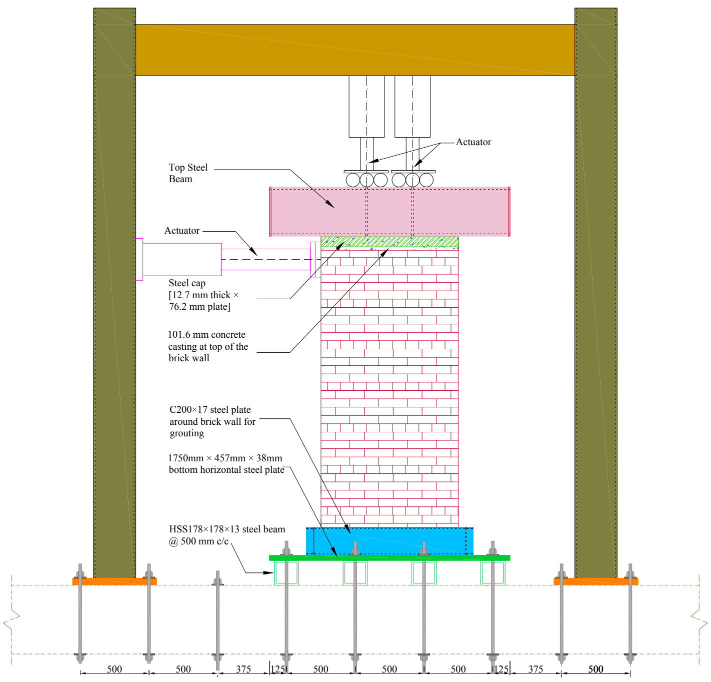
Specimen designation	High, *h* (mm)	Width, *a* (mm)	Thickness, *b* (mm)
Wall-1	1000	1040	218
Wall-2	1500	1018	212
Wall-3	2000	1015	220

Table 2: Material Properties of Masonry Walls

Specimen designation	Air content of mortar (%)	Compressive strength of masonry prism, f'_m (MPa)	Compressive strength of brick unit (MPa)	Compressive strength of mortar (MPa)
Wall-1	11.4	6.73	34.04	2.50
Wall-2	7.00	7.96		2.73
Wall-3	15.00	7.87		3.55

TEST SETUP

A typical test setup for the experimental program is shown in Figure 3. A steel beam was constructed at the top of each wall to facilitate the application of horizontal as well as vertical loads and ensure that the walls remain horizontal upon loading. The bottom face of the wall was fixed with the laboratory strong floor through a base steel beam. Horizontal and vertical loads were applied at the top of the wall through a load actuator. Several LVDTs and strain gauges were installed to measure the deflection and strain values of the masonry walls as demonstrated in Figure 4. During each test, the horizontal movements shown in Figure 5 was recorded at the top face of the wall and were used to determine the uncracked modulus of elasticity and the shear modulus of the brick masonry wall using equations (1) through (4). After cracking the effective modulus of elasticity and shear modulus were calculated using equations (5) through (9).



Elevation

Figure 3: Test Setup

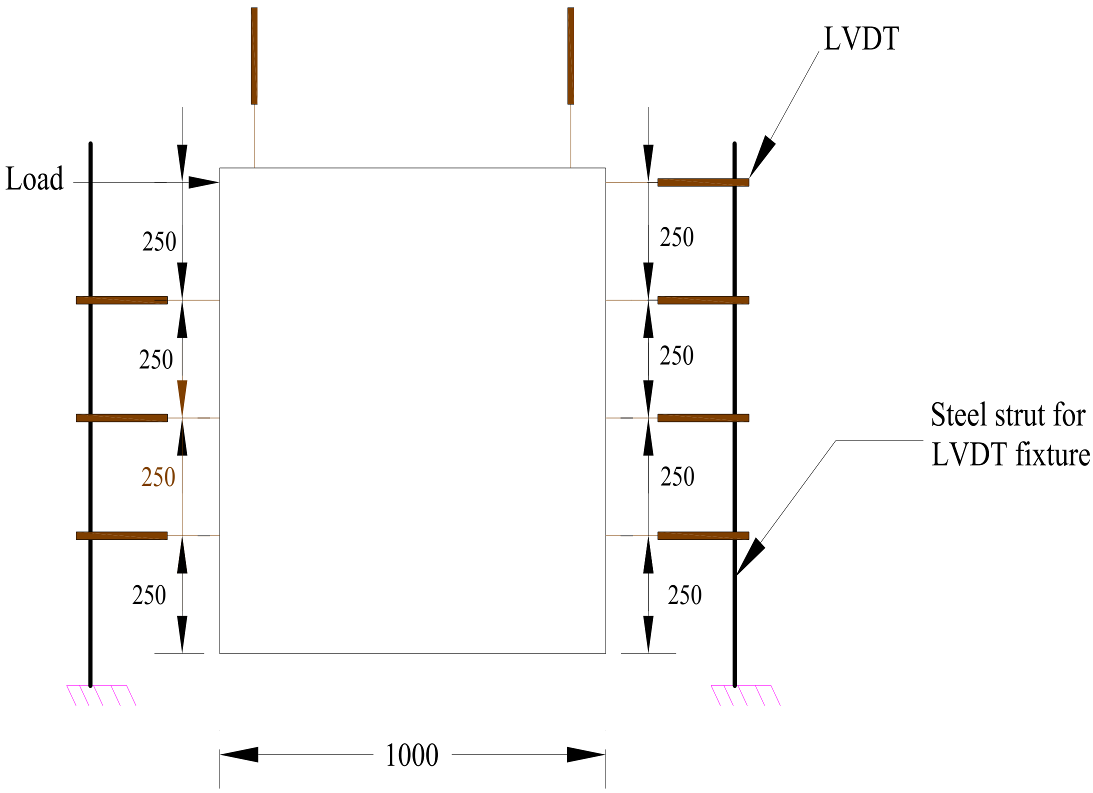


Figure 4: Typical Locations of Mounted Displacement Transducer

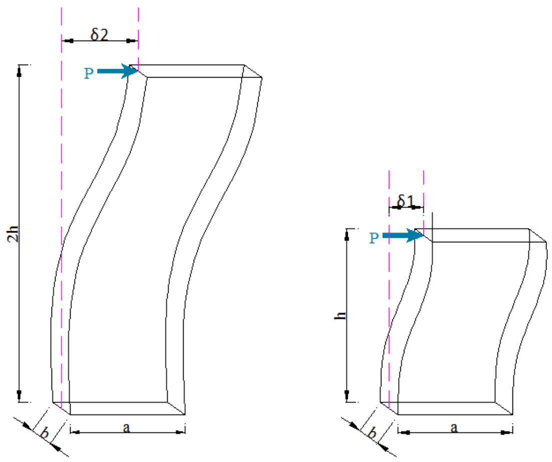


Figure 5: Deflection of Masonry Wall under Lateral Load

SUMMARY OF TEST RESULTS AND NUMERICAL ANALYSIS

The test results presented in this section are the lateral load versus lateral displacement, lateral load versus vertical displacement, and crack patterns on the masonry walls. In the interest of adhering to paper guidelines individual test results will not be discussed herein, however, the final test results are presented in Table 3. Table 4 presents the E and G values obtained using the calculation given in CSA. Tables 5, 6 and 7 present the calculated E and G based on the Jaeger and Mufti method for Wall-1, Wall-2 and Wall-3 respectively.

Table 3: Summary of Test Results

	Wall-1	**Wall -2**	**Wall -3**
Wall height, h (mm)	1000	1500	2000
Horizontal load at initiation of first crack, P (kN)	22	15	12.42
Maximum horizontal deflection at initiation of first crack, δ (mm)	0.69	0.96	1.20
Ratio between deflections at initiation of first crack and wall heights (δ/h)	1 /1450	1/1563	1/1667
Type of first visible crack	Flexural	Flexural	Flexural
First flexural crack visible at	South (tension) side	South (tension) side	South (tension) side
First flexural crack initiated at	Support bed joint mortar	Support bed joint mortar	Support bed joint mortar
Initiation of shear crack with increment of horizontal load	Yes	No	No

Table 4: E and G values calculated using CSA Standard

Specimen designation	**Compressive strength of masonry prism, *f'm* (MPa)**	**Modulus of elasticity, *E* (MPa) *E* = 850 *f'm***	**Shear modulus of rigidity, *G* (MPa) *G* = 0.4 *E***
Wall-1	6.73	5,720	2,288
Wall-2	7.96	6,766	2,706
Wall-3	7.87	6,689	2,676
Average	7.52	6,392	2,557

Table 5: E and G Values for Wall-1

r	***G (MPa)***	***E (MPa)***
2.5	273	683
3.0	246	738
3.5	227	793
4.0	212	848
4.5	201	903
5.0	192	958
5.5	184	1013
6.0	178	1,069

Table 6: E and G Values for Wall-2

r	***G (MPa)***	***E (MPa)***
2.5	227	567
3.0	197	592
3.5	176	618
4.0	161	643
4.5	149	668
5.0	139	694
5.5	131	719
6.0	124	744

Table 7: E and G Values for Wall-3

r	*G (MPa)*	*E (MPa)*
2.5	590	1,476
3.0	506	1,517
3.5	445	1,558
4.0	400	1,599
4.5	364	1640
5.0	336	1,681
5.5	313	1722
6.0	294	1,762

Figure 6 shows the graph comparison of the experimental result; finite element result using E and G values calculated using CSA and finite element analysis results using E and G calculated using Jaeger and Mufti method. Wall-1 and wall-2 showed behaviour similar to the numerical analysis based on E and G calculated using CSA, and it was higher than the values revealed by the experiments.

Numerical analysis performed using E, and G calculated by Jaeger and Mufti method was lower than that of CSA's and much closer to the physical experiments.

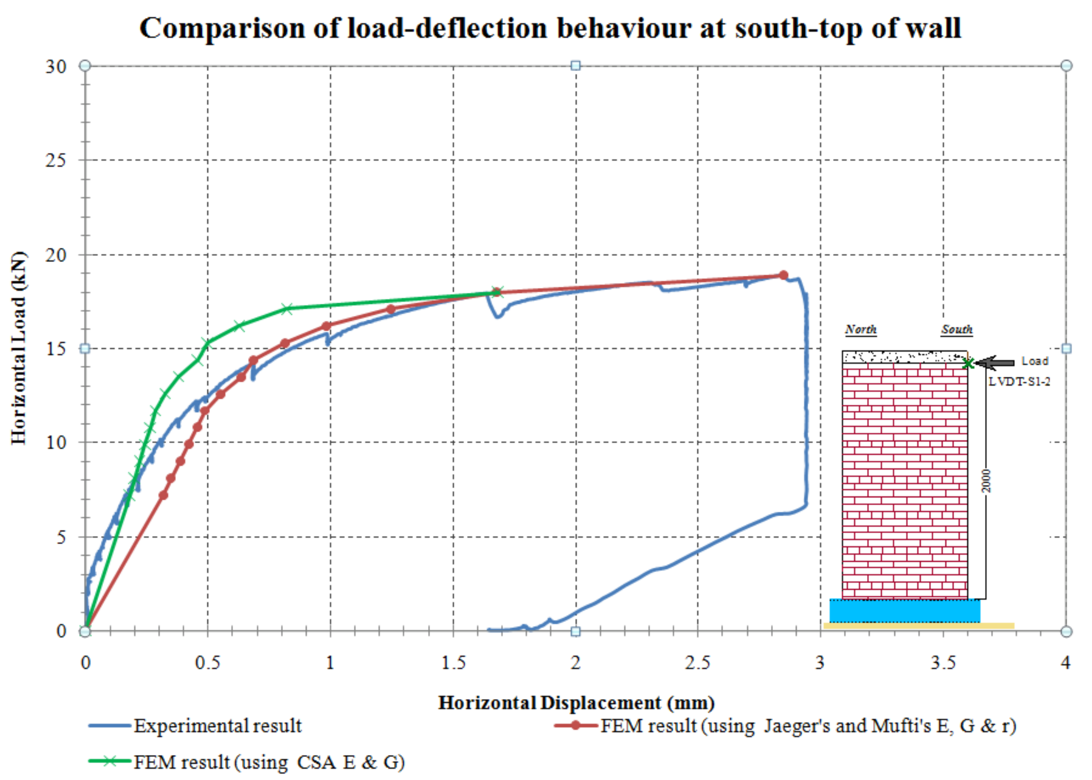


Figure 6: Comparison of Load-Deflection Behaviour of Wall-3

CONCLUSION

This research showed that the modulus of elasticity and the shear modulus of unreinforced brick masonry walls subjected to lateral load will be lower than the traditional values, which are estimated for masonry walls subjected to vertical load; as suggested by Jaeger et al. (2008). Accurate estimation of the uncracked value of the modulus of elasticity under lateral load is an important parameter for the rehabilitation of existing buildings and the resistance of masonry walls to shear effects in earthquake prone areas.

A more detail conclusion of this research is presented in point format:

1. The first horizontal flexural cracks were visible at mortar of support-bed joint of walls at tension side.

2. The horizontal load required to initiate first cracking decreased with increments of the walls' height.

3. Comparing the load-displacement profiles obtained from laboratory tests, by the Jaeger and Mufti method, and by CSA specification; it can be concluded that the Jaeger and Mufti method yields conservative values of horizontal deflection at cracking load which are very close to the experimental results.

4. From experimental results, it was found that the deflections at initiation of first crack at Wall-1, Wall-2 and Wall-3 respectively are ($0.69\ mm/1000\ mm$) 1/1450, ($0.96\ mm/1500\ mm$) 1/1563 and ($1.2\ mm/2000\ mm$) 1/1667 of the corresponding wall heights. From the above observation it is recommended that for safe estimation the deflection of the wall at initiation of first crack can be considered as 1/1200 of the wall height.

5. The finite element analysis results, using E and G from the Jaeger and Mufti method for r = 3, match best with the experimental results. Therefore, r = 3 is considered to give reasonable estimate of the uncracked effective modulus of elasticity and shear modulus of the walls.

6. Both the laboratory tests and finite element analysis of the models validate the Jaeger and Mufti method.

7. E and G of masonry walls calculated following the Jaeger and Mufti method is effective for design purpose. These values can also be used for the rehabilitation of old deteriorating buildings and for the strengthening of unreinforced masonry structures subjected to lateral load.

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