Structural Analysis of Historical Constructions, New Delhi 2006
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Analytical Modeling of Dry Stone Masonry Wall Under Monotonic and Reversed Cyclic Loading

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ABSTRACT: A numerical simulation based on experimental test data has been carried out to model the monotonic and reversed cyclic load-displacement hysteresis curves of dry-stack mortarless sawn stone masonry using a multi-surface interface model where stone units and joints are assumed elastic and inelastic respectively. Finite element software, Diana version 8.1 has been employed to carry out the present numerical modelling. The stone units were modelled using an eight node continuum plane stress elements with Gauss integration and the joints were modelled using a six node zero thickness line interface elements with Lobatto integration. This paper describes outline of the experimental research work and details of numerical modelling carried out and reports the numerical monotonic load-displacement curve and reversed cyclic load-displacement hysteresis curves.

1 INTRODUCTION

Dry stone masonry is the most ancient, durable, widespread, and environmentally kind building method devised by mankind. Stone structures built without mortar rely on the skill of the craftsmen and the forces of gravity and frictional resistance. Stone has been a successful building medium throughout the ages and around the world because of its unique range of benefits. The structures are remarkably durable; indeed, if correctly designed, they are earthquake resistant. They resist fire, water, and insect damage. The mason needs a minimum of tools; the work is easily repaired; the material is readily available and recyclable. Dry stone masonry does not deplete resources and, aesthetically, complements and enhances the landscape. Archaeologists have determined that the Chinese built dry stone terraces at least 10,000 years ago. In Britain, ancient tribes built dry stone shelters just after the last ice age, 8,000 years ago. High quality stone tools recently found in Europe are 2.2 million years old. The technique of dry stacking in construction has existed in Africa for thousands of years. The Egyptian pyramids and the Zimbabwe ruins, a capital of ancient Shona Kingdom around 400AD, are good examples. In addition to the neglect and destruction of historic structures, the craft is handicapped by lack of technical information and lack of skilled preservation personnel. Construction and engineering data that professionals need are scarce and, if recorded at all, are difficult to locate. A large number of historical buildings in Portugal are built with stone without bonding mortar. The primary function of masonry elements is to sustain vertical gravity load. However, structural masonry elements are required to withstand combined shear, flexure and compressive stresses under earthquake or wind load combinations consisting of lateral as well as vertical loads. A research program was carried out by Vasconcelos (2005) at the University of Minho to experimentally evaluate the in-plane seismic performance of ancient sawn dry stack masonry without bonding mortar. Monotonic and reversed cyclic loading tests with varying pre-compression were performed to investigate the strength, deformation capacity, monotonic and cyclic load-displacement hysteresis response and stiffness characterization. The data obtained from the above experimental research has been used as a base for the present numerical simulation. The simulation was carried out using a multisurface interface model where stones and joints are assumed elastic and inelastic respectively. The stones were modelled using an eight node continuum plane stress elements with Gauss integration and the joints were modelled using a six node line interface elements with Lobatto integration. This paper presents outline of the experimental research work and details of numerical modelling of carried out and reports the numerical monotonic load-displacement curves, reversed cyclic load-displacement hysteresis curves and conclusions.

2 OUTLINE OF EXPERIMENTAL RESEARCH WORK

The main goal of the experimental research work carried out by Vasconcelos (2005) was to evaluate the seismic performance of dry stack masonry shear walls found in ancient masonry structures. A typical dry stacked mortarless sawn stone masonry test specimen is shown in Fig. 1. The dimension of the sawn stone was 200 mm (length) x 150 mm (height) x 200 mm (width) and the dimension of test specimen was 1000 mm (length) x1200 mm (height) x 200 mm (width), and the height to length ratio was 1.2. Static monotonic and reversed cyclic tests were carried out with three distinct pre-compressions levels such as 100 kN (σ_0=0.5N/mm^2), 175 kN (σ_0=0.875N/mm^2) and 250 kN (σ_0=1.25N/mm^2) using the experimental set-up shown in Figure 1. The base of the wall was fixed to the reaction slab through a couple of steel rods and the pre-compression load was applied through top vertical actuator. A stiff steel beam was used to distribute the vertical pre-compression loading and a set of steel rollers were placed between the test specimen and the top stiff steel beam to allow relative horizontal displacement due to the imposed lateral load or displacement with respect to the vertical actuator. The seismic action was simulated by imposing incremental static lateral displacements. The deformation of the wall was measured by means of needle type Linearly Variable Differential Transducers (LVDTs).

3 DETAILS OF NUMERICAL MODELLING

The data obtained from the above experimental research carried out by Vasconcelos (2005) has been used as a base for the present numerical analysis/ simulation. A non-linear finite element analysis has been carried out using the DIANA (version 8.1) software. The simulation was carried out using a multi-surface interface model where stones and joints are assumed elastic and inelastic respectively. The stones were modelled using an eight node continuum plane stress elements Diana (2000) with Gauss integration and the joints were modelled using a six node and zero thickness line interface elements Diana (2000) with Lobatto integration proposed by Lourenco and Rots (1997). Figure 4 shows the combination of stone and interface model. The present interface material model is also know as the `Composite Interface model', is appropriate to simulate fracture, frictional slip as well as crushing along material interfaces, for instance at joints in masonry. Usually the brick units are modelled as linear elastic, or viscoelastic continua, while the mortar joints are modelled with interface elements, which obey the nonlinear behaviour described by the following combined cracking-shearing-crushing model (Lourenço and Rots 1997). In some cases it is justified to model also the mortar with continuum elements, and the interface elements and material behaviour are employed to capture the physical interface between bricks and mortar. The finite element mesh was generated using an external masonry preprocessor called make wall developed by Lourenço (1996b) and the run-command is make_wall mesh.dat.

Dry stone masonry exhibits a peculiar "elastic" behaviour under compressive loading (Vasconcelos 2005). The average value of Young's modulus based on 10 monotonic uniaxial compressive tests performed on cylindrical specimens was 15500 N/mm^2. Young's modulus of stone prisms built with four stacked stones and subjected to uniaxial compression reads 14800 N/mm^2 (average of 4 prisms result). The Young's modulus of the stone was fixed as 15500 N/mm^2 in the present micro-modelling simulation. Young's modulus of large walls is considerably different from the Young's modulus measured in small test specimens. This phenomenon has been found and reported by Lourenço (1996) from the modelling of masonry shear walls tested at the Eindhoven University of Technology. The reason for the difference in stiffness between large and small specimens is because of poor alignment in case of large specimens.

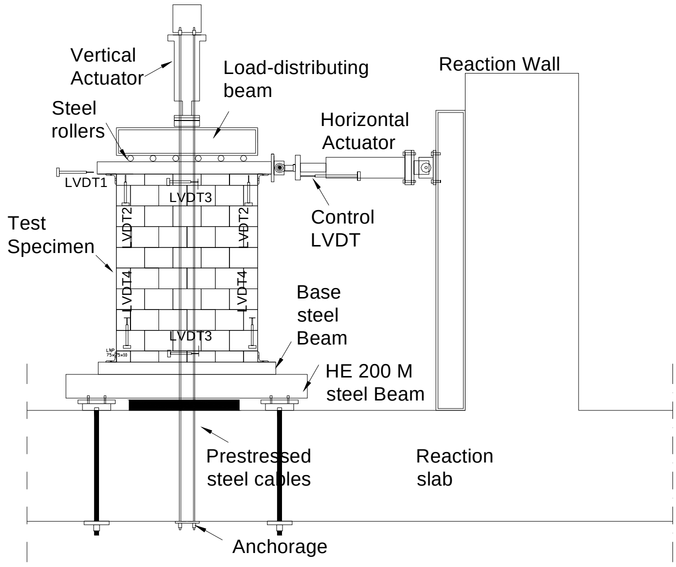


Figure 1: Experimental Test Set-Up and Position of LVDTs (Vasconcelos 2005)

Normal joint stiffness ($K_{n,\ joint}$) was calculated using the following formulation proposed by Lourenco (2006a) in which the wall is consider as a series of two spring in vertical direction, one representing a stone and the other representing a joint.

$$K_{n,\ joint} = 1/(h(1/E_{wall} - 1/E_{stone})) \tag{1}$$

Where

$K_{n,\ joint}$ = Normal joint stiffness
h = Height of stone (150 mm)
E_{wall} = Young's modulus of wall
E_{stone} = Young's modulus of stone

The tangential stiffness ($K_{n,\ joint}$) was calculated directly from the normal stiffness using the theory of elasticity as follows, Lourenco (2006a):

$$K_{s,\ joint} = K_{n,\ joint}/\ 2(1+v) \tag{2}$$

Where

$K_{s,\ joint}$ = Tangential stiffness
$K_{n,\ joint}$ = Normal joint stiffness
v = Poisson's ratio (0.2)

The tensile strength and cohesion of the joints are assumed as zero. An experimental study on similar stone was carried out by Ramos (2001) found the tensile strength of stone is 3.7 N/mm^2 and fracture energy is 0.11 Nmm/mm^2. In addition, Lourenco and Ramos (2004) found the values for tanf (0.6) and tany (0) where f is friction angle and y is dilatancy angle of the stone joints. The uniaxial compressive strength of stone assembly was found equal to 57 N/mm^2. The fracture energy in compression was assumed to be half of the value given by Model Code 90 (CEB-FIB, 1990) for concrete, due to the higher brittleness of stone. The necessary input parameters such as elastic, inelastic and strength data required for the present analysis was are extracted from the experimental research work done by Vasconcelos (2005) and Oliverira (2003).

4 ANALYSIS RESULTS AND DISCUSSION

Fig. 2 presents the finite element model before deformation. Figs. 3a-3c presents the shape of the total deformed mesh under monotonic loading with different level of pre-compression loading conditions. Rocking failure was observed for lower level of pre-compression and rocking with toe crushing failure was observed for higher level of pre-compression. The observed failure mode is in good correspondence with the experimental failure mode. Figure 3d presents shape of the incremental deformed mesh at ultimate lateral load/ displacement for 250 kN pre-compression load.

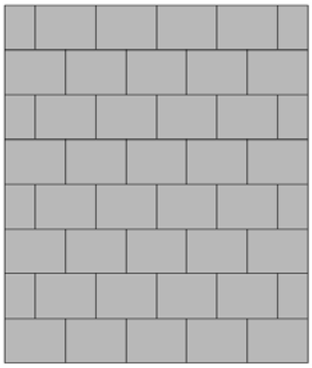
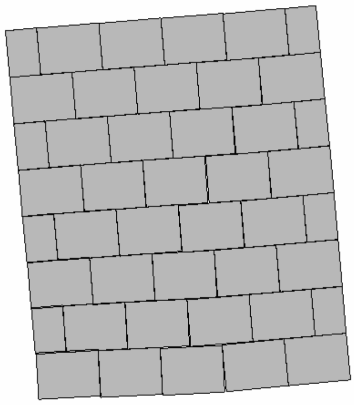
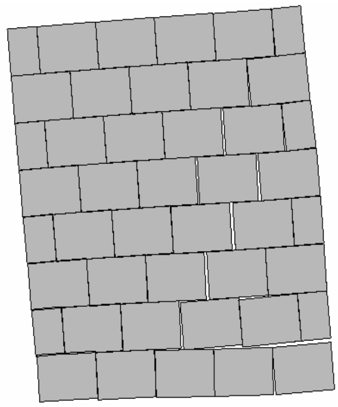


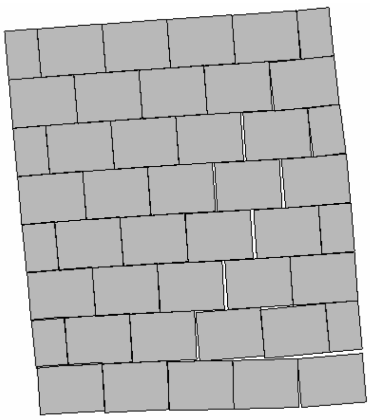
Figure 2 : Model before Deformation



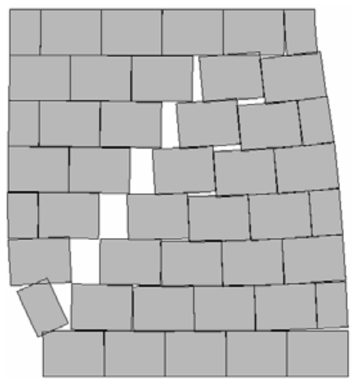
(a) Pre-compression, 100 kN



(b) Pre-compression, 175 kN



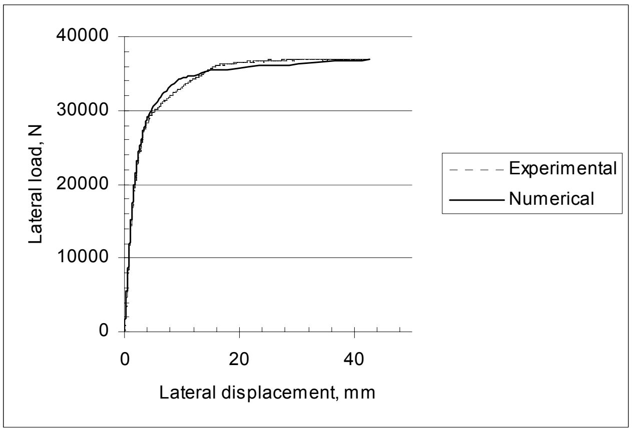
(c) Pre-compression, 250 kN



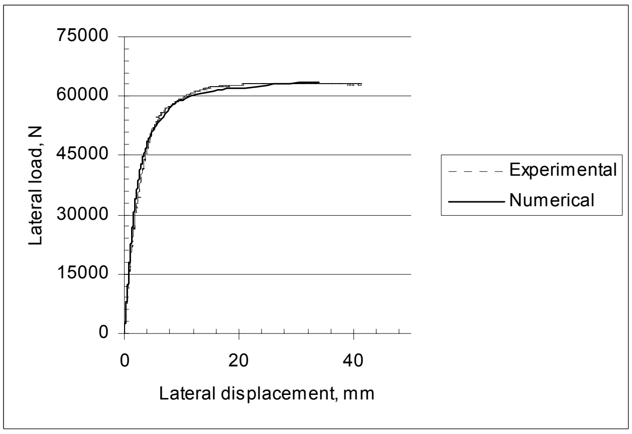
(d) Incremental deformed shape at collapse (250 kN)

Figure 3 : Deformed and Incremental Deformed Shape at Collapse

The monotonic load and corresponding displacement obtained from the numerical analysis has been plotted. The Numerical load-displacement curves and experimental load-displacement curves are compared and presented in Figs. 4a-4c.



(a)



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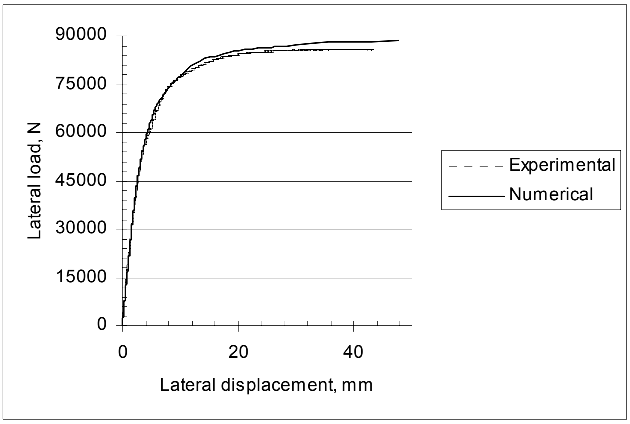
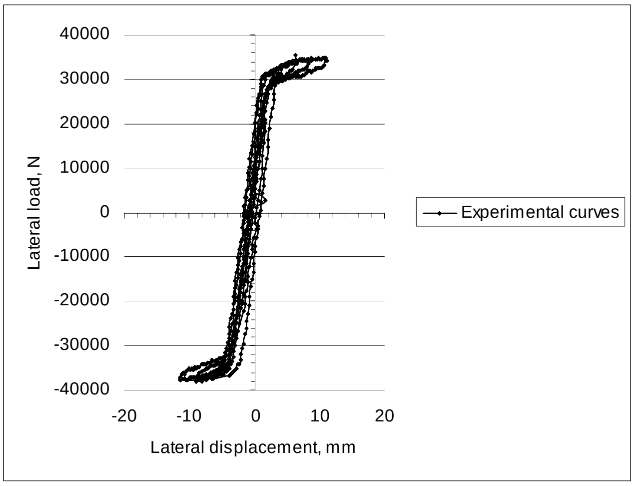


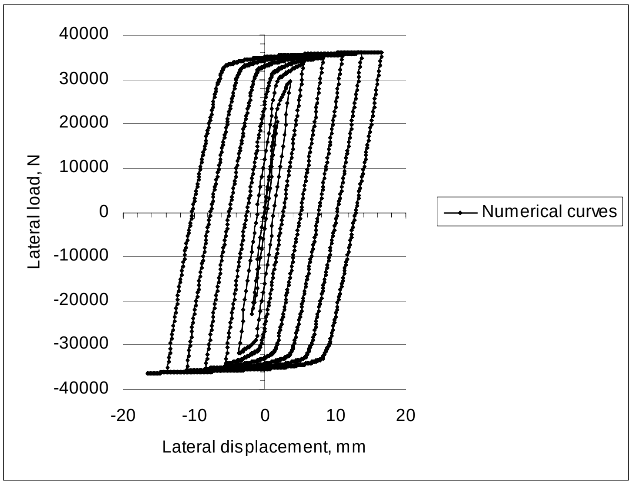
(c)

Figure 4 : Load-displacement curves for different pre-compression levels; (a) axial pre-compression, 100 kN; (b) axial pre-compression, 175 kN; (c) axial pre-compression, 250 kN

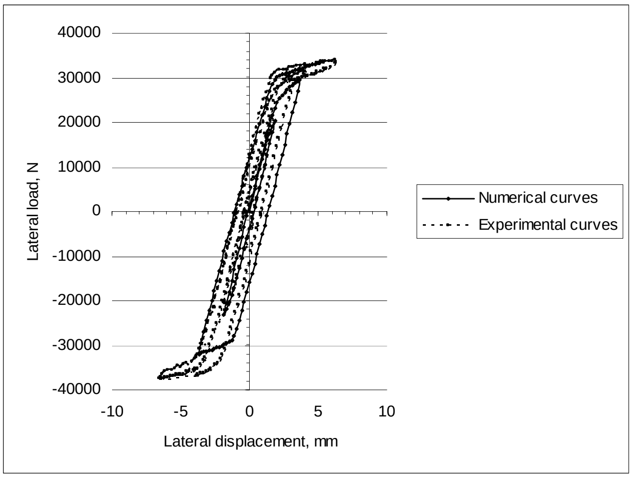
A good correspondence between numerical and experimental response has been found for all the cases of pre-compression level. Experimental reversed cyclic hysteresis curves are shown in Fig. 5a and Fig. 5b shows the numerical reversed cyclic load and corresponding displacement obtained from present analysis.



(a)



(b)



(c)

Figure 5 : Experimental and numerical reversed cyclic hysteresis curves (100 kN); (a) experimental reversed cyclic hysteresis curves (100 kN); (b) Numerical reversed cyclic hysteresis curves (100 kN); (c) Initial experimental and numerical reversed cyclic hysteresis curves (100 kN)

The numerical model used in this study produces adequate results for monotonic loading but it is not capable of predicting the experimental cyclic behaviour accurately, due to inadequate crack closure. Figure 5c shows comparison of cyclic curves at initial stage (3 revered cycles) where good agreement between experimental and numerical curves is found.

5 SUMMARY AND CONCLUSIONS

The main object of the present numerical analysis/ simulation is to evaluate the seismic performance of dry stack masonry shear walls found in ancient masonry structures. A non-linear finite element analysis has been carried out using the DIANA (version 8.1) software. The simulation was carried out using a multi-surface interface model where stones and joints are assumed inelastic and elastic respectively. The stones were modelled using an eight node continuum plane stress elements with Gauss integration and the joints were modelled using a six node and zero thickness line interface elements with Lobatto integration proposed by Lourenco and Rots (1997). Elastic inelastic parameters, strength have been calculated based on the experimental test data.

Rocking failure was observed for lower level of pre-compression and rocking with toe crushing failure was observed for higher level of pre-compression. The observed failure mode is in good correspondence with the experimental failure modes. The load and corresponding displacement obtained from the numerical analysis has been plotted. The numerical load-displacement curves and experimental load-displacement curves are compared and presented. A good correspondence between numerical and experimental response has been found for all the cases of pre-compression level in case of monotonic loading.

The cyclic load and corresponding displacement obtained from the numerical analysis has been plotted. The numerical model used in this study produced better results at initial stage of loading (for 3 reversed cycles) but it is not capable of predicting the whole experimental cyclic behaviour accurately. It is because the present model does not close the bed joint opening on release of the lateral cyclic load. An attempt has been under way to use different model to accurately predict the whole experimental cyclic load-displacement hysteresis curves.

REFERENCES

Oliveira, D. 2003. *Experimental and numerical analysis of block masonry structures under cyclic loading*, Ph.D. Thesis, University of Minho, Portugal, Available at www.civil.uminho.pt/masonry.

Ramos, L.F. 2001. *Experimental and numerical analysis of historical masonry structures*, Msc Thesis, University of Minho (in Portuguese). Available at www.civil.uminho.pt/masonry.

Vasconcelos, G. 2005. *Experimental Investigations on the Mechanics of Stone Masonry: Characterization of Granites and Behavior of Ancient Masonry Shear Walls*, PhD Thesis, University of Minho, Portugal. Available at www.civil.uminho.pt/masonry

Lourenço, P.B. 1996a. *Computational strategies for masonry structures*, Ph.D. Dissertation, Delft University of Technology, Delft, 1996.

Lourenço, P.B. 1996b. A user/programmer's guide for the micro-modelling of masonry structures. Relatório nº 03.21.1.31.35, Universidade Técnica de Delft, Delft, Países Baixos e Universidade do Minho, Guimarães, 50.

Lourenço, P. B. and Rots, J.G. 1997. A multi-surface interface model for the analysis of masonry structures. J. Struct. Eng., ASCE 123, (7), 660-668.

Lourenço, P. B. and Ramos, L. F. 2004. Characterization of the cyclic behaviour of dry joints, J. Struct. Eng., ASCE, 130, (5), pp. 779-786.

MC90. 1993. *CEB-FIB Model Code 1990 for concrete structures*, CEB Bulletin d'Information, No.213/214, Comité Euro Interantional du Béton, Lausanne.

Diana v8. 2000. *User's Manual*, TNO Company, The Netherlands, 2000, www.tnodiana.com