Numerical Simulation of Compression and Shear Behaviour of Unreinforced Brick Masonry

Selvakumar Viswanathan[1*], Sinthiya Ravi[1], Thanikasalapradeep Nagarajan[1], V. Srinivas[2], and Premavathi Narayanan[3]

Abstract—The research work presented in this paper constitutes the study of numerical simulation of unreinforced brick masonry under compression and shear loading. The process of computing the behaviour of brick masonry in real time conditions is complex. Hence, simulating them under various loading conditions in numerical modelling would be prudent. The material properties of the brick and mortar which are required for numerical analysis are obtained experimentally. The brick masonry prisms are numerically modelled using finite element analysis software, ANSYS. The materials of unreinforced brick masonry exhibit both linear and non-linear properties which are analyzed numerically. Furthermore, studies are conducted for three different mortar ratios to compare the behaviour of brick masonry in each mortar ratio. The shear bond strength and compressive strength are computed from three stack brick prisms. The numerical behaviour of the unreinforced brick masonry are compared and validated with the experimental results.

Keywords— Compression, Finite element analysis, Shear, Unreinforced Brick masonry.

I. Introduction

BRICK masonry is one of the most significant type of construction practices adopted worldwide, especially for housing in rural areas. Construction with brick masonry has evolved since ancient times extending from houses to forts. Even though many new construction technologies have been developed, construction with brick masonry is inevitable.

The cost-effective means of housing can be achieved by enhancing the existing properties of brick masonry. The shortcomings can be rectified by finding an optimal solution to prevent the failure of brick masonry under different types of load.

Brick masonry is non-homogenous as the masonry is constituted by materials like brick and mortar. The mortar forms the binding between bricks in the masonry and hence it acts as an interface layer in the masonry structure. The behaviour of materials in brick masonry are non-linear and do not have similar material properties. This impedes the experimental investigation of their behaviour under different types of loading. Moreover, the comparative studies on masonry behaviour for different cement mortar ratios are also indispensable for utilization of brick masonry in various applications and the response of masonry in each mortar type helps in evaluating their properties. Reference [1] has suggested that the strength of masonry increases with increase in mortar strength.

The mechanical behaviour of masonry possesses many parameters like mechanical properties of brick and mortar, geometry of bricks, joint arrangement, etc. The estimation of influence of these parameters on the overall behaviour of masonry is obscure and hence it is often assumed as isotropic elastic.

The difficulties in experimental research of existing masonry structures have resulted in the adoption of numerical analysis of the brick masonry. Numerical simulation would help in determining the weaker regions of stress-strain distribution and also other parameters like displacement and development of cracks. The masonry exhibits anisotropic behaviour due to the joints present in horizontal and vertical joints and possess orthotropic strength and softening characteristics as explained by [2]. In order to perform the numerical investigations on masonry various methods have been developed. Reference [3] stipulated the methods for numerical investigation of masonry as below,

1. Geometric load factor
2. Linear elastic finite element analysis.
3. Limit block analysis.
4. Non-linear elastic-plastic finite element method.
5. Differential element method.

Reference [4] has formulated a mechanism to investigate the shear behaviour of masonry. Triplet brick prisms were used in the study with shear load applied on the middle unit. Finite element analysis of triplet shear model would help in defining the failure mechanisms of the masonry which can be used in the analysis of masonry structures as specified by [5]. Various experiments have been conducted to study the shear behaviour of the masonry by evaluating masonry walls, but there are only few research works that have been carried out on masonry prisms like the works of [1], [6]. In this paper,

[1] – Final year Civil Engineering, Bannari Amman Institute of Technology, Sathyamangalam.
[2] – Principal Scientist, CSIR-Structural Engineering Research Centre, Chennai.
[3] – Assistant Professor, Department of Civil Engineering, Bannari Amman Institute of Technology, Sathyamangalam.
* – Corresponding author. e-mail: vselvakumar07@gmail.com

numerical simulation studies are carried out on brick masonry for compression and shear loading.

II. Finite Element Analysis

The finite element method incorporates as a significant method used in the analysis of structures. The structural system replaces the continuum elements of the structure with discrete elements which are called as finite elements. It works on the principle of dividing the continuum into a finite number of elements connected by nodes present on the boundaries. The structure to be analyzed can be idealized into triangular or quadrilateral elements. Non-linear behaviour of mortar joints plays a crucial role in the response of masonry structures subjected to horizontal and vertical loading. Various researchers [1]-[3], [7], [10]-[16] have performed finite element analysis to study the behaviour of brick masonry under different loading conditions. The behaviour of masonry can be studied in depth for every node by dividing it into numerous elements.

III. Numerical Modelling

The analytical software employed in this research work is ANSYS, finite element analysis software for analyzing various complex structures. A comprehensive numerical model is created with suitable boundary and loading conditions for the numerical simulation in this investigation. From the extensive research work on finite element analysis, various modelling techniques have been developed [7]-[9] by researchers. They are distinctively classified into,

- Micro or discrete modelling
- Macro or continuous modelling

Reference [17] has put forward that the analysis and design of buildings require the material properties of masonry, for example, the modulus of elasticity of masonry is required for the non-linear static analysis. Stress-strain curves of masonry are required for more detailed non-linear analysis of masonry structures. Limited research has been carried out to obtain a realistic material property for masonry.

In micromodelling, the brick units and mortar are considered as two different materials joined by a continuum brick-mortar interface layer between brick and mortar. It regards the masonry as heterogeneous and on the other hand macromodelling considers the brick units, the mortar and the brick-mortar interfaces as a single continuum element by homogenizing the masonry. Homogenized macromodelling method is efficient due to less demand on computational effort compared to the micromodelling [7] and is suitable for large scale structural analysis. Conversely, the 'micromodelling' can present imminent into the localization of the brick–mortar interfaces depending on the level of details required.

The elements used in the numerical simulation are solid brick elements which possess three degree of freedom at each node having translations in the nodal directions along x, y, and z directions.

1. Micromodelling

This model considers the brick masonry as present in the structure. The material property of the prism is different as the materials are non-linear and non-homogenous. In micromodelling of unreinforced brick masonry, three brick prisms are developed as shown in Fig. 1. The brick and mortar layer of 10mm thickness are modelled using 3-D iso-parametric Solid-65 element, which has large deflection and strain capabilities. A steel plate is used to evenly distribute the load on the brick prism using linear elastic solid element, 3-D Solid-45. The micromodelling method characterizes the joints of brick and mortar as 3-D continuum with a perfect bond between the brick and the mortar. The bottom of the brick prism is constrained in all degrees of freedom in micromodelling and the load is applied as pressure over the steel plate under compression load.

The shear behaviour can be analyzed using a similar model of three brick prism. Constraints are at the bottom of side bricks and the sides of bricks for three degrees of freedom and loading is applied as pressure over the steel plate of centre brick as shown in Fig. 2.

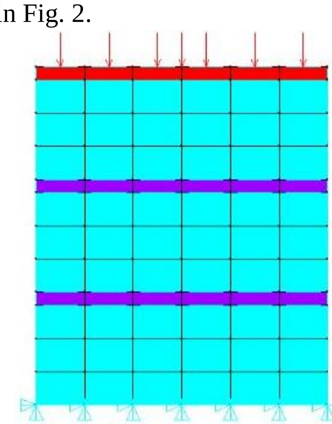

Fig. 1 Micromodelling of triplet brick prism for Compression

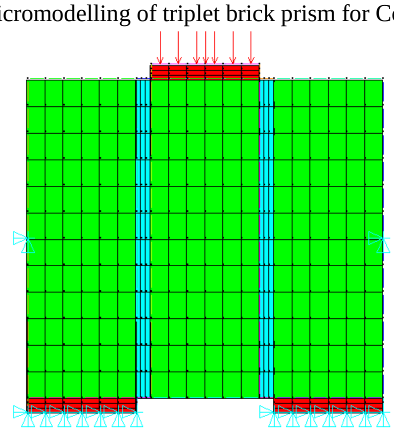

Fig. 2 Micromodelling of triplet brick prism for Shear

2. Macromodelling

The macromodelling in this research work considers the brick prism as composite instead of discrete elements. The brick masonry is supposed to be made of a single kind of material possessing isotropic material properties. It is modelled using element type Solid-65. A steel plate of 10mm thickness is modelled using Solid-45 on top of the masonry to distribute the load over the prism as shown in Fig. 3. This helps in analyzing the overall behaviour of the structure under compression loading. The homogenous member is meshed equally along with steel plate. Constrain is provided at the bottom of the masonry for three degrees of freedom and loading is applied as pressure on top of the masonry as shown in Fig. 3.

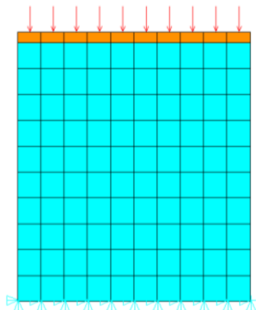

Fig. 3 Macromodelling of triplet brick prism

IV. Material Properties

The material properties essential for the numerical simulation of the unreinforced brick masonry are evaluated from the compression tests on materials of brick masonry. Both bricks and mortar cubes are tested under compression load to find the material properties like young's modulus, Poisson's ratio and stress-strain properties. These are used on the models created to simulate the behaviour of brick masonry under compression load. Three different cement mortar ratios such as 1:2, 1:3 and 1:4 are used in this research work. Their material properties are calculated from the tests as per standards

The material properties of the brick, mortar and the masonry prism to be used in the numerical modelling are listed in Table 1. Macro modelling requires the young's modulus of homogenized brick triplet prism. According to [9], [10], the modulus of elasticity for homogenized brick masonry is as follows.

$$E = \frac{1.25\xi + 1}{1.25\xi + \beta} E_b \qquad (1)$$

Where E_b and E are the modulus of elasticity of brick and homogenized brick masonry.

$$\beta = \frac{\text{Young's modulus of brick}}{\text{Young's modulus of mortar}}$$

$$\xi = \frac{\text{Height of brick}}{\text{Thickness of mortar}}$$

Poisson's ratio for the numerical simulation is obtained from the works of various researchers [7], [12]-[13].

The material properties of brick unit, mortar and brick masonry prism under compression load for different types of mortar ratios arrived from the experimental study are listed in Table I and Table II. The stress-strain plots of different mortar ratios are shown in Fig. 4.

TABLE I
Material properties of brick and mortar

Material	Stress (MPa)	Strain	Young's modulus (E) (MPa)	Poisson's ratio
Brick	4.52	0.0045	3070	0.2
Mortar 1 (1:2)	18.19	0.00832	5385	0.15
Mortar 2 (1:3)	15.47	0.00782	4075	0.16
Mortar 3 (1:4)	11.81	0.00758	3600	0.17

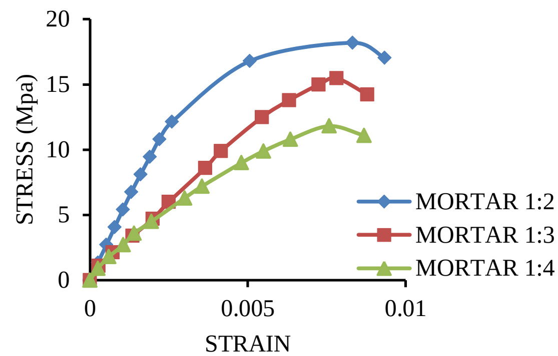

Fig. 4 Stress-strain plot for different mortar ratios

TABLE II
Material properties of brick prism

Material	Stress (MPa)	Strain	Young's modulus (E) (MPa)
Mortar 1 (1:2)	2.4255	0.000981	3202
Mortar 2 (1:3)	2.0304	0.00084	3144
Mortar 3 (1:4)	1.92	0.00079	3114

The modulus of elasticity for different mortar ratio listed in the above table is calculated using equation (1).

The maximum stress taken by the specific brick prism for a particular cement mortar ratio is used in the numerical simulation as pressure.

V. Results of Masonry Behaviour in Numerical Simulation

The numerical behaviour of unreinforced brick masonry is investigated for the mortar ratios 1:2, 1:3 and 1:4. The failure of masonry under compression is a result of the differing deformation characteristics and material properties of the brick units and mortar. The numerical simulation results of brick masonry under compression and shear loading can be observed in detail by removing the steel plate.

A. Numerical behaviour of unreinforced brick masonry for Mortar ratio 1:2 under compression

The cement mortar ratio 1:2 has higher strength when compared to other mortar types used in brick masonry as shown in Table 1. In the numerical simulation of triplet brick prism under compression load, it is observed that the brick-mortar interface layer and the corner regions are subjected to maximum stress as shown in Figs. 5 & 6. The numerical results are obtained from the micromodelling with the application of load in sub-steps. Similar way of loading (in sub-steps) is carried out on macromodelling, so that the variation in behaviour of brick masonry in each step while loading can be plotted. The stress distribution in micro and macromodelling are shown in Fig. 5 & 6. The stress-strain plots of experimental and numerical investigation are compared in Fig.7, where micromodelling has high stress value.

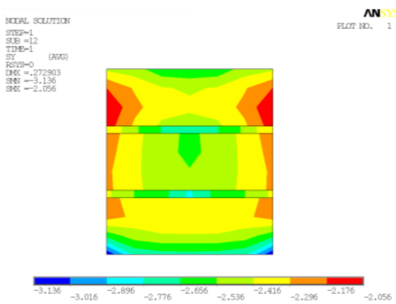

Fig. 5 Distribution of stress in brick masonry prism obtained in micromodelling for the mortar ratio 1:2

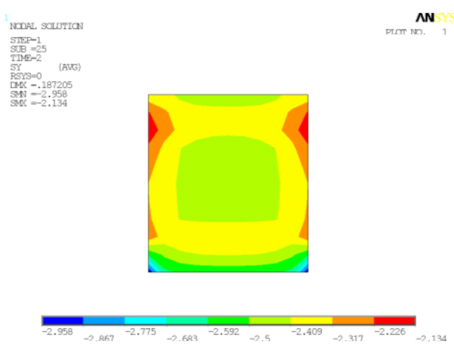

Fig. 6 Distribution of stress in brick masonry prism obtained in macromodelling for the mortar ratio 1:2

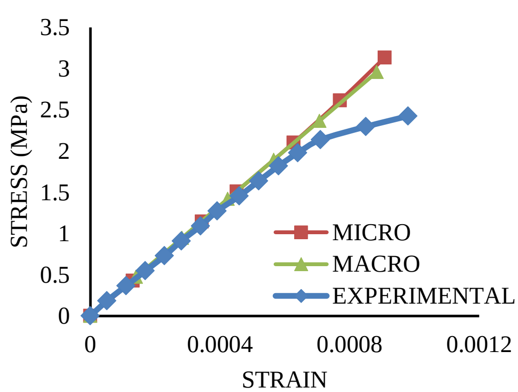

Fig. 7 Comparison of stress-strain values obtained from numerical simulation for the mortar ratio 1:2

B. Numerical behaviour of unreinforced brick masonry for Mortar ratio 1:3 under compression

The results obtained from the numerical modelling of masonry for the mortar ratio 1:3 are shown in Figs. 8 & 9. The stress distribution of the composite model shown in Fig. 9 divulges that the bottom region of the triplet brick prism is subjected to higher stress than the other areas of the masonry. The stress distribution in micromodelling is shown in Fig. 8. The stress-strain plot for the micro and macromodelling of the masonry for the mortar ratio 1:3 is obtained in reading the results in steps. The comparison of experimental and numerical behaviour of masonry for the mortar ratio 1:3 in Fig. 10 shows that micro and macromodelling traces a similar stress-strain plot.

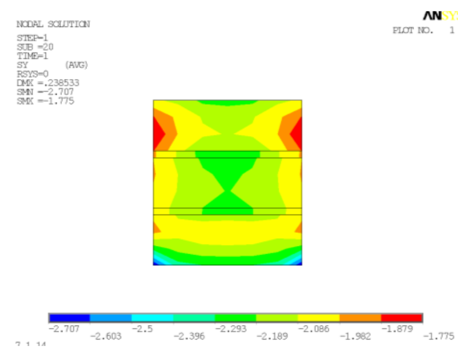

Fig. 8 Distribution of stress in brick masonry prism obtained in micromodelling for the mortar ratio 1:3

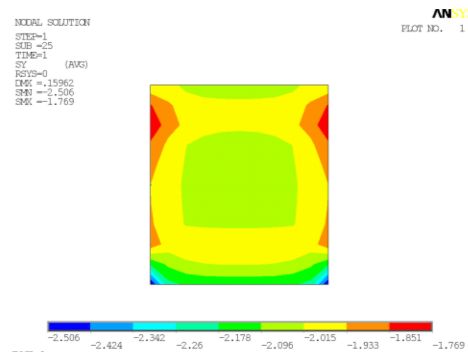

Fig. 9 Distribution of stress in brick masonry prism obtained in macromodelling for the mortar ratio 1:3

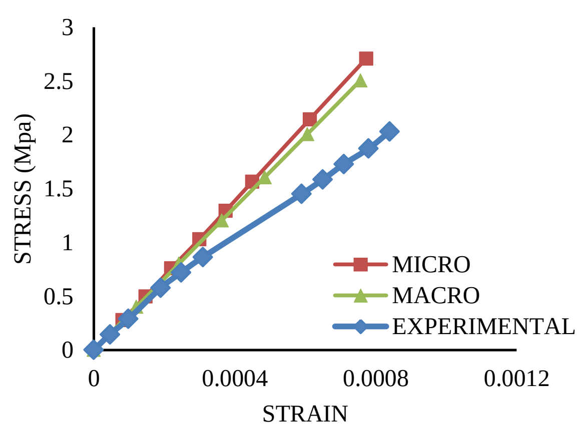

Fig. 10 Comparison of stress-strain values obtained from numerical simulation for the mortar ratio 1:3

C. Numerical behaviour of unreinforced brick masonry for Mortar ratio 1:4 under compression

The cement mortar ratio 1:4 has the least strength among the mortar ratios taken into account for this research work as shown in Table. 1. The stress distribution of the masonry in macromodelling and micromodelling for the mortar ratio 1:4 is shown in Fig. 11 and 12. The stress-strain values obtained from micro and macromodelling for the masonry prism with mortar ratio 1:4 are compared and validated with experimental results in Fig. 13. Micromodel has high stress values than macromodel and experimental as shown in Fig. 14.

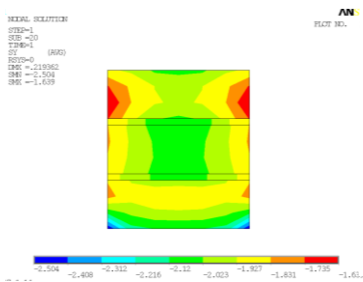

Fig. 11 Distribution of stress in brick masonry prism obtained in micromodelling for the mortar ratio 1:4

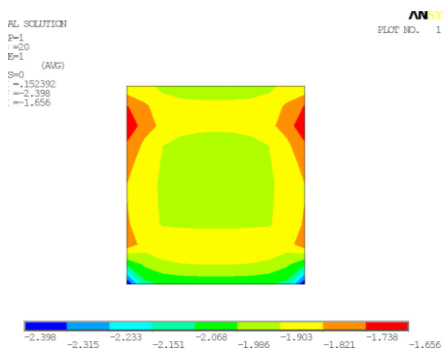

Fig. 12 Distribution of stress in brick masonry prism obtained in macromodelling for the mortar ratio 1:4

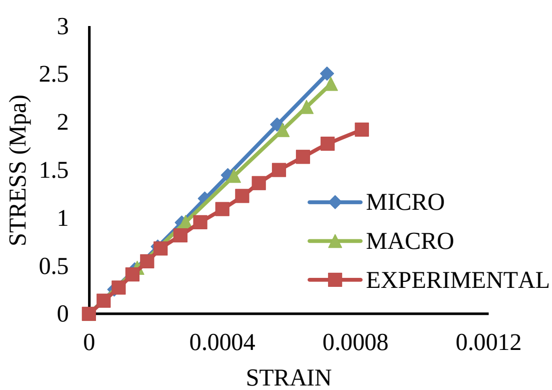

Fig. 13 Comparison of stress-strain values obtained from numerical simulation for the mortar ratio 1:4

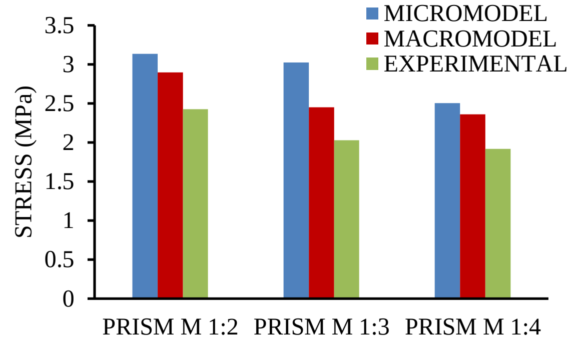

Fig. 14 Comparison of stress values of masonry obtained from experimental and numerical studies

D.Numerical simulation of Shear behaviour for brick masonry

The unreinforced brick masonry is simulated under shear loading to investigate their shear behaviour which is very vital in seismic analysis of masonry structures. The ultimate load obtained from experiment is applied as pressure on the prism. The material properties evaluated in this research work are used for brick and mortar in the numerical simulation. The bond stress is predominant at the joint of the triplet shear prism as shown in Fig. 15. The displacement of the triplet shear prism in shown in Fig. 16. The numerical simulation under shear loading would help in attaining the bond strength of the brick masonry. The bond strength obtained from the experimental and numerical investigation of triplet shear prism is compared in Fig. 17.

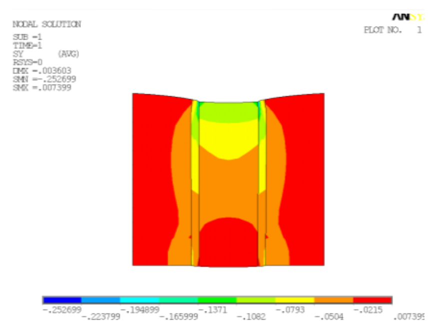

Fig. 15 Stress distribution in triplet shear prism obtained in numerical simulation for mortar ratio 1:2

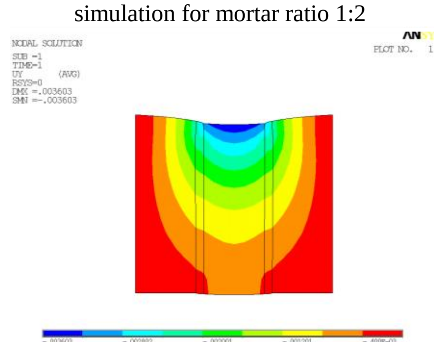

Fig. 16 Displacement in triplet shear prism obtained in numerical simulation for mortar ratio 1:2

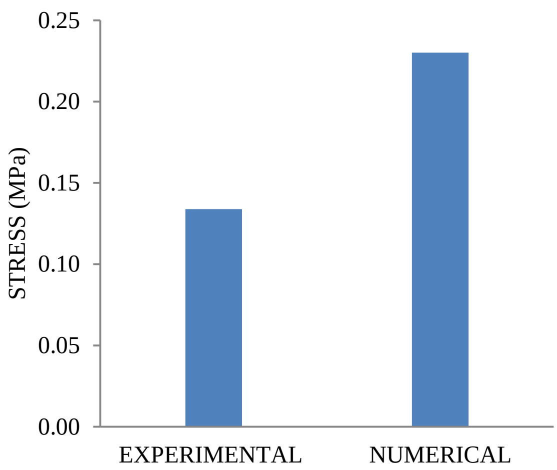

Fig. 17 Comparison of bond stress obtained from numerical and experimental investigation for the mortar ratio 1:2

VI Conclusion

The finite element models developed in ANSYS for the numerical simulation of brick masonry facilitated the investigation of composite and homogenized behaviour of unreinforced brick masonry. It also helps in tracing the failure and recognize the region where crushing occurs. The material properties for the brick and mortar are arrived from the experimental results of the materials. The stress-strain plots traced from the numerical investigation of unreinforced brick masonry under compression proves that the micro and macromodelling have good correlation. The behaviour of masonry in micro and macromodelling in compression loading are validated by comparing with the experimental results. From the results, it is evident that the masonry prism with mortar ratio 1:2 has higher strength than the masonry prism with mortar ratios 1:3 and 1:4 in experimental as well as numerical investigation. The study of triplet shear prism facilitated the evaluation of the bond strength of unreinforced brick masonry. The investigation of shear behaviour was performed experimentally and compared with the numerical simulation. The numerical models presented in this paper can also be used for different types of mortars or bricks with their material properties evaluated experimentally.

Acknowledgment

This paper is being published with the kind permission of The Director, CSIR-SERC, Chennai, India. The Scientists, Project assistants of Bridge engineering division, Technical and supporting staffs of Structural Testing Laboratory are highly acknowledged for their kind support in this research work. We thank the Dean, Head of department and the faculty members of department of Civil Engineering of Bannari Amman Institute of Technology for their support and encouragement.

References

[1] C Freeda Christy, D Tensing, R Mercy Shanthi,"In-plane shear behaviour of Brick Masonry – A Literature Review on experimental study," in *International journal of Civil and Structural engineering* Volume 2, No 4, 2012

[2] M Dhanasekar, W Haider, "Explicit finite element analysis of lightly reinforced masonry shear walls," in *Computers and Structures 86 (2008)* 15–26 (Science direct). http://dx.doi.org/10.1016/j.compstruc.2007.06.006

[3] Sami Döndüren,"Investigation of using ANSYS software in the determination of stress behaviour of masonry walls under out of plane cycling load," in *International Journal of the Physical Sciences* Vol. 5 (2), pp. 097-108, February, 2010.

[4] A Gabor, A Bennani , E Jacquelin, F Lebon , "Modelling approaches of the in-plane shear behaviour of unreinforced and FRP strengthened masonry panels," in *Composite Structures 74 (2006)*, pp. 277–288 (Science Direct). http://dx.doi.org/10.1016/j.compstruct.2005.04.012

[5] Sergey Churilov, Elena Dumova-Jovanoska, "In-plane shear behaviour of unreinforced and jacketed brick masonry walls," in S*oil Dynamics and Earthquake Engineering 50 (2013)*, pp. 85–105 (Elsevier). http://dx.doi.org/10.1016/j.soildyn.2013.03.006

[6] Fazia Fouchal, Frédéric Lebon, Isabelle Titeux, "Contribution to the modelling of interfaces in masonry construction," in *Construction and Building Materials* 23 (2009), pp. 2428–2441 (Elsevier). http://dx.doi.org/10.1016/j.conbuildmat.2008.10.011

[7] Shahid Nazir, Manicka Dhanasekar, "Modelling the failure of thin layered mortar joints in masonry," in *Engineering Structures 49 (2013)*, pp. 615–627 (Science direct). http://dx.doi.org/10.1016/j.engstruct.2012.12.017

[8] G Giambanco, L D Gati, "A cohesive interface model for the structural mechanics of block masonry," in *Mechanics Research Communications, 1997*; 24(5):pp. 503–12. http://dx.doi.org/10.1016/S0093-6413(97)00055-4

[9] V G Haach, G Vasconcelos, PB Lourenco, "Parametrical study of masonry walls subjected to in-plane loading through numerical modelling," in *Eng Struct*, 2011;33:pp.1377–89. http://dx.doi.org/10.1016/j.engstruct.2011.01.015

[10] P B Lourenço, J Pina-Henriques, "Validation of analytical and continuum numerical methods for estimating the compressive strength of Masonry," in *ISISE*, University of Minho, Department of Civil Engineering, Guimarães, Portugal.

[11] Mieczysław Kuczma, Krystyna Wybranowska, "Numerical homogenization of elastic brick masonry," in *Civil and Environmental engineering reports* of University of Zielona Góra, Poland.

[12] R Ciesielski, "The dynamic modules of elasticity of brick walls", in *XLV Scientific Conference Wroclaw - Krynica*, 1999, pp.117-124.

[13] Jahangir bakhteri, Ahmad mahir makhtar, Shamala sambasivam,"Finite element modelling of structural clay Brick masonry subjected to axial compression," in *Jurnal Technology (Jurnal Teknologi)*, 41 (B) Ten (Dis). 2004: pp. 57-68.

[14] Abrams, P. D. 1993. *Masonry Structures*. 2nd edition. Boulder. Colorado. USA: Masonry Society.

[15] Prajwal Lal Pradhan, C V R Murty, Karl Vincent Hoiseth, Mohan Prasad Aryal,"Nonlinear simulation of stress-strain curve of Infill materials using plp fit model," in *Journal of the Institute of Engineering*, Vol. 7, No. 1, pp. 1-12.

[16] C Remayanti, L Susanti, "Experiment and Numeric Analysis of Brick Masonry Wall with Bracing under Cyclic Loading," in *International Journal of Emerging Technology and Advanced Engineering*.

[17] T C Nwofor, "Experimental determination of the mechanical properties of clay brick masonry," in *Canadian Journal on Environmental, Construction and Civil Engineering* Vol. 3, No. 3, March 2012.