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In-Plane Capacity of Multi-leaf Stone Masonry Walls

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Abstract
In this article, the properties of multi-leaf stone masonry is discussed, and a 'Standard Wall', with properties typical of multi-leaf stone masonry construction is defined. A nonlinear finite element model of multi-leaf stone masonry is proposed and implemented in ANSYS. The model proposed showed reasonable accuracy with the experimental model. The relationship of height, length, thickness, compressive strength, precompression ratio and coefficient of friction between leaves of a multi-leaf stone masonry wall with the ultimate capacity of the wall is examined.

Keywords
Multi-leaf Stone Masonry, Pushover, Masonry, Finite Element Modelling, ANSYS

1. Introduction

Joining bricks, stones or similar materials (known as masonry units) by mud, lime, cement, sand, etc. (known as mortar) have been used for different structures in the past and present. Due to the inherent differences in the materials, construction techniques and workmanship, there exist numerous, if not infinite, combinations and types of masonry. Most of these constructions don't have tension taking elements in them and known as unreinforced masonry (URM).

Due to its low cost, local availability of materials, easy construction and thermal insulation, widespread use of masonry can be found. Most of the ancient structures, often with historical and cultural significance, such as the temples and monasteries in Nepal, churches and mosques in Europe are constructed out of masonry structures. Majority of buildings – residential and public are built out of masonry in Nepal, and many are vulnerable to earthquake-like loading, evident from the percentage of collapsed and damaged masonry houses in Gorkha earthquake 2015, amounting to around 99% and 93% of the total collapsed and damaged houses respectively [1] .

2. Nonlinear Analysis of Masonry

As masonry was thought of as brittle material with no nonlinear capacity, the nonlinear study of masonry started rather late. One of the first simplified approaches of nonlinear analysis of masonry was by Tomazevic [2]. Then came the Simplified Analysis Method (SAM) [3] . More recently developed Equivalent Frame Method (EFM) is an extension of well-known SAM. Different authors have modified SAM [4, 5, 6, 7]. Lagomarsino et al. [8] devised a software package (TREMURI) with capability of nonlinear analysis of masonry building.

Apart from these simplified macro-modelling techniques, Finite Element Method (FEM) has been used. Zheng et al. [9] have used the time history analysis using micro-mesh for low-strength brick masonry. Authors [10, 11] have compared results from different modelling techniques and concluded that macro-modelling technique gave results in close agreement with the detailed micro-modelling technique. Apart from FEM, numerical modelling of brick masonry has been formulated [12].

3. Stone Masonry

Stone masonry is popular in Nepal owing to the local availability of stones in Himalayan region. Stone, as it is derived from natural sources, has a vast range of physical and strength properties. The size of the stone, its strength, dressing of the stones before construction and the placing method of the stones make the stone masonry vary largely.

3.1 Types of Stone Masonry

Different sizes and placement of the stones make the classification of stone masonry challenging. Nepal National Building Code NBC 203:2015 [13] doesn't classify stone masonry but requires the use of through stone or dowels during the construction to make the behaviour of wall as a single leaf or solid wall. Indian Code IS 1597:1992 [14] provides provides similar recommendations. IS 1905:1987 [15] recognizes multi-leaf stone masonry as cavity wall "consisting of two leaves, each leaf built of masonry units and separated by a cavity." Eurocode 6 [16] divides wall into single-leaf wall, cavity wall, double-leaf wall and grouted cavity wall. Anzani et al. [17] have classified the stone masonry into four distinct classifications as shown in Figure 1 .

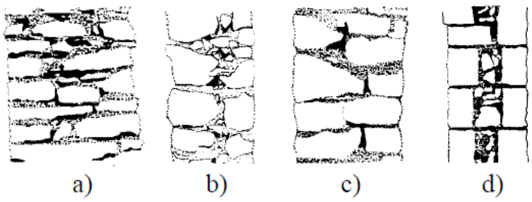

Figure 1: Stone Masonry classification by cross section: a) single leaf or solid, b) two leaves without connection, c) two leaves with connection, d) three leaves (Figure Courtesy : [18])

3.2 Modelling of Stone Masonry

Several analytical and numerical models have been proposed for stone masonry. Numerical modelling of three leaf stone masonry has been proposed by Ramalho et al. [19]. Elasto-plastic damage model has been proposed for the multi-leaf heritage masonry walls by Al-Gohi et al. [20]. Castellazzi et al. [21] have proposed a simplified micro-modelling approach for historical stone masonry walls. Betti et al. [22] have used finite element modelling approach and simplified macro-modelling approach for two layered stone masonry and compared the damages with the test results. In his Ph.D. Thesis, Krzan [23] performed the performance based experimental and numerical assessment of multi-leaf stone masonry walls.

3.3 Experimental Works

An intensive experimental testing on multi-leaf stone masonry has been done by Krzan [23]. Ali et al. [24] have conducted shake table tests on three-leaf stone masonry common masonry in Himalayan region. A similar experimental investigation on multiple leaf stone masonry have been conducted by Anzani et al. [17]. Similarly, a full-scale shaking table test on two-storied masonry building made with two-layered stone masonry walls has been conducted at the Eucentre laboratory by Magenes et al. [25]. Another shake table test has been conducted on similar two-leaf unreinforced stone masonry and strengthened buildings by Mazzon, et al. [26] at University of Padua.

Chiostrini et al. [27] have determined the strength of ancient masonry walls via experimental tests. Similarly, Milosevic et al. [28] have conducted diagonal compression, triplet and compression tests on rubble stone masonry specimens. Magenes et al.[29] has also conducted experiment on characterization of stone masonry mechanical properties.

3.4 Practices in Nepal

Though NBC does not consider multi-leaf stone masonry, these constructions can be seen in residential houses in the rural hilly regions of Nepal. A recent photograph of such construction is presented in Figure 2.

Figure 2: Multi leaf stone masonry construction in Ruby Valley, Dhading, Nepal (Photo taken: Sep-Dec 2018)

4. Finite Element Modelling of In-Plane Behaviour

In-Plane response of masonry structure is of crucial importance due to large stiffness in in-plane direction as compared to out-of-plane direction. During lateral loadings, the capacity of masonry structure is chiefly governed by the capacity of walls in direction of loading.

4.1 Modelling in ANSYS

The modelling of wall is done in a software capable of finite element modelling, ANSYS Mechanical APDL version 19.2. SOLID185 elements, defined by eight nodes each having three degrees of freedom, i.e. translation in three orthogonal directions [30] is used with enhanced strain formulation, that prevents volumetric and shear locking and hence well-suited for bending problem in nearly incompressible solids. The contact between leaves is modelled by 2-D contact (CONTA174) and target (TARGET170) elements in ANSYS, defined by the coefficient of friction and adhesion between the surfaces.

To represent weak tension and strong compression behaviour of masonry, a composite failure surface consisting of Rankine tension failure surface and Drucker-Prager surface in tension (Drucker-Prager Concrete failure model) has been employed. This model is well-suited for brittle materials with high compressive strength and low tensile strength such as masonry and concrete [30]. The hardening-softening behaviour of the yield surfaces is defined by nonlinear hardening and linear softening functions. Detailed explanation on failure surface and hardening and softening behaviour are given in Material Reference on ANSYS Help [30].

4.2 Validation of Model

Meta Krzan [23] performed experimental assessment of 18 multi-leaf stone masonry walls. The test carried out on wall with no connecting stones, namely SNK7.5-1 is used for the validation of the modelling approach in ANSYS. The test wall has a length of 1 meter and height of 1.5 meter. The thickness of the outer walls is 0.15 meter, and the thickness of core is 0.1 meter. The construction of wall is shown in Figure 3.

Figure 3: Construction of wall with no connecting stone [23]

The mechanical properties of the wall are taken from the experimental results [23], and relevant literature [7, 31].

For the analysis, the bottom is fixed to the ground, and the top face is left as free end, with precompression pressure on the face. The pushover curve of the analysis and experimental result is presented in Figure 4. It can be seen that the results are in close agreement.

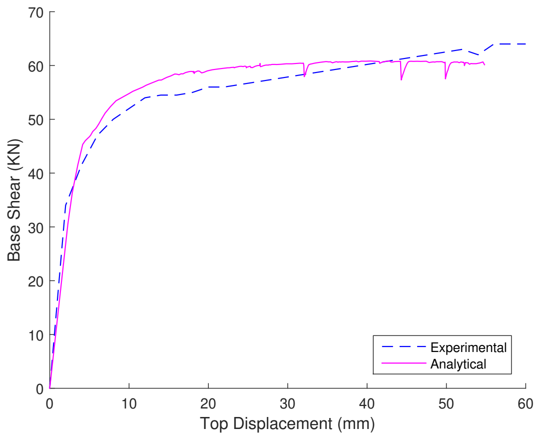

Figure 4: Pushover curve of wall SNK 7.5: Analytical and Experimental

5. In-Plane Capacity of Multi-Leaf Stone Masonry Wall

5.1 Properties

5.1.1 Masonry Unit (Stone)

Stones can vary in shape, size, texture and strength. The density of stones varies from 1500 kg/m3 to 3000 kg/m3, compressive strength may vary from as low as 5 MPa to as high as 400 MPa while flexural strength may vary from 1 MPa to 35 MPa. Similarly, the value of modulus of elasticity may vary from 4,000 MPa to 100,000 MPa. (Based on compilation by Krzan [23].

5.1.2 Mortar

Mortar is used to provide uniform bedding for the units and to bind together the masonry. As with the masonry units, the physical properties vary widely in masonry with the compressive strength being 0.5-3 MPa for soil binder to 10-50 MPa for Cement binder. Similarly, the Young's Modulus may vary from less than 1 MPa for soil/clay mortar to 20-30 MPa for Cement mortar [23].

5.1.3 Masonry

The properties of masonry are governed by the properties of the constituent materials, their positioning in the masonry, construction techniques and workmanship. There have been formulas to derive the compressive strength of masonry from its constituent materials[16]. The mechanical properties of stone masonry as found from experiments and codes are compiled in Table 1.

Apart from the mechanical properties given in Table 1, other values are of interest are density, cohesion and coefficient of friction. NTC08 [33] recommends a value of 21 KN/m3 for masonry, while the value based on experimental tests by Magenes et al. [29] is 23 KN/m3. Rizzano and Sabatino[7] had used a value of 0.5-0.58 for coefficient of friction, and a value of 0.1-0.23 MPa for cohesion. Eurocode 6 [16] implicitly purposes a value of 0.4 for coefficient of friction and 0.1 MPa for cohesion in its formula for shear strength. There is no consensus on determination of Modulus of Elasticity of stone masonry walls from compressive strength. The relation given by Eurocode 6[16], Turkish code[33] and Building Code of Pakistan[34] is a linear relationship with a multiplying factor of 1000, 200 and 750 respectively.

5.2 Properties of 'Standard Wall'

To determine the effect of a parameter on the lateral load carrying capacity of the multi-leaf stone masonry, a 'Standard Wall' is proposed with properties that are a representation of a three-leaf masonry wall prevalent in historic and existing structures. While it has been established in the former section that the properties may vary widely, care has been taken so as the "Standard Wall" represents a typical three-leaf stone masonry wall in practice.

5.2.1 Physical Dimensions

The floor to floor height of a typical wall may range from 2.0 meters to 3.5 meters. However, the pier height between windows and doors may vary between 0.5 meters to 2 meters. A standard height of 1.5 meter and a length of 1 meter will be taken. A thickness of 0.4 meters with inside to outside thickness ratio (β) of 0.67 will be taken for 'Standard Wall', in line with the dimension used by Krzan [23] in the experimental study.

5.2.2 Mechanical Properties

As represented in Table 1, the compressive strength (f_{ck}) of stone masonry varies widely from 0.25-7.34 MPa. A value of 3.2 MPa shall be taken for the outer leaf of 'Standard Wall', in accordance with the average value from the experimental tests by Magenes et al.[29]. The compressive strength of the inner wall is taken as 50% of the compressive strength of the outer wall. The flexural strength (f_t) is expected to vary with the compressive strength and is taken as 4% of compressive strength, in line with the values from experiments of Magenes et al. Experiments by Magenes et al.[29] on stone masonry walls, similar in properties and construction to historic and prevalent multi-leaf constructions. Modulus of Elasticity (E) is taken as linearly varying with the compressive strength, but the constant given is taken as 750 so that it is in line with the average value given by the experiment and Building Code of Pakistan, as given in Equation 1.

$$E_m = 750.f_m \tag{1}$$

The Shear Modulus (G) is taken as 0.4 times Modulus of Elasticity (E) as given by Eurocode 6[16]. The density is taken as 2300 kg/m3, for the outer walls and inner core. While a value of 0.5-0.58 for coefficient of friction has been used by Rizzano and Sabatino[7] for the analysis, a value of 0.4 as given as Eurocode 6 has been taken for the 'Standard Wall'. A value of 0.1 MPa will be used for cohesion, as the lower value used by Rizzano and Sabatino in analysis and as suggested by Eurocode 6. The initial pressure is taken as 7.5% of the compressive strength of the outer wall. The pressure on the wall will be distributed on the ratio of modulus of elasticity and thickness of the wall, as given by Binda et al. [18], simplified version presented in Equation 2 and Equation 3.

$$p_o = \frac{E_o t_o}{2E_o t_o + E_i t_i} . \frac{2t_o + t_i}{t_o} .p \tag{2}$$

$$p_i = \frac{E_i t_i}{2E_o t_o + E_i t_i} . \frac{2t_o + t_i}{t_i} .p \tag{3}$$

where, p is the initial total pressure taken as percentage of compressive strength of outer wall, p_o and p_i are the distributed pressure on the outer and inner leaves respectively, E_o and E_i are the Modulus of Elasticity of the outer and inner leaves respectively, t_o and t_i are the thickness of outer and inner leaves respectively.

Table 1: Mechanical Properties of Stone Masonry*

Source	Comp. Strength (f_ck, MPa)	Flexural Strength (f_t, MPa)	Elastic Modulus (E, MPa)	Shear Modulus (G, MPa)
Magenes et al.[29]	3.09-.76 (3.28)	0.112-0.161 (0.14)	2200-3000 (2550)	739-940 (840)
M. Krzan[23]	6.0-7.34	0.03	534-1570	214-661
Rizzano, Sabatino** [7]	2.4-6.2	0.1-0.18	1400-1650	250-660
Silva et al.** [31]	-	0.02-0.2	226.5-6708	24.8-546
Valluzi et al. [32]	1.45-1.97	-	1450-2390	-
IS 1905:1987 [15]	0.25-8.35	0.05-0.14	-	-
Eurocode 6 [16]	-	0.05	$1000.f_ck$	$0.4.E$
NTC 08 [33]	2.6-3.8 (3.2)	0.084-0.111 (0.10)	1500-1980 (1740)	500-660 (580)

**Values in braces represent the average or suggested values*
*** Used for analysis or compiled in the literature*

5.2.3 Plasticity Parameters

For the nonlinear properties, Drucker-Prager Concrete model is used as described in Section 4. The biaxial compressive stress is taken as 1.15 times the uniaxial compressive stress. The masonry is assumed to have very low dilatancy value. The strain at uniaxial compressive strength is taken as 0.005. The residual compressive and tensile strength has been taken as 20% of the ultimate value.

5.3 Bilinear Idealization of Pushover Curve

The pushover curve obtained through the nonlinear finite element analysis is to be idealized into bilinear or multilinear curves so that the results obtained can be compared.
The determination of the bilinear curve is based on assumption that the areas under the actual and the idealized force - displacement diagrams are equal. The bilinear idealization for this study is taken as elastic-perfectly plastic idealization as it is one of the simplest approach, and serves well for this analysis. For the idealization of curves, the ultimate displacement is limited to 80% of the maximum resistance obtained. Initial stiffness (K_{ef}) is taken at two-third of maximum resistance according to Equation 4.

$$K_{ef} = \frac{2/3.F_{max}}{d_{2/3.F_{max}}} \tag{4}$$

where, $d_{2/3.Fmax}$ is the displacement where the shear force reaches two thirds of the maximum shear force.

6. Results

The modelling is done in ANSYS as described in Section 5 by varying different parameters as presented in Table 2. All other parameters are same as that of 'Standard Wall'. A total of 260 models have been analysed. A adaptive meshing has been utilised with the coarsest mesh size of 0.15 m in walls of larger dimensions and a mesh size of 0.1 m in walls of lesser dimensions than 'Standard wall'. The pushover curves obtained by the analysis are bilinearized as in Section 5.3.

Table 2: Parameters of Standard wall and Range used for Analysis

Properties	Standard Wall	Range
Height (m)	1.5	0.25-3
Length (m)	1	0.25-3.5
Thickness (m)	0.4	0.2-0.75
Strength, f_{ck}, (MPa)	3.2	1-10
Precompression ($\% f_{ck}$)	7.5	5-50

6.1 Effect of Dimensions

The effect of height on ultimate force of multi-leaf stone masonry walls for different precompression ratios is shown in Figure 5, and the effect of length with varying compressive strength is shown in Figure 6. Similarly, the relationship between ultimate force and thickness with varying coefficient of friction between the leaves is shown in Figure 7. As is seen from the figure, the ultimate lateral force resisted by a wall decreases with increase in height, and increases with increase in length and thickness. It has been seen that inner to outer thickness ratio doesn't bear significant correlation with the ultimate capacity of wall and hasn't been presented here.

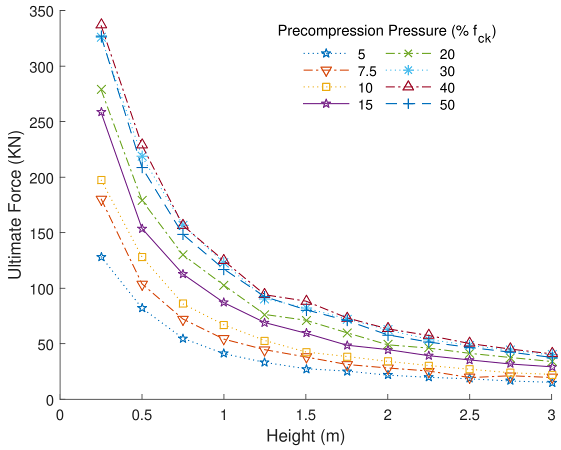

Figure 5: Ultimate force versus height for different precompression ratios

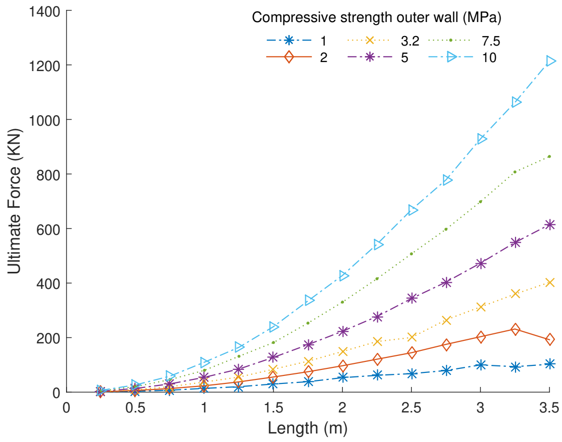

Figure 6: Ultimate force versus length for different compressive strength

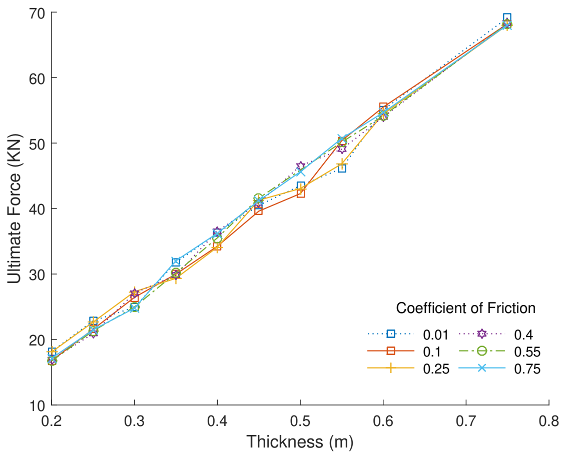

Figure 7: Ultimate force versus thickness for different coefficient of friction

6.2 Effect of Strength Parameters

Increase in compressive strength of multi-leaf stone masonry walls increases the ultimate capacity of the wall, as evident from the graph shown in Figure 8. However, the change in the ratios of strengths between the inner to outer walls doesn't have a definite correlation as seen from analysis and the result isn't presented here. The effect of precompression pressure on ultimate force of multi-leaf stone masonry walls for different aspect ratios is shown in Figure 9. As is seen from the figure, the ultimate lateral force resisted by a wall increases with increase in precompression ratio, but the effect is more pronounced for walls with lower aspect ratios. It is seen from Figure 10 that the coefficient of friction between the leaves doesn't have a pronounced effect on the ultimate resistance of the wall.

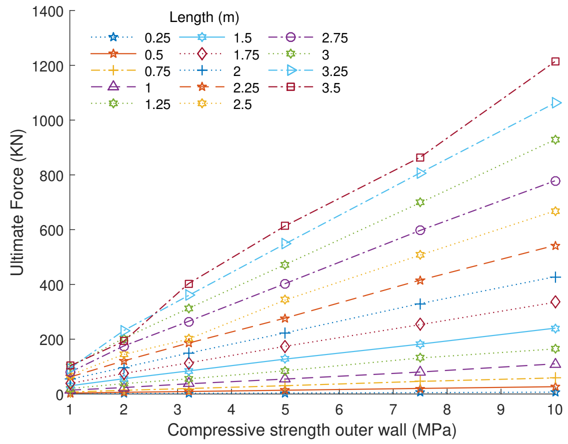

Figure 8: Ultimate force versus compressive strength for different lengths

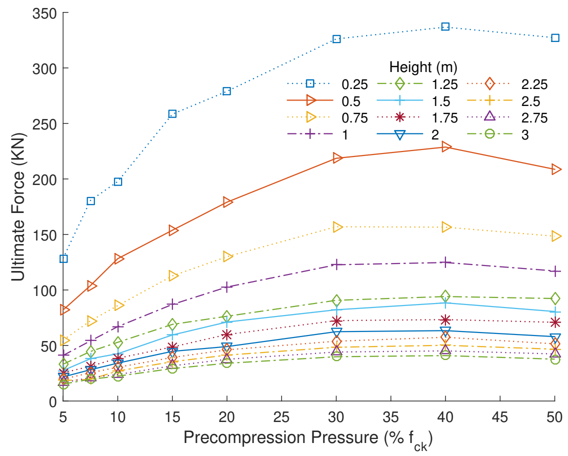

Figure 9: Ultimate force versus precompression ratio for different heights

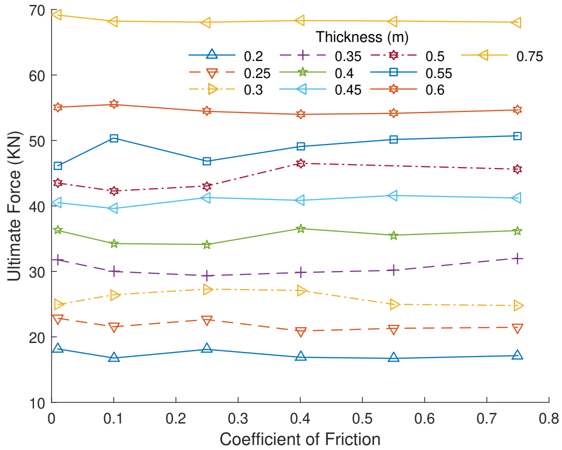

Figure 10: Ultimate force versus coefficient of friction for different thicknesses

7. Conclusions

It can be concluded that the proposed model of the nonlinear analysis of multi-leaf stone masonry wall can be used for the capacity assessment of multi-leaf stone masonry wall with reasonable accuracy and easily implemented in general finite element software such as ANSYS. Increase in length, thickness, compressive strength and precompression pressure increases the ultimate force of the multi-leaf stone masonry; increase in height decreases the capacity and coefficient of friction between the leaves doesn't have a significant effect.

This study can serve as a starting point in development of simplified capacity assessment technique for multi-leaf stone masonry structures. Further research on the topic may be to find the effect of other parameters such as adhesion between leaves, change in plasticity parameters and with the use of different failure criteria.

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