Investigation of Mechanical Properties of Mud Bonded Kathmandu World Heritage Buildings

Hari Ram Parajuli

IOE, Tribhuvan University, Nepal

Abstract: Kathmandu World heritage buildings are made from low strength construction especially traditional bricks. From the lesson from 2015 Gorkha earthquake, saving those buildings in severe quake has been a challenging job. It requires proper assessment of its mechanical properties and strengthening as per seismic requirement. An investigation of mechanical properties on brick masonry heritage building has been done and presented here. Nondestructive test - elastic wave tomography at existing walls of the buildings and destructive tests shear, compression and combined loadings on the wallets made from bricks collected from old buildings. The several test tests were conducted to find the properties of brick elements and walls such as, density, modulus of elasticity, Poisson’s ratio, shear modulus, shear wave velocity.

Keywords: Brick masonry, material property, Kathmandu World Heritage, mud.

1. Introduction

Kathmandu valley, the capital city of the Himalayan country, Nepal, is a living heritage which offers beautiful landscapes, aesthetics and architecture of structures. It was inscribed on the List of World Heritage in 1979, as a single site comprising seven best monuments. They are Durbar Squares (Patan, Kathmandu and Bhaktapur), Pashupatinath, Swoyembhunath, Bouddhanath and Changu Narayan. One of the seven monument zones, Patan Durbar Square, the palace where Malla king (three hundred ago). The department of Archaeology of Nepal (DOAN) and the World heritage community (WHC) have made demarcation of core and buffer areas (Fig. 1a). It comprises ensembles of Durbars (Fig. 1b) and residential buildings. They were designed and built for vertical loads before enforcing any seismic resistant design guidelines and cannot resist earthquake loads as evidenced by the damages (Fig. 1c) of 1934 earthquake [1] and 2015 earthquake (Fig 2) have become the prime cause of death and destructions in earthquakes. The city lies in the Himalayan zone which is a part of most seismically active zones in the world. It has the recorded history [2] strong earthquakes occurred since 1223AD. At least one third of the populations were killed and most of the houses were damaged severely in 1223 and 1255. A great earthquake occurred in 1934 [1] which killed ten thousand people and damaged most of the residential houses, temples and royal palaces. Big earthquake occurred on 25th April 2015 which killed 8900 peoples, twenty two thousands were injured and seven billion rupees lost in damages of various sectors [3, 4]. Severe damages are observed in the heritage structures. All together 753 structures in heritage area have been damages. Some of them are collapsed and other are severely damaged. Even after 2015 earthquake, seismologists are predicting that there is still huge seismic gap remaining in the Himalayas which could produce great earthquake soon [5] and damages and death could be hundred times more than that occurred in the past due to increased population and low strength houses.

In 2015 earthquake severe damages in heritage buildings because of low seismic capacity of brick masonry structures. All heritage buildings are made of
brick with mud or lime surkhi mortar. They are very weak in seismic forces. Thus, sever damages were found in heritage properties.

All such low strength structures were completely damaged. Hundreds of thousands of people were made homeless with entire villages collapsed across many districts of the country. Very old buildings which had historic values were destroyed at World Heritage sites in the Kathmandu Valley, including some at the Kathmandu Durbar Square, the Patan Durbar Square, the Bhaktapur Durbar Square, the Changunarayan Temple and the Swayambhunath Stupa. Properties are shown in this research.

Looking at the extensive damages in heritage structures both in 2034 and 2015 earthquake, if not strengthened, restored and preserved properly, we loss not only the physical structures but also the heritage, cultural values and the earnings through tourisms. So, preserving heritages in earthquake is a most important task. Thus, economical strengthening of these buildings using locally available materials and indigenous technology that abide the heritage properties guidelines without compromising their values is a key issue of preserving heritages which requires detailed structural assessment and investigations of strength and properties at existing conditions. So, it requires detailed investigations and numerical study. One of the key requirements of numerical calculation for evaluating seismic capacity is mechanical properties. So, an investigation for finding out mechanical properties of world heritage brick masonry buildings has been done.

Thus, a research project was done in Institute of Engineering (IOE), Tribhuvan University, Nepal taking the case study of Patan Durbar Squares, Sree Mahal and Kathmandu Durbar. Three methods – non-destructive-elastic wave tomography, and destructive tests – compression, shear and combined tests walls and bricks were carried out.

2. Description of the sample building and the site

The heritage site, Patan Durbar Square (PDS) Area is located in Lalitpur Sub-Metropolitan city of the Kathmandu Valley. Fig. 1a shows the demarcation of core area of the heritage site. The sample buildings is in Fig. 3. They have been using for public purposes.

Test samples elements- bricks, mud, surkhi are collected from heritage locations such as Patan, Kathmandu Durbar Squares and Sree Mahal (Figs. 1-3). The sample building (Fig. 3), is two storied, 16.5 m in length and 5.6 m in width. Wall is made of traditional brick with thickness 60cm at bottom and 50 cm at top tapering slightly from bottom to top. It was constructed three hundred years ago. It sustained damages in earthquakes and repaired many times. Recently, its original roof has been replaced by corrugated galvanized iron sheet which rests over wooden beams and battens, and wall interior has been plastered by cement sand mortar. The floor has been recently replaced by concrete which rests over wooden boards supported by planks and beams. Now, it looks like completed repaired hiding its original construction. The building has very large opening in the front side.

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Fig. 1  Patan Durbar Square area.

(a) Core and Buffer zone  (b) Contemporary view  (c) Damages in 1934 earthquake
Wooden posts are supporting the wall of upper storey. In the upper storey, there is big wooden window placed at mid span of wall which is slightly projected outside showing nice aesthetic view.

3. Non-destructive Tests

Two types of experiments – destructive and nondestructive tests were done in order to investigate the material properties of the heritage buildings. In nondestructive tests, elastic moduli were investigated from elastic wave tomography and pocket AE measurements.

3.1 Elastic Wave Tomography

Elastic waves produced by a sudden redistribution of stress in a material due to external forces such as pressure, load, temperature etc., releases energy in the form of stress waves and propagates through the surfaces and can be recorded by sensors. The back side wall of the sample building was selected for the elastic wave measurement and instrumented as shown in Fig. 4. An area of 1.5 m X 1.5 m was taken and 16 sensors were placed at equal distances. Sensor arrangements at inner and outer surfaces are shown in Fig. 4.

Then impact on wall was given by a steel hammer having a small spherical ball at its edge near one sensor to generate the stress waves and obtained waves at all sensors were recorded. Similarly, impact was given near to each sensor turn by turn and measurements at other sensors were recorded. For detail, Parajuli et al. [6-8] is referred. Based on the first arrival time of P waves at various sensors, stress wave velocities in divided cells were obtained. Fig. 4 shows the distribution of P waves at outer surface and inner surfaces respectively. The P wave velocity varies 500 to 1000 m/sec. It shows that interior of wall is stronger than the inner surface.

3.2 Pocket AE Measurement

Pocket AE is a handheld instrument for acoustic emission testing and performs advanced wave-form based signal acquisition and processing. Elastic wave velocities estimated by tomography give a wide range of values. When looking at Fig 4, P wave velocity ranges from 500 to 1000 m/sec. For FEM analysis, we need specific value rather than the range. Thus using pocket AE, series of measures were taken at various locations of different walls (Fig. 5). Noting first arrival time of elastic waves, time differences of successive peak amplitudes at near and far end sensor channels were calculated. Then, velocity was calculated by thickness through which wave passes, divided by the time difference between two sensors. Then, from primary wave, velocity, unit weight (measured 19KN/m³), and Poison’s ratio (assumed 0.2), modulus of elasticity (E) and shear wave velocity (Vₕ) of the material are calculated. The variation of P wave with wall thickness is shown in the Fig. 5. The experiment results show that as the wall thickness increases its P wave velocity decreases. The joints and voids inside
the wall sharply decrease its strength, as a result P wave velocity is found decreasing. If the P wave velocity from the equation shown in Fig. 5 is projected for 55cm wall, it becomes 547 m/sec. which lies in the ranges shown in Fig. 4 and seems reasonable. Though, interpolation and extrapolations would not be the case always, rather vary wall to wall depending upon its own properties. However, the trend of curve in the Fig. 5 shows, elasticity decreases with the increase of joints and voids in thicker wall.

4. Destructive Tests on Mud Bonding

Intrusive experiments designed for brick, mortar and wallets separately. The test specimen were prepared from the material collected heritage sites such as Sreemahal and Patan Durbar Square buildings where severe damaged observed in 2015 earthquake. All the test experiments were done in Institute of Engineering (IOE).

4.1 Brick Wallet Tests

It is a destructive test. The main purpose of this test was to take the core samples from the existing buildings and test in the lab. But, it was not possible because of various reasons such as difficulty of transportation, and stability of the core after taking out of wall, and owners do not want to drill in their walls. So, bricks fabricated in MaIla period were collected from the old buildings which were dismantled recently. Following the traditional method of constructed which used to construct such kinds of buildings in ancient times, sample brick wallets were constructed at IOE.

Three kinds of tests – compression, shear, and combined shear and compression loading tests were done on the brick wallets test samples. Mud mortar cubes were made from the water and clay mixture following the same techniques as in the wall making. The mud mortar cube samples were tested when they became fully dry. Brick units, mortar cubes and wallets were applied with three kinds of loadings. They are diagonal shear, vertical compression and combined vertical and lateral loads. The numbers of samples, sizes, method of load application, reading of load and deformations etc. have been given in the Table 1.
4.1.1 Compression

Compressive loads were applied on test walls and the loads versus deformations were recorded at various intervals of loadings. The results initial stress and strain, modulus of elasticity (E), Poisson’s ratio (v), shear modulus (G) and shear wave velocities (V_S) of the walls are given in the Table 2. Initial stress is load divided by area and initial strain is initial deformation divided by height at first step of loading. Because of constraint of loading machine, smaller load could not be apply such that initial stress is lesser than 0.1N/mm². All the properties have been calculated from initial tangent stress strain ratios. Shear modulus and shear wave velocity is calculated from their usual relations. Same symbols have been used in the following sections also. As in the walls, brick units and mortar blocks were tested and the obtained result are presented in Table 2-3. We weighed brick and mud mortar samples, measured their size and calculated density. Shear modulus and shear wave velocity were calculated. The modulus of elasticity of mortar is found very low as compared to brick units and walls. The compression tests are presented on Fig. 6.

Compressive stress and strain obtained from the test is plotted in Fig. 6. At the beginning, the ratios which is in fact modulus of elasticity, is higher and after small increment of loads it starts cracking and the ratio drops. It is because of cracks at mortar joints. Again after few steps of loadings bricks starts taking loads and the relationship becomes linear.

Table 1  Experiment plan.

| S.N | Description                                                                 | Testing method                                                                 |
|-----|-----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| 1   | **Compression**                                                             | Type: Bricks and mortar cubes, mud bonded wall                               |
|     | Samples: 90 bricks, 11 mortar cubes and 3 walls                             | Measure: Vertical load, vertical and lateral deformations.                   |
|     | Sizes: Wall- Length=35cm, Width=35cm & Height=35cm                          | Plot: Compressive stress vs. strain                                           |
|     | Brick units - 45 mm cut cubes                                               | Calculate: Stress, strain, elastic modulus and Poisson’s ratio               |
|     | Mud mortar - 48mm cubes                                                    |                                                                               |
| 2   | **Shear**                                                                  | Test: Diagonal shear                                                         |
|     | Type: Mud bonded wall                                                       | Measure: Force and deformation                                                |
|     | Samples: 4                                                                  | Plot: Shear stress vs. strain                                                 |
|     | Size: Length=60cm, Width=60cm & Thickness=35cm                             | Calculate: Ultimate shear stress, strain and modulus                         |
| 3   | **Combined horizontal and vertical loading**                               | Type: Mud bonded wall                                                         |
|     | Samples: 5                                                                  | Measure: Vertical load and horizontal load                                    |
|     | Sizes: Length=35cm, width=70cm and height=70cm                             | Plot: Horizontal and vertical stress relationship                            |
|     |                                                                           | Calculate: Elastic modulus, cohesion and tangent angle                       |

Table 2  Experiment results of compression test.

| Sample | Initial stress N/mm² | Initial strain | E N/mm² | G N/mm² | V_S m/sec |
|--------|-----------------------|----------------|---------|---------|-----------|
| 1      | 0.10                  | 0.00043        | 234     | 0.32    | 88        |
| 2      | 0.10                  | 0.00037        | 270     | 0.24    | 109       |
| 3      | 0.10                  | 0.00031        | 319     | 0.17    | 136       |
| Average|                      |                | 274     | 0.24    | 111       |

Table 3  Properties for brick units and mud mortar cubes.

| S.N | Location          | Type      | Nos. of specimen | Density $\text{kg/m}^3$ | Compressive Strength $\text{N/mm}^2$ | E $\text{N/mm}^2$ | G $\text{N/mm}^2$ | Vs $\text{m/sec}$ |
|-----|-------------------|-----------|------------------|--------------------------|--------------------------------------|------------------|------------------|------------------|
| 1   | Patan Durbar Square | Brick     | 12               | 1768                     | 11.03                                | 3874             | 0.11             | 1745             | 984              |
| 2   |                    | Mud mortar| 9                | 1705                     | 1.58                                 | 33               | 0.19             | 14               | 85               |
| 3   | Sree Mahal         | Brick     | 9                | 1768                     | 6.4                                  | 3874             | 0.11             | 17609            | 998              |
| 4   | Wallet            | 4         | 1770             | 1.29                     | 89.14                                | 0.19             | 235              | 115              |
| 5   |                    | Mud mortar| 6                | 1700                     | 1.32                                 | 66.08            | 0.19             | 174              | 101              |

Fig. 6  Compressive strength Test of wall: Load deformation curve.

4.1.2 Shear

Sample walls were placed diagonally on the testing platform as shown in Table 1. The load was applied at the top and increased gradually. Deformations of wall along the bed of the joint were measured. The dimensions, shear height and obtained shear modulus have been given in the Table 4. Shear modulus is calculated from the ratio of shear stress and shear deformation.

The shear stress and strain relationships are plotted in Fig. 7. As the load increases, the stress strain behavior gets nonlinear. Thus shear modulus is calculated from initial three values which are very close before starting to decline. Taking Poisson’s ratio equal to 0.24 obtained from the compression test modulus of elasticity is calculated. The obtained results are given in Table 4. Average value of shear modulus, elastic modulus and shear wave velocity are found to be 250 $\text{N/mm}^2$, 621 $\text{N/mm}^2$ and 366 m/sec. respectively. Similarly, average shear stress and strain at ultimate stage are found to be 0.126 $\text{N/mm}^2$, 0.00646 respectively. Shear strength of the wall is governed by the mortar interface which comes from friction due the asperities between the surface of mortar layer and the surface of the brick unit, and the bond between mortar and brick units. Normal compression perpendicular to the interface further increases its shear strength because the asperities cannot easily slide over one another. In Fig. 7, shear stress and strain relationship looks linear; however, it behaves non-linearly. Only in
the very small stress levels the wall as a whole behaves and the shear modulus looks linear. However, quickly after increasing the loads, the wall tries to shear at the joint. Then crack initiates at the weakest bed and starts to slip forming two rigid bodies. Thus, the deformation is controlled by the mortar joint and the shear modulus for joint and wall remains same as the deformation phenomenon totally governed by joint.

4.1.3 Shear and Compression

Five wallets were given vertical 10KN load initially and then lateral load were applied at upper edge to the specimen (Table 1).

From the plot modulus of elasticity was calculated from the initial tangent stiffness ($k_0$) obtained from the initial load divided by initial deformation. The results are given in Table 5. Average modulus of elasticity is 632 N/mm². In the Table, $\Delta_0$ is horizontal displacement at initial force $P_0$. For historic masonry structures, it is widely accepted to examine E and G for a wall as a whole, rather than for the constituent materials, since brick masonry is not an elastic, homogeneous, or isotropic material. Because the value of initial stiffness $k_0$ represents the elastic stage of the wall, $k_0$ can be calculated for walls with the fix-ends against rotation as in Ref. [1].

Horizontal loads were gradually increased on the four walls with vertical loads 10, 12, 14 and 16 KN. The loads were kept constant and horizontal load was increased until the wall fails. The obtained results are given in Table 6 and plotted in Fig. 7d. $\sigma_n$ and $\tau$ are normal and shear stresses. The coefficients are 0.0857 and 0.9174 which are equivalent to cohesion and Coulomb friction $\tan \Phi$.

4.1.4 Test Summary

We have investigated the mechanical properties of brick masonry from three kinds of experiments. Brick masonry is a composite material of brick units and mortar joints and interface between mortar and unit. Together, they determine the properties of masonry. The interface is known as the weak link in the system with minimal or almost nil tensile bond strength and thus only compressive and shear strength were investigated. In all experiments on wall specimen, interfaces between the brick units initiate and lead to fail. Final results obtained from the experiments are summarized in the Table 7. Material properties and strengths for these kinds of constructions have never been investigated. The modulus of elasticity is average

| Test | Length mm | Width mm | Area mm² | Height mm | $G$ N/mm² | $E$ N/mm² | $\rho$ kg/m³ | $V_s$ m/sec | Stress N/mm² | Strain |
|------|-----------|----------|----------|-----------|-----------|-----------|-------------|------------|-------------|--------|
| 1    | 585       | 365      | 213525   | 585       | 225       | 0.24      | 557         | 17.68      | 353         | 0.154  |
| 2    | 585       | 365      | 213525   | 585       | 280       | 0.24      | 695         | 17.68      | 394         | 0.128  |
| 3    | 585       | 365      | 213525   | 255       | 352       | 0.24      | 874         | 17.68      | 442         | 0.128  |
| 4    | 585       | 365      | 213525   | 485       | 137       | 0.24      | 339         | 17.68      | 275         | 0.097  |
| Average |        |          |          |           | 250       | 0.24      | 621         | 17.68      | 366         | 0.126  |

![Fig. 6 Shear Test of Wall.](image-url)
### Table 5: Results from combined lateral and vertical loadings.

| S.N. | $P_0$ (KN) | $h_0$ (mm) | $k_b$ (KN/mm) | $E$ (N/mm$^2$) | $G$ (N/mm$^2$) | $V_s$ (m/sec) |
|------|-------------|-------------|---------------|----------------|--------------|--------------|
| 1    | 6.03        | 0.07        | 86            | 955            | 0.25         | 17.68        | 382          | 444          |
| 2    | 6.03        | 0.08        | 75            | 836            | 0.25         | 17.68        | 334          | 415          |
| 3    | 6.03        | 0.14        | 43            | 477            | 0.25         | 17.68        | 191          | 314          |
| 4    | 6.03        | 0.12        | 50            | 557            | 0.25         | 17.68        | 223          | 339          |
| 5    | 6.03        | 0.20        | 30            | 334            | 0.25         | 17.68        | 134          | 263          |
| Average |           |             | 57            | 632            | 0.25         | 17.68        | 253          | 355          |

### Fig. 7: Experiment results.

### Table 6: Relationship between shear and normal stresses.

| S.N. | Horizontal force (KN) | Vertical force (KN) | $h$ (N/mm$^2$) | $N$ (N/mm$^2$) | Remark          |
|------|------------------------|---------------------|----------------|----------------|-----------------|
| 1    | 30.10                  | 9.81                | 0.123          | 0.040          | Equivalent Coulomb parameters |
| 2    | 31.50                  | 11.77               | 0.129          | 0.048          | $C=0.0857$      |
| 3    | 33.90                  | 13.73               | 0.138          | 0.056          | $\tan\phi=0.9174$ |
| 4    | 35.30                  | 15.70               | 0.144          | 0.064          |                 |

### Table 7: Summary of brick wallet test result.

| S.N. | Type | Density (kg/m$^3$) | Compressive Strength (N/mm$^2$) | Shear Strength (N/mm$^2$) | $E$ (N/mm$^2$) | $G$ (N/mm$^2$) | $V_s$ (m/sec) |
|------|------|-------------------|---------------------------------|--------------------------|---------------|--------------|--------------|
| 1    | Brick | 1768              | 11.03                           | 0.15                     | 3874          | 0.11         | 1745         | 984          |
| 2    | Mortar | 1705              | 1.58                            | 0.15                     | 509           | 0.25         | 204          | 336          |
| 3    | Wall  | 1768              | 1.82                            |                          |               |              |              |              |
of three compression, shear and combined loading tests. The shear modulus and shear wave were calculated from eqns. 1 and 2 from average elastic modulus. The results are novel and useful for precise analysis and capacity evaluation of the structures.

5. Conclusion

Two non-destructive and one destructive test were carried out to investigate the mechanical properties of the old existing brick masonry buildings. We can get the properties of reinforced concrete material and cement sand mortar bonded masonry structures but very hard to get the properties of such typical old buildings which is most necessary to do detailed analysis and evolution of their capacity in static and dynamic loadings. Thus, these data are very useful to analyze such kinds of materials.

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