Determination of mechanical properties of the Kathmandu World Heritage brick masonry buildings

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SUMMARY:
One of the typical old brick masonry buildings and its surrounding area of the Patan Durbar Square area, one of the seven monument zones of the Kathmandu World Heritage site were selected to determine the mechanical material properties. Three testing methods - elastic wave tomography at existing walls of the buildings, shear and compression loadings on the wallets made from bricks collected from old buildings, and micro-tremor measurements of the ground and ambient vibration measurements of the building were carried out. The first two tests were to find the properties of brick elements and walls such as, density, modulus of elasticity, Poisson's ratio, shear modulus, shear wave velocity etc. and to verify the results each others. The third test was to determine the dynamic properties of the building and the surrounding ground such as natural frequencies of the building vibration, damping and fundamental frequency of the ground.

Keywords: Brick masonry, material property, Kathmandu World Heritage, non-destructive testing

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. One of the seven monument zones is 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 (Rana, 1935) and 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 (Pant, 2000) 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 (Rana, 1935) which killed ten thousand people and damaged most of the residential houses, temples and royal palaces. Severe damages in the Patan Durbar Square area can be seen in the Fig. 1c. Seismologists are predicting that there is huge seismic gap in the Himalayas which could produce great earthquake soon (Bilham and Ambresays, 2005) and damages and death could be hundred times more than that occurred in the past due to increased population and low strength houses. 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 risk management which requires detailed structural assessment and investigations of strength and properties at existing conditions.

(a) Core and Buffer zone (b) Contemporary view (c) Damages in 1934 earthquake

Figure 1. Patan Durbar Square area

Thus, a research project was designed in 2009 between Institute of Engineering (IOE), Tribhuvan Univesity, Nepal and Research Center for Disaster Mitigation of Urban Cultural Heritage, Ritsumeikan University (Rits-DMUCH), Japan. In this research, one of the typical old brick masonry buildings of the Patan Durbar Square area and the surrounding ground were selected to determine the mechanical properties required for structural analysis. Three methods – elastic wave tomography, micro-tremor measurements, and shear and compression loading tests on the wallets constructed by the bricks collected from old buildings 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. The Fig. 2a shows the demarcation of core area of the heritage site. It has been numbered 1-4. These are the point where microtremor measurements were taken by seismometers. The sample building (Fig. 1b) is at the no. 1 location and the PDS is located at nos. 3-4.

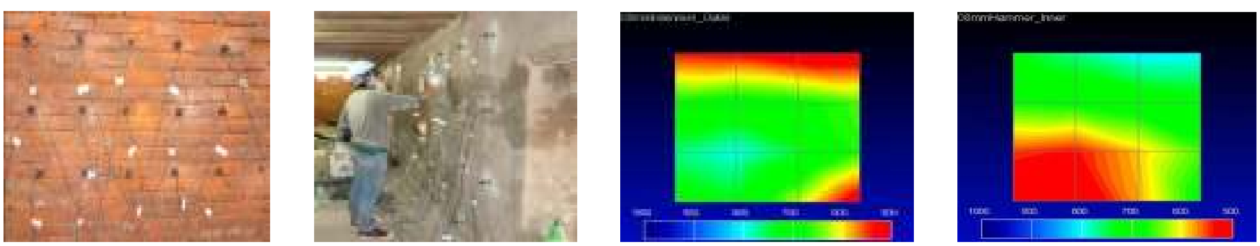
(a) Durbar Square Area (PDS) (b) Sample building (c) Plan of sample building

Figure 2. Location plan, sample building and its plan

The sample building and its plan view are shown the Fig. 2b-c. The plan is numbered 1-7. These are the points where ambient vibration measurements of the building were taken. It has been using for public purposes. The house is two storeyed, 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 sustrained 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. 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.

2. 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 (box shown in Fig. 2c) wall of the sample building was selected for the elastic wave measurement and instrumented as shown in Fig. 3. 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. 3a-b. 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 2009 is referred. Based on the first arrival time of P waves at various sensors, stress wave velocities in divided cells were obtained. The Fig. 3c-d show the distribution of P waves at outer surface and inner surfaces respectively. The P wave velocity varies 500 to 1000 m/s. It shows that interior of wall is stronger than the inner surface.



(a) Outer surface (b) Inner surface (c) Outside P wave velocity (d) Inside P wave velocity

Figure 3. Sensor arrangement and P wave velocity

2.1 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 looked at Figs. 3c-d, it ranges from 500 to 1000 m/s. 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. 4). 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/m^3), and Poison's ratio (assumed 0.2), modulus of elasticity (E) and shear wave velocity (V_s) of the material are calculated. The variation of P wave with wall thickness is shown in the Fig. 4. 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. 4 is projected for 55cm wall, it becomes 547m/s which lies in the ranges shown in Fig. 3c-d 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. 4 shows, elasticity decreases with the increase of joints and voids in thicker wall.

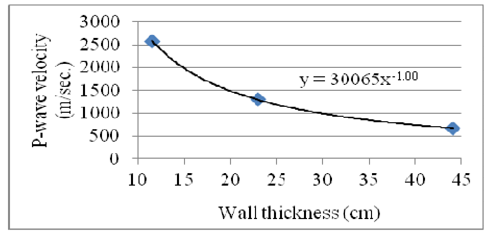
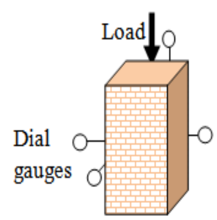
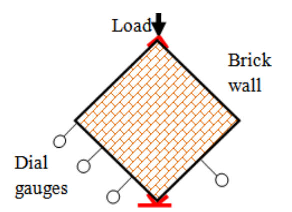
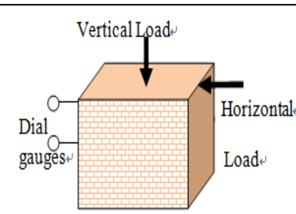


Figure 4. Pocket AE measurement (left) and variation of P wave with wall thickness (right)

3. 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 Malla 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 (Parajuli et al., 2011).

Table 1. Experiment plan

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

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.

3. 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 (ν), 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 $0.1N/mm^2$. 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 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.

Table 2. Experiment results of compression test

Sample	Initial stress N/mm^2	Initial strain	E N/mm^2	ν	G N/mm^2	V_S m/s
1	0.10	0.00043	234	0.32	88	221
2	0.10	0.00037	270	0.24	109	246
3	0.10	0.00031	319	0.17	136	275
Average			274	0.24	111	247

Table 3. Properties for brick units and mud mortar cubes

S.N.	Type	Nos. of specimen	Density kg/m^3	Compressive Strength N/mm^2	E N/mm^2	ν	G N/mm^2	V_S m/s
1	Brick	12	1768	11.03	3874	0.11	1745	984
2	Mud mortar	9	1705	1.58	33	0.19	14	85

Compressive stress and strain obtained from the test is plotted in Fig. 5a. 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 craks at mortar joints. Again after few steps of loadings bricks starts taking loads and the relationship becomes linear.

3.2 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 the Fig. 5b. 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 N/mm^2, 621 N/mm^2 and 366m/s respectively. Similarly, average shear stress and strain at ultimate stage are found to be 0.126N/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 the Fig. 5b, 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.

Table 4. Results from diagonal shear tests

Test	Length mm	Width mm	Area mm^2	Height mm	G N/mm^2	ν	E N/mm^2	ρ kg/m^3	V_S m/s	Stress N/mm^2	Strain
1	585	365	213525	585	225	0.24	557	17.68	353	0.154	0.00582
2	585	365	213525	585	280	0.24	695	17.68	394	0.128	0.00599
3	585	365	213525	255	352	0.24	874	17.68	442	0.128	0.00606
4	585	365	213525	485	137	0.24	339	17.68	275	0.097	0.00646
Average					**250**	**0.24**	**621**	**17.68**	**366**	**0.126**	**0.00646**

3.3 Combined 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). The deformations at each load increment were noted and load displacement curve is plotted. 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 632N/mm^2. In the Table, Δ_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 (Drysdale and Hamid, 2005).

Table 5. Results from combined lateral and vertical loadings

S.N.	P_0 kN	Δ_0 mm	k_0 kN/mm	E N/mm^2	ν	ρ kg/m^3	G N/mm^2	V_S m/s
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

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. 5d. σ_n, and τ are normal and shear stresses. The coefficients are 0.0857 and 0.9174 which are equivalent to cohesion and Coulomb friction tanΦ.

Table 6. Relationship between shear and normal stresses

S.N.	Horizontal force kN	Vertical force kN	σ_n N/mm^2	τ N/mm^2	Remark
1	30.10	9.81	0.123	0.040	Equivalent Coulomb parameters C=0.0857 tanΦ=0.9174
2	31.50	11.77	0.129	0.048	
3	33.90	13.73	0.138	0.056	
4	35.30	15.70	0.144	0.064	

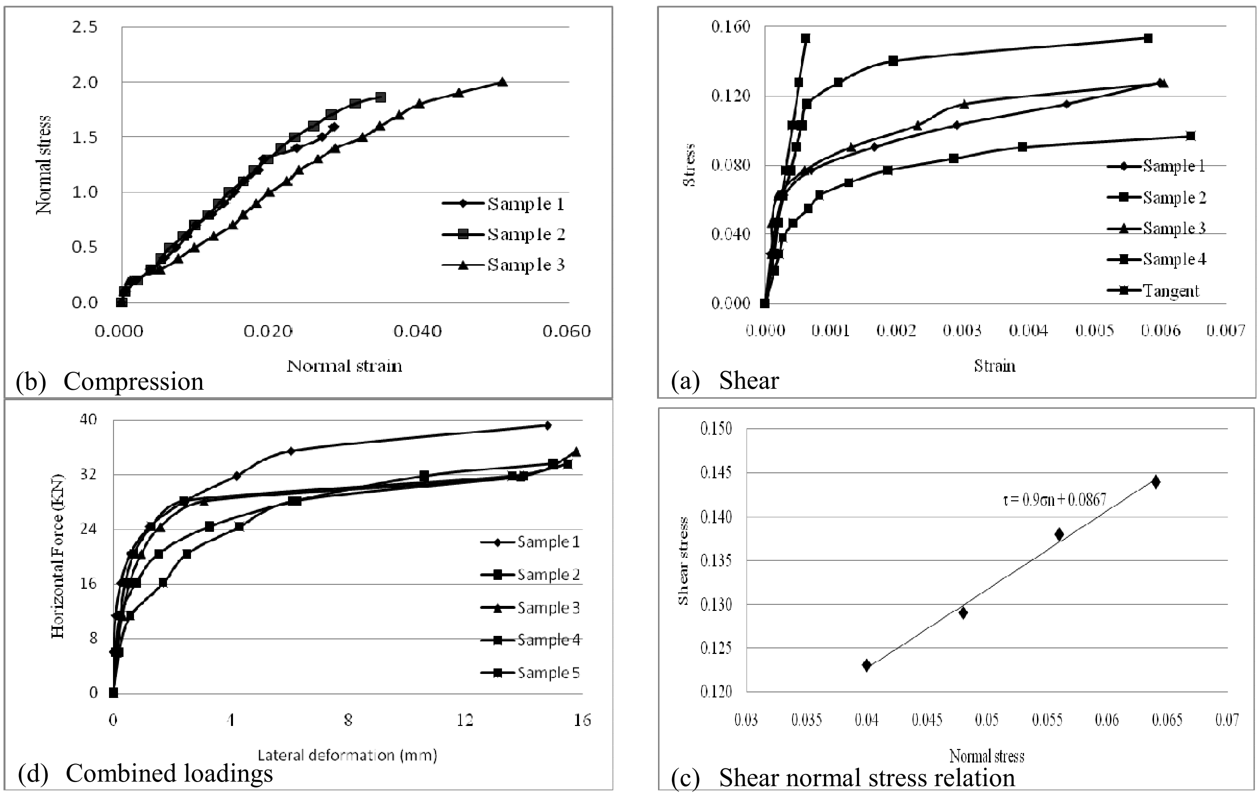


Figure 5. Experiment results

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	ν	G N/mm^2	V_S m/s
1	Brick	1768	11.03		3874	0.11	1745	984
2	Mortar	1705	1.58	0.15	509	0.25	204	336
3	Wall	1768	1.82					

3.4 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 of three compression, shear and combined loading tests. The shear modulus and shear wave were calculated from average elastic modulus and Poisson's ratio. The results are novel and useful for precise analysis and capacity evaluation of the structures.

4. MICRO-TREMOR MEASUREMENT

Micro-tremor of the ground and the ambient vibrations of the building (Fig. 6) were measured by seismometers and their responses were studied in frequency domain. Since, the amplitudes of ambient vibration are very small, they describe only linear behavior of the structures. Ambient vibration signal get amplified at the natural frequency of ground and structures. Taking advantages of those characteristics of response natural frequencies are obtained. Micro tremor measurements on the four locations shown in the Fig. 2a and ambient vibrations of the building at seven locations shown in the Fig. 2c were recorded. The measurements are shown in the Fig. 6 The dynamic properties such as natural periods, mode shapes and damping ratios are obtained and discussed.

(a)Measurements on ground (b) Measurements on building (c) Push off on building

Figure 6. Micro-tremor measurements

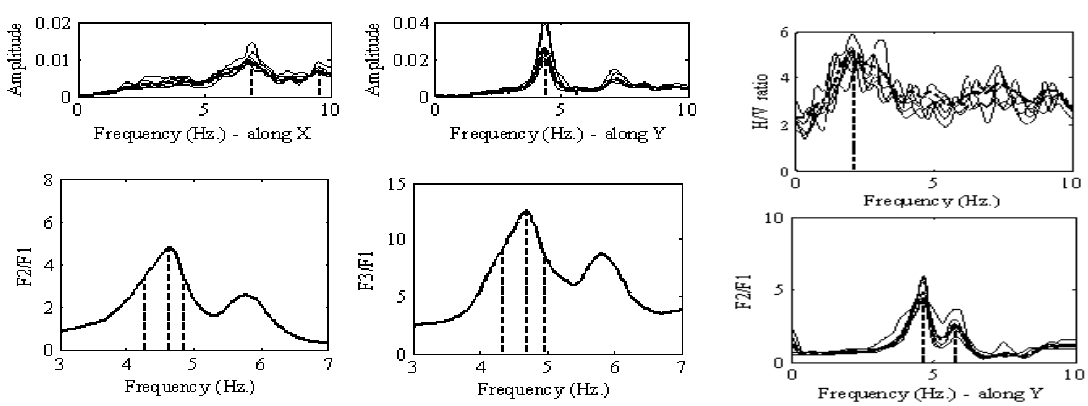


Figure 7. Fourier spectrum from micro tremor measurements

4.1 H/V Spectrum

Micro tremor measurement has been long recognized in site evaluation and micro-zonation which are widely used by engineers and planners. The most commonly used way to interpret the records is horizontal to vertical ratio namely H/V spectrum. This technique was originally introduced by Nakamura (Nakamura, 2000) to analyze Rayleigh waves in micro-tremor records. Now, it has been the method to estimate the site characteristics such as predominant frequency of site, amplification and vulnerability assessment. However, in this study, only predominant frequency of the ground is evaluated. For this purpose, seismometers were placed at four locations of the city as shown in the Fig. 1a and three components of micro-tremors were recorded for 12 minutes. Considering the records are stationary, the whole record is cut into various segments having number of data in each segment equivalent to 2^N which is essential to do Fast Fourier Transform (FFT). Then Fourier spectrum of each segment was obtained and few samples of Fourier amplitude are shown in Fig. 7. From the calculation predominant frequency of the ground is found 2.07Hz (Parajuli et al., 2010).

4.2 Natural Frequency of Building

The building has been partitioned into two parts along longitudinal direction. The front side has big opening. Series of ambient vibration measurements were taken at various locations of the building in the ground, first and second floors respectively. The measurements were recorded at seven different locations of the building as shown in the plan of the building in Fig. 2c. As in the H/V ratio calculation, twelve minutes long records are cut into six segments making 4096 data in each segment to make compatible for FFT excluding the possible noise caused by external factors such as pedestrians and vehicles etc. Fourier spectra of all the records obtained along both longitudinal and transverse directions at various locations of the building were calculated. The most dominant natural frequencies are 4.30Hz and 6.52Hz along transverse direction and 6.80Hz and 9.39Hz along longitudinal direction.

4.3 Transfer Function and Damping

In order to see amplification of seismic motions, ratio of Fourier spectrum between first floor to ground floor, and second floor to ground floor was calculated and plotted in Fig. 7. It shows that the response along transverse direction is more amplified than in longitudinal direction. It also justifies the point that the building is vulnerable along transverse direction. From this ratio, the natural frequencies in rocking modes are identified at 4.69 and 5.85 Hz along transverse direction and 7.72Hz along longitudinal direction which is shown in Table 3. Other modes are not detectable.

Damping is estimated by half power band width method (Chopra, 1995) given by the equation taking the transfer function obtained from the ratio between floors and ground responses of transverse direction. Average damping value of damping is estimated 6.4%. Then, as an alternate method of estimation of damping, the building was pushed by 4-5 persons in both longitudinal and transverse direction. The micro tremor was taken when the building was pushed at each story. Then, ratio of Fourier spectrum between the floors and ground were plotted to see whether there is changes from the transfer functions plotted without pushing the building. No significant changes were noticed. Then, the time history records were cut just after the building was pushed and damping is calculated by random decrement method (Chopra, 1995). From logarithmic decrement of wave, the damping ratios are obtained 3.6% and 5.2% along longitudinal and transverse directions respectively.

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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