STRUCTURAL ASSESSMENT OF THE KATHMANDU WORLD HERITAGE BUILDINGS

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Seven monuments have been registered as World Heritage properties in the cultural city Kathmandu. They have sustained in vertical loads for years but very weak in earthquakes. In order to find out adequate strengthening measure, investigations in Durbar Square Area of Patan, one of the seven monuments zones, are ongoing. Material properties of old masonry building were investigated. Structural survey has been done and all buildings are classified into different categories. 45% of the buildings are found cracked. Sample buildings from reinforced concrete and brick masonry have been selected. Their finite element models have been made for further analysis to estimate the fragility, vulnerability and risk.

Key words: *Kathmandu World Heritage, brick masonry, elastic properties, structural analysis, structural survey, finite element method*

1. INTRODUCTION

Kathmandu valley, the capital city of Himalayan country Nepal, is 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 of Hanuman Dhoka (Kathmandu), Patan and Bhaktapur, the Hindu temple of Pashupati and Changu Narayan, and the Buddhist stupas of Swayambhu and Bhuddhanath. For this study, Durbar Squares of Patan (Fig. 1) and surrounding area has been taken. All the Heritage structures are brick masonry constructed over 300 years ago. Brick masonry is the oldest construction material in the history of mankind. Since the civilization in the Egyst, masonry has been exploited to construct significant and long lasting structures all over the world. From Roman aqueducts and public buildings to the Great Wall of China, from the domes of Islamic architecture to the early railway arch bridges, from early 19th century American tall buildings to the 20th century nuclear power plants, bricks have

been used as structural material in all applications of building and civil engineering (Ayala). Due to simplicity in construction, it has been used in residential dwelling commonly. Asthetics, solidity, durability, low maintenance, sound absorption and fire resistant are the main important characteristics of bricks that have made them to be used consistently long time throughout the world. Shape and size of bricks can vary depending upon availability of local material and mortar used, and geographical variations. Despite these advantages masonry has been the main cause of claiming lives in many earthquakes. Most recent damages and deaths caused in the earthquakes in India (Saito et al. 2004), Pakistan (Naeem at al. 2005), China (Wang 2008) and Haiti (Fierro and Perry 2010) are sufficient to imagine the future scenario. The worst death toll from an earthquake in the past century occurred in 1976 in China (T'ang Shan Province), where it is estimated that 240,000 people were killed (USGS). Most of the deaths were due to the collapse of low strength masonry buildings such as brick, stone and block masonry. Thus, masonry is no longer preferred structural material in many parts

of the developed world, especially in seismically active areas of the world. Partly, masonry and especially unreinforced masonry (URM) has mechanical properties such as strength and ductility inferior to those of reinforced concrete and steel (Mosalam et al. 2009). Moreover, masonry structures were traditionally built based on rules of thumb acquired over many years of practice and empirical data from testing. Accordingly, we do not have a rigorous and uniform method of analysis and design for masonry. Nevertheless, the world still possesses numerous historic and ordinary masonry structures, which require maintenance and strengthening to withstand against any adverse environmental forces. Hence, it is important to study fundamental properties of existing old masonry buildings, analyze the buildings considering the probable earthquake loadings, estimate the vulnerability and risk, and determine effective strengthening techniques.
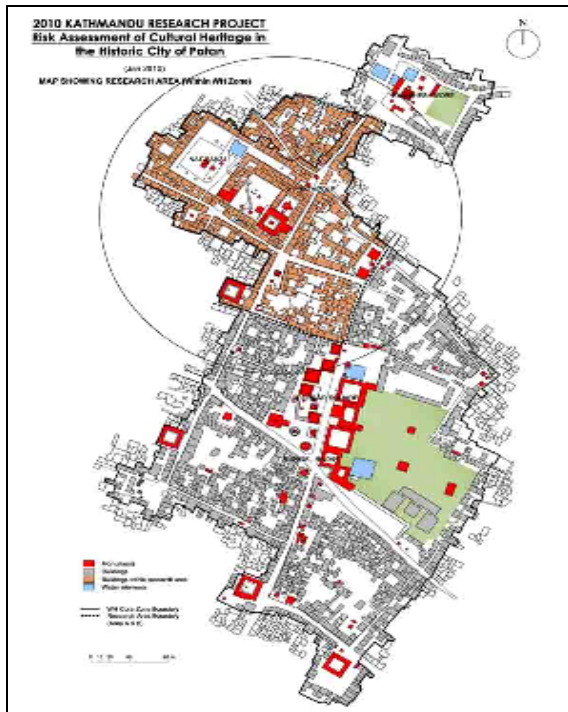

Fig. 1 Durbar Square of Patan

Brick masonry is heterogeneous construction in which bricks are laid one over another joined by mortar. Mortar can be mud (clay), lime, cement-sand etc. mixed with water in various proportions. In the Kathmandu Valley, modern masonry constructions are made by bricks with cement sand-mortar, but, in the past, most of the constructions had been made by mud mortar bonded bricks made of local technology since the beginning of the Malla period (300 years ago). There are hundreds of temples and residential buildings still

existing and being used. Most of them have gained aged value and are included in the site of the Kathmandu World Heritage. Now, they are serving public facilities and private dwelling and have become the primary source of income of the tourism industry. But the problem is they are deteriorated due to aging and adverse environmental degradation. The question arises what happen if natural disaster such as big earthquake hits them. The history (Pant 2000) has recorded various earthquakes with deaths and damages occurred in the past. We have already seen the worst damage scenario in the 1934 earthquake (Rana 1935). More than three thousand houses have been damaged in the recent 18th Sept. 2011 M6.9 (USGS) earthquake occurred in the eastern Nepal India boarder. Strong shaking was felt and damages and deaths were reported in Kathmandu which is more than 200KM from the source. There would be sever situation in Kathmandu if a strong quake hits in near future.

2. MATERIAL PROPERTIES

A key thing required for doing analysis of any structures is the elastic properties. Being very typical old masonry building, their properties have not been investigated and reported in literature and obtaining material properties for old masonry building is very difficult task. Thus, we have investigated the mechanical properties of brick masonry from three kinds of experiments. The obtained properties are given in the Table 1. In the Table 1, ρ is density (kg/m^3), σ is for compressive strength (N/mm^2), τ shear strength (N/mm^2), E is modulus of elasticity (N/mm^2), G is shear modulus (N/mm^2), ν is Poisson's ratio and V is shear wave velocity (m/sec.).

Table 1 Summary of results

Type	ρ	σ	τ	E	ν	G	V
Brick	1768	11		3874	0.11	1745	984
Mortar	1705	1.6	0.15	509	0.25	204	336
Wall	1768	1.8					

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. Material properties and strengths for these kinds of constructions have never been investigated experimentally. The modulus of elasticity is average of three compression, shear and combined loading tests. The shear modulus and shear wave were calculated from the mathematical relation between them. For detail Parajuli et al 2011 is referred. These properties are used in the following finite element analyses.

3. STRUCTURAL SURVEY

Investigation site is shown in the Fig. 1. There are thousands of buildings in the core area of the World Heritage site of Patan. For our study we just surveyed all buildings houses inside the circle shown in the Fig.1. Total 218 buildings are there. Structural survey (The format of survey is given in Appendix A.) form was filled for every building. It was based on visual inspection. We categorized all the buildings into different groups. Most of the buildings are traditionally made brick masonry. The summary of the building categories have been shown in the Table 2. In the Table 2, S is number of storeys, T is total number of buildings, C is concrete buildings, B is brick masonry buildings, O is any other types such as wood, stone etc. made buildings, D is damaged, R is residential, E is both commercial and residential purpose buildings and M is modified buildings.

Table 2 Classification of buildings

S	T	Building type			D	Uses			M
		C	B	O		R	E	O	
1	13	2	10	1	6	0	1	12	0
2	2	0	2	0	0	0	0	2	0
3	35	5	30	0	18	16	14	5	3
4	90	18	72	0	43	46	41	3	35
5	71	18	52	1	32	35	32	4	39
6	7	3	4	0	1	3	4	0	4
T	218	46	170	2	100	100	92	26	81

Buildings were found one to six storeys. Total numbers of buildings at each storey are separately noted. Majority of buildings are of 3-5 storeys with large openings (windows). Most of the buildings are brick masonry and reinforced concrete buildings. Among them, three quarter of the buildings is brick masonry. All buildings are categorized into damaged and non- damaged. A building is categorized as damaged if it has cracks or inclinations at any locations such as near the openings (windows, doors), walls and foundations.

Out of 218 buildings, 100 i.e. 45% buildings have damaged already because of sustained vertical loads, environmental deterioration and aging. Thus, we can easily estimate severe damages in those buildings if the moderate or great magnitude earthquake hits the city.

From aspect of utility, buildings are categorized into two groups-residential and commercial. Approximately half of the buildings have been using dual (residential and commercial) purpose. People give the ground floor of the building for shops or other rental purposes. Thus these buildings are the source of income as well and residence. If the buildings faces any damages due either vertical, environmental or earthquake loads the people loss both the income and residence.

A building is categorized modified if any kind of repair, maintenance works has been made on the building either for vertical load or for later loads. It also includes the addition of floors. We can see maximum number of modification and damages in 4th and 5th storey buildings. That is because of floor additions which has more vulnerable even in vertical loads.
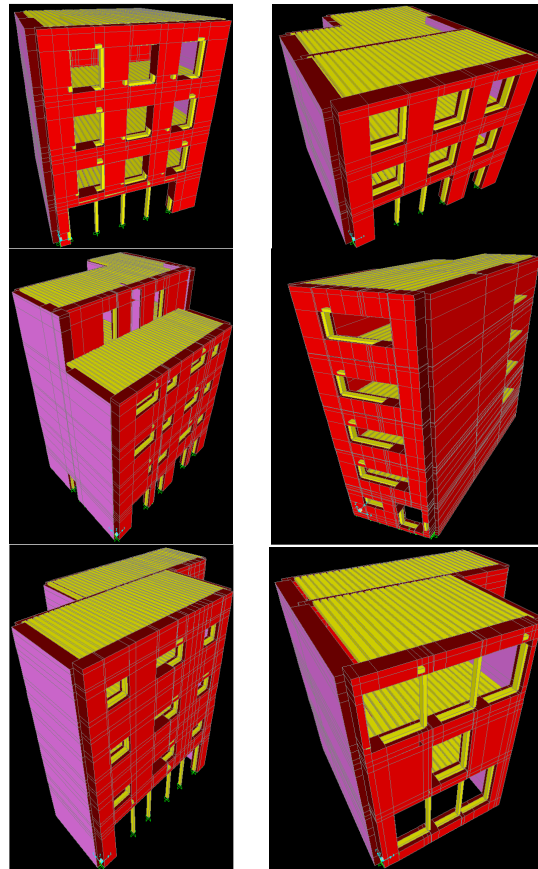

Fig. 2 FEM models of brick masonry building

4. FINITE ELEMENT MODELS

From the structural survey, basically, we found two categories of buildings. Survey based upon visual examination gives only basic idea cannot help to estimate the structural performance of the buildings. To know actual condition of the building either experiments or analyses are required. Doing in-situ experiments on all those buildings is very difficult task. Only way left is to make numerical model. Modeling of all buildings is time consuming and costly work. Thus, certain representative buildings from both concrete buildings and brick masonry buildings were selected and finite element models have been prepared in SAP2000 software. Modelings of reinforced concrete frame buildings are simple but masonry buildings are difficult. The masonry buildings consist of thick wall 45-60cm tapered from bottom to top with wooden door and windows. The floor is made of bricks laid over wood purloins and plain cement concrete over wooden planks and board. They are flexible floors. There is no actual data showing or proving exact percentage of fixity of flexibility of these floors which poses difficulties in modeling. In this analysis, wooden purloins are modeled as beam members and end moments are released then it act like hinge member. Six models of the building are given the Fig. 2.

5. DISCUSSION AND CONCLUSIONS

Investigation on World Heritage site of Patan is part of an ongoing project. Material properties of the buildings were investigated from two experiments (Parajuli et al. 2009, 2011). Visual inspection of the buildings from structural survey is made for 218 buildings. Three quarter of the buildings are made of traditional bricks have sustained stresses and cracks due ageing. Forty five percentages buildings are already sustained some kinds of damages even in vertical and environmental attacks. Then question arises what would happen if an earthquake hit the buildings. Finally some representative buildings have been modeled to analyze in earthquake loads. The objectives of this analysis are to estimate fragility, vulnerability and risk of the representative buildings. The obtained results from representative buildings will be interpreted as the scenario of the research area.

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Appendix A: Building Survey Form

Date:	Name of the building:	Name of Observer:
Time:	Address:	Building no. in map:

General information of building								Photographic ref.

Uses	1	■Res. & Com.	2	□Only residential	3	□Apartment
	4	□Commercial	5	□Ritual buildings	6	□Monuments
	7	□Store	8	□Unknown	9	□Others（ ）

Building type	□Continuous 1 □Courtyard 2■No-courtyard 3□Unknown
	4 □Single stand 5 □Unknown 6 □Others(attached to big building）

Construction patterns	■Traditional brick 1 ■Non plastered 2□Plastered 3□Mortared
	4 □Carved brick 5□Others （ ）
	6 □Concrete frame with brick infill 7 □RC with shear wall
	8 □Wooden 9 □Others 10 □Remarks（ ）

Storey	1	Total (3)	2	Const. Initial (3)	3	Added storey (0)
	4	Unknown	5	Others （ ）		

Modification	1	□No	2	■Yes	3	□Unknown

Damages in the buildings	Photographic ref.

Inclination (degrees)	□No ■Yes
	■Inclination towards adjacent building (parallel to the observer)
	□whole building 1■small(< 0.5) 2□middle(0.5～1.0) 3□large(>1.0)
	□ 1 st storey 4□small(< 0.5) 5□middle(0.5～1.0) 6□large(> 1.0)
	□2nd storey 7■small(> 0.5) 8□middle(0.5～1.0) 9□large(>1.0)
	□ 3 rd storey 10□small(<0.5) 11□middle(0.5～1.0) 12□large(> 1.0)
	□ 4 th storey 13□small(< 0.5) 14□middle(0.5～1.0) 15□large(>1.0)
	■Inclination to the front (road/opening of courtyard) side （bulging）
	□whole building 1■small(<0.5) 2□middle(0.5～1.0) 3□large(>1.0)
	□ 1 st storey 4□small(<0.5) 5□middle(0.5～1.0) 6□large(>1.0)
	□ 2 nd storey 7■small(<0.5) 8□middle(0.5～1.0) 9□large(>1.0)
	□ 3 rd storey 10□small(<0.5) 11□middle(0.5～1.0) 12□large(>1.0)
	□ 4 th story 13□small(<0.5) 14□middle(0.5～1.0) 15□large(>1.0)

General information and damages of foundation	1 ■brick 2□ R C 3□Stone 5 □Unknown 6 □others( )
	settlement 1■No 2 □all part 3 □parts only
	Inclination 1 ■No 2 □all part 3 □part only
	cracks 1 □No 2 □all 3 ■part
	others （ ）

Structural condition of brick wall deterioration and damages	0 □No damage
	■Vertical cracks
	□all over the wall 1□small 2■middle 3□large
	□ 1 st story 4□small 5□middle 6□large
	□ 2 nd storey 7■small 8□middle 9□large
	□ 3 rd story 10■small〈 11□middle 12□large
	□ 4 th storey 13□small 14□middle 15□large
	■Cracks surround the windows
	□whole 1□small 2□midddium 3□large
	□ 1 st storey 4■small 5□middle 6□large
	□ 2 nd storey 7□small 8□middle 9□large
	□ 3 rd storey 10■small 11□middle 12□large
	□ 4 th storey 13□small 14□middle 15□large

Material condition of brick wall- deterioration and damages	0 □No damage
	damages in the bricks 1□whole 2□near the foundation
	3□ 1 storey 4■ 2 nd storey 5□ 3 rd storey 6□ 4 th storey
	bricks fallen out 1□whole 2□near the foundation
	3□ 1 st storey 4■ 2 nd storey 5□ 3 rd storey 6□ 4 th storey
	damages in the joints 1□whole 2□near the foundation
	3□ 1 st storey 4■ 2 nd storey 5□ 3 rd storey 6□ 4 th storey
	Lack of mortar 1□whole 2□near the foundation
	3□ 1 st storey 4■ 2 nd storey 5□ 3 rd storey 6□ 4 th storey