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Evaluation of Seismic Resilient Characteristics of Traditional Stone Masonry in Mud Mortar Houses

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Abstract
Stone Masonry in Mud Mortar (SMM) is one of the oldest construction technique in Nepal with dominant practice in construction both pre and post Gorkha earthquake, 2015. The structural properties and seismic strength of these rural vernacular constructions have not been investigated in detail. This study aims to verify the hypothesis that "Traditional Stone Masonry in Mud Mortar (SMM) Buildings in Nepal followed dimensional earthquake resilient features as per provisions of code". The study is also intended to compare damage pattern in SMM houses based on their satisfactory level to codal provisions. For the analysis, dimensional data of SMM houses of Sindhupalchowk was collected and their intensity of damage were determined. IBM SPSS Version 25 was used to compare observed and standard criteria set forth in building code. The study showed that 80.9% of SMM houses satisfied the dimensional criteria of code NBC 202:1994 and NBC 203:2015 showing that traditional SMM houses comply with structural earthquake resilient characteristics of code. However, the use of timber bands was seen only in 23.5% of SMM houses. The comparative study of SMM houses satisfying and not satisfying codal criteria showed that width of masonry pier in between opening, distance of opening from corners and height to length ratio is also an important parameter in out of plane stability of masonry wall. The observation indicated that vertical crack at intersection of walls is dominant in SMM houses even with presence of bands. Hence, retrofitting technique for strengthening of wall corner should be given importance.

Keywords
stone masonry in mud mortar, seismic, damage pattern

1. Introduction

Nepal is one of the most earthquake prone countries of the world struck by multiple disastrous earthquakes of magnitude greater than 7.5[1]. The recent Gorkha earthquake of 2015 led to damage of more than 75,000 houses of which 74% were constructed with mud bonded stone masonry[2]. Stone masonry in mud mortar is dominant building practice in Nepal both pre and post Gorkha earthquake,2015 due to ease in construction and presence of skilled labor forces in rural areas for its construction. Although the use of burnt bricks is on the rise, stone masonry remains the primary construction material in the country's higher hilly and mountainous regions[3].

Mandatory Rule of Thumb (MRT) provides ready to use dimensions and details of various structural and non-structural components mainly for ordinary residential buildings commonly being built by owners and builders in Nepal. NBC 202:1994 and NBC 203:2015 provides regulations in the dimensional features of SMM houses along with enhanced techniques that can raise the level of seismic safety of these buildings. Traditional SMM houses have been built based on these criteria even before the formation of code[4, 5].

Due to lack of integral action, lack of strong and ductile connections between walls, roof elements, and foundation, inadequacy for out-of-plane forces, low tensile and shear strength of mortar, masonry construction is still vulnerable to earthquake forces. The damage pattern observed after Gorkha earthquake,2015 are common due to similarities in plan and configuration of these SMM houses[6].

1.1 Traditional SMM Houses

In Nepal, traditional SMM buildings are rectangular and 1–3 stories tall with or without attic. The foundation is normally laid at a depth of 1–2 feet, with 1.5 feet being the most common[2]. The foundation courses are usually made up of stronger stone units. Stone masonry projects in Nepal have a very regular wall thickness, with an average of 18 inches. The standard floor height is 6 feet, but there is wide variety in floor height. The lowest floor height will be found on the third story of a stone masonry construction. The barn is on the ground floor, the first floor is for lodging, and the attic is for the kitchen and grain and produce storage. The homeowner's agrarian lifestyle necessitates two levels and attic room. The building is normally made up of 450mm thick SMM load bearing walls with two faces of laid stone and a rubble filling in the wall cavity. A timber framing diaphragm supports the floor, which is usually mud[2].

Figure 1: Traditional SMM house in Nepal

The mud floors in these structures are supported by a central timber beam that runs through the middle of the floor and supports the timber joists, which in turn support the mud floor. The central beam is supported by timber posts that appear in roughly the same location on each floor and finally extend upwards to support the roof's ridge beam. The central beam is supported by the transverse walls at the two extreme ends. A timber band can be seen at the floor level, however it is frequently discontinuous throughout the structure. The ridge beam in the middle and the eaves on the opposite end support the roof. Openings are usually provided in longitutidinal walls with litlle to no opening in transverse wall.

2. Failure Modes in SMM Houses

Common failure in typical SMM houses were seen during field observation. The structural typology, construction location, and construction type of masonry buildings vary depending on the region, however the damage brought on by seismic activity can be distinguished consistently. Out-of-plane failure and in-plane failure are the two most typical types of masonry failure. Out-of-plane bending of the structural walls that are perpendicular to seismic motion causes out-of-plane failure with vertical cracks at the corners and in the middle of the walls. A brief discussion of each mode of failure in stone masonry found dominant in most of the houses observed in field is given below:

2.1 Out of Plane Failure Mechanism

Partial or complete overturning or instability of load bearing walls was common, as expected for buildings with architectural features, flexible floor diaphragms and weak connections between return walls with damage ranging from moderate to severe as well as collapse. Poor return wall connections appeared to be the cause of most out-of-plane failures, resulting in return wall separation and subsequent out-of-plane failure of whole walls. No connection between roof diaphragm and walls were observed in majority of SMM houses in the field where rafters rest directly on walls.Figure 2 depicts the characteristics of out-plane failures.

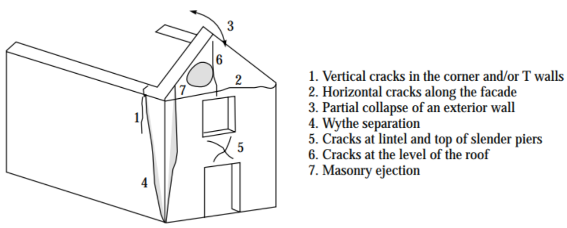

Figure 2: Out-of-plane failure characterization (Source: Zuccaro and Papa, 1999)

2.2 In Plane Failure Mechanism

In-plane collapses of walls in unreinforced masonry structures are most frequently caused by severe bending or shear. This pattern of cracking, which is frequently seen under cyclic loading, shows that the walls' primary tensile stress planes are still unable to endure repeated load reversals without completely collapsing.Short piers are more likely to develop diagonal tension, or ”X” cracks, whereas thin piers are more likely to rock (top and bottom). The lower the storey, the worse the cracks are. Figure 32.2 depicts the characteristics of in-plane failures.

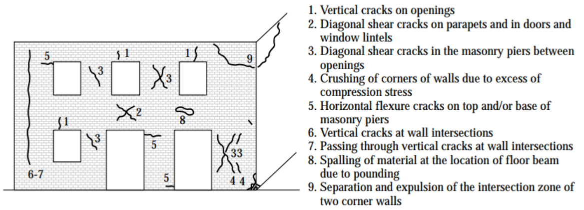

Figure 3: In-plane failure characterization (Source:Pasquale and Orsmi, 1999)

2.3 Diagonal Cracking

The most typical earthquake-induced damages on the walls of masonry buildings were diagonal cracks. Shear failure is a type of earthquake damage induced by the major tensile stress surpassing the shear strength of masonry. On the longitudinal walls, particularly between the door or window openings of practically every floor, through X-shape gaps were quite popular.

2.4 Corner Failure

Lack of through stones and cornerstones at the intersection of perpendicular walls was the reason for corner failure in SMM buildings. Proper connection between orthogonal walls is required to maintain the inter connectivity in masonry.

2.5 Gable Collapse

Above the attic walls, SMM buildings often have stone masonry gables that stretch all the way to the roof. In normal situations, this wall has no adequate connection to the roof and is supported solely by the weight of the roof. Due to the lack of a solid link between these walls and the ceiling, they crumbled during earthquakes, sometimes assisting the following collapse of the transverse wall below. This was one of the most common types of damage seen in filed observation.

3. Objectives

The general objective of this research is to verify that traditional stone masonry in mud mortar buildings have dimensional earthquake resilient features of codal provisions due to which complete collapse of these houses were prevented during Gorkha earthquake, 2015. Specific objectives of the research are:

1. To determine the structural indicators of NBC 202:1994 and NBC 203:2015 fulfilled by traditional SMM houses built before Gorkha earthquake
2. To compare the damage pattern in SMM houses satisfying and not satisfying the provisions of the code.

4. Methodology

Barhabise Municipality of Sindhupalchowk district was selected as the study area. As per National Census Report of 2011, 5288 houses with foundation of stone/brick in mud have been constructed in this municipality. Sample size was calculated with 90% Confidence Interval at 10% margin of error. Data of 68 random sample of SMM houses were collected from field for study. The major dimensions required for comparison to codal criteria such as length, breadth, height of building and opening criteria were measured for each houses in the field. Presence of horizontal resisting members, damage grade and their pattern in each SMM houses were recorded.

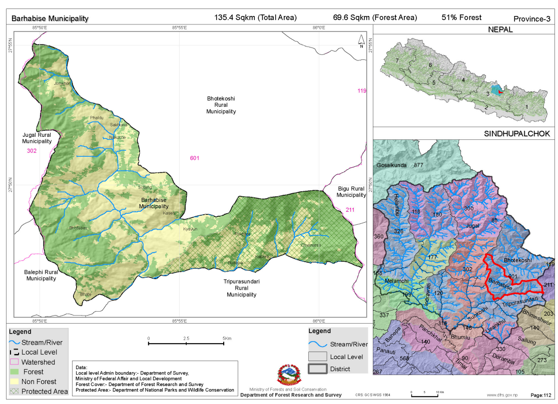

Figure 4: Bahrabise Municipality Source:Nepal in Data,2017

Standard parameters to be compared were obtained from code. NBC 202:1994 states the building to be symmetrical and regular in plan configuration. Length to width ratio, interstorey height and unsupported wall length are restricted to prevent bending due to greater slenderness ratio of wall. NBC 203:2015 has set criteria for openings in wall where distance from corner and distance between two openings are limited to maintain the strength of masonry pier between the walls. The greater openings disrupt the flow path of load from roof to floor level. The code has also restricted height to width ratio of the building to prevent in plane failure of the walls.

IBM SPPS 25 was used to carry out paired sample t test, one sample t test and descriptive statistic test as required for various category to determine the difference in observed and standard value given by the code.

5. Analysis and Results

Each of the criteria of code were compared in IBM SPSS V25 and the results for different codes are presented below:

5.1 MRT criteria as per NBC 202:1994

As per observations of Table 1, data analysis of 68 random SMM houses showed the mean interstorey height to be 2.35m with deviation of 0.33m. One sample t test result shows that interstorey height of SMM houses is significantly less than 3.2m. Similarly, paired t test result showed that distance of opening from wall corner is significantly greater than 25% of height of shorter opening (t=14.53,p=0.00). The result obtained also displayed that length of opening in walls is significantly less than 30% of length of wall(t=-14.56,p=0.00).

Table 1: Comparison of observed and standard MRT criteria

Categorical Variable	Mean±SD
Interstorey Height	2.35±0.3
Less than 3.2 m	3.2
Distance of opening from wall corner	5.99±2.62
$\geq$ 0.25* Height of short opening	1.3±0.2
Length of opening in walls	6.5±2.91
$\leq$ 0.3*length of wall	7.61±1.35

5.2 NBC 203:2015 criteria

Results obtained in Table 2 for one sample t test shows that length: breadth and Height to Thickness ratio of SMM houses are significantly less than 3(t=-37.46,p=0.00) and 8 (t=-37.49,p=0.00) respectively satisfying the criteria given in code. Results derived from paired t test shows that height of the building is significantly less than 3 times its width and interstorey height is significantly less than 12 times wall thickness of the building (t=-69.71,p=0.00). The result satisfied the provisions of the code where distance between two openings were significantly greater than 50% height of shorter openings (t=13.63,p=0.00).

Table 2: Comparison of observed and standard criteria of NBC 203:2015

Categorical Variable	Mean±SD
Length: Breadth	1.64±0.29
Less than 3	3
Building Height	15.81±3.0
$\leq$ 3 * width of building	47.02±5.39
Height : Thickness	7.71±1.00
ł12* wall thickness	19.63±1.18
Distance between two openings	4.57±1.52
$\geq$0.5*height of shorter opening	1.82±0.3

5.3 Percentage Distribution

Each of 68 random sample SMM houses were observed for the presence of earthquake resisting elements suggested by the code. Presence of different bands were also identified in these houses.Timber band were mainly present in separation at floor level which restricted the propagation of crack within a storey. Rare cases of presence of lintel band were observed. Figure 5 showed that 80.9% SMM houses satisfied the structural provisions of the code.

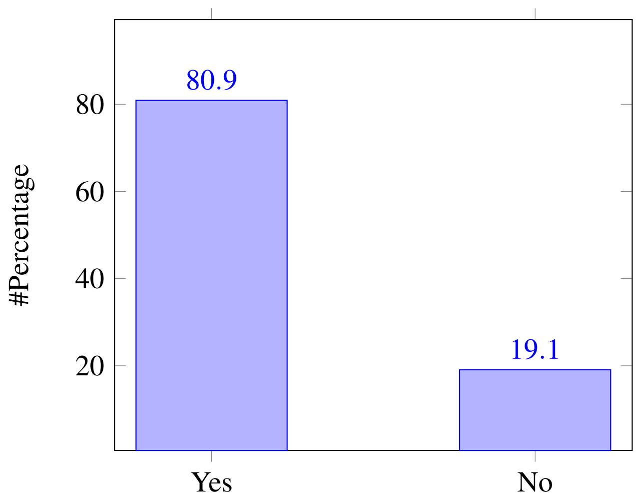

Figure 5: SMM Houses satisying structural criteria of code

Figure 6 and 7 showed that 69.1% SMM houses made use of throughstones in construction whereas corner

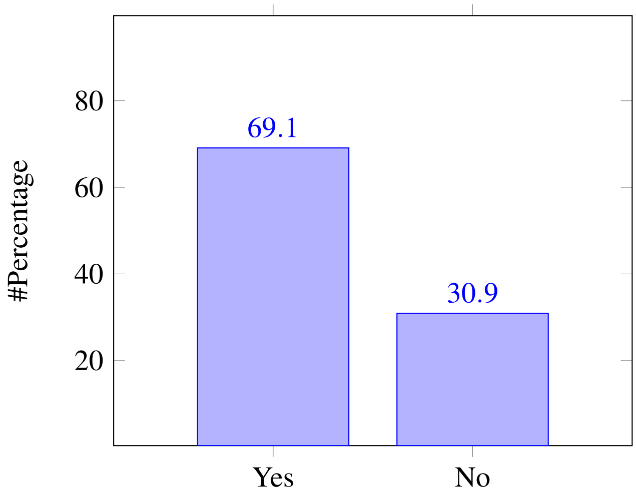

Figure 6: Use of Throughstones

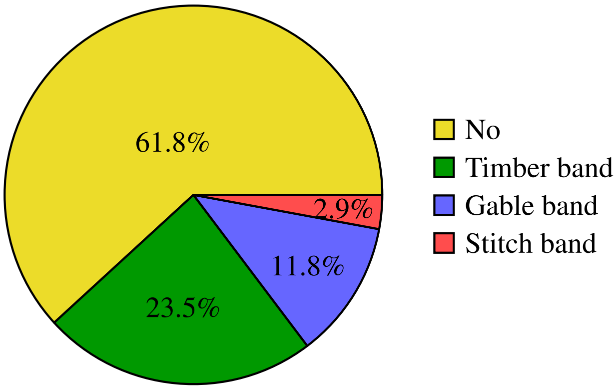

Figure 8: Presence of horizontal band

stones was present in 67.6% of houses in Sindhupalchowk. Presence of timber band was seen in 23.5% of SMM houses for separation at floor level. Gable band were also present in 11.8% houses with rare cases of stitch band. Field observation showed prevention of collapse of roof in SMM houses with the provision of stitch bands.

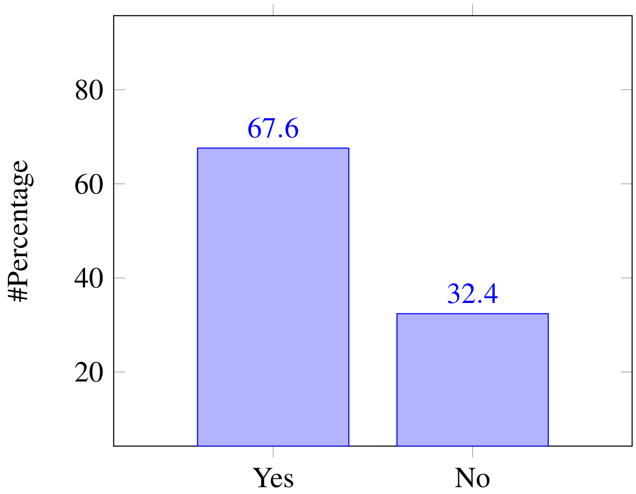

Figure 7: Use of Cornerstones

Majority of traditional SMM houses built before formation of code shows compliance with criteria of standard building codes of Nepal designed for low strength masonry.Thus, it can be stated that traditional SMM buildings built before the formation of code had structural earthquake resistance features in their construction methods as mentioned in today's codal practice due to which they were able to achieve life safety level of performance during Gorkha Earthquake,2015.

6. Comparative Study of SMM Houses based on Provisions of Code

Field based observations revealed that various damage pattern in SMM houses were dependent on their structural parameter. Vertical cracks at wall intersections and corners were observed in SMM houses satisfying overall structural criteria of code along with the presence of timber band. The reason for flexural failure of wall is greater height to length ratio which is not regulated by our code[7]. Lack of vertical reinforcement and lintel band is also a major reason of damage observed in wall intersection.

Figure 9: SMM house satisfying dimensional provision of code

Similar damage pattern were observed in SMM houses without the presence of timber bands where the only difference was the continuous propagation of crack from roof to ground. The result obtained from observation was verified as similar results were obtained in shock table test where the damage in corners are unavoidable even with the presence of sill and lintel band[6].

Figure 10: SMM house not satisfying dimensional provision of code

Vertical cracks and separations on openings in transverse wall and diagonal cracking leading from floor to opening were observed in SMM houses with greater than 30% opening in transverse wall.Short piers formed by openings in the masonry walls will face concentrated shear stresses and, as a result, diagonal cracks. Tension cracks may develop in the corners of openings as a result of the lateral loading-induced reverse cyclic stress. Hence, the code has restricted the opening percentage to less than 25% for two storeyed SMM houses. Lack of vertical reinforcement and framing system in opening is the major cause of these damage. However, the width to height ratio of pier in masonry wall, distance between openings and distance of openings from corners is adequately maintained which led to lesser damage in these SMM houses.

Figure 11: SMM house with greater opening in transverse wall

For SMM houses without timber bands at floor level and greater percentage of opening in both direction, minor cracks with some damage in pier between openings were observed. The application of adequate thickness to height ratio, greater wall thickness and small interstorey height led to out of plane stability of these walls. However, use of well dressed stone, great bonding between stone masonry and mud as well as use of skilled mason are also major indicators leading to stability of load bearing masonry wall in these houses.

7. Discussion and Conclusion

In this study, statistical analysis was carried out for comparison of standard parameters of code and observed data in field of sample SMM houses. At first, the criteria of code satisfied by traditional SMM houses were determined. The result showed that 80.9 % of traditional SMM houses satisfied the dimensional characteristics of the code. On observing the horizontal and vertical resisting elements, the practice of use of through stones and corner stone was greater than 65%. The use of horizontal bands was not common and vertical square or circular post with capital were most communal practice as seen in traditional SMM houses of Sindhupalchowk. Structural adequacy of traditional SMM houses showed that these structures are compliant with the given provisions of the code.Thus, it can be stated that traditional SMM buildings have certain earthquake resilient dimensional features within them which are essential for resistance of a building to earthquake force.

The informal study and observations of various SMM buildings in different localities of Nepal showed that these houses have respective traditional technology which bind the whole building into one form. The timber band provided below and above joist used to support it in all walls performs partly as a ring beam and binds the whole component into a single structure. Similarly, proper placement of rafters and purlins along with gable bands makes the roof system more durable. Thus, a minimum intervention is sufficient to improve the rigidity of these structures in future.

Comparative study shows that vertical separation in wall corner is dominant damage in all cases and hence should be focused in retrofitting. Mud bonding, use of well dressed stone and skilled labor can be equally important as using timber band in making a SMM house earthquake resilient. Distance of opening from corner and distance between two opening plays an important role in type of damage that have occurred in different SMM houses.

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