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STRUCTURAL CLASSIFICATION SYSTEM FOR LOAD BEARING MASONRY SCHOOL BUILDINGS

Rohit Kumar ADHIKARI[1], Dina D'AYALA [2], Carina Fonseca FERREIRA[3], Fernando RAMIREZ[4]

ABSTRACT

Many school infrastructures around the world have poor seismic performance exposing millions of school children to significant seismic risk. School facilities also serve as shelters for communities during disasters. Many of these school buildings were constructed long before the development of seismic design practices and in developing countries, school buildings are still being built locally without any seismic design. Moreover, unreinforced masonry construction, using brick, stone, mud etc., is rather vulnerable to earthquakes. Thus, it is important to understand the seismic performance of masonry school buildings, and then to seismically strengthen them to stand stronger during destructive seismic actions. For the seismic vulnerability analysis, a comprehensive structural classification is crucial for grouping the school buildings into distinct structural typologies. This paper focuses on the development of a globally applicable structural classification system for load bearing masonry (LBM) school buildings, as a first step towards the seismic vulnerability analysis and strengthening strategy selection for risk reduction of school buildings at regional level. A number of seismic vulnerability parameters specific to masonry school buildings (such as load bearing wall type, building height, diaphragm flexibility etc.) are identified for the development of a comprehensive structural classification system which collectively result in a taxonomy string for a building structure unique to each building type. Finally, the application of this classification system to identify index buildings in each typology of LBM school buildings for the seismic vulnerability analysis at regional level is presented.

Keywords: Structural Classification System; Taxonomy; Masonry Structures; Educational Buildings; Seismic Vulnerability Assessment

1. INTRODUCTION

School buildings are very important infrastructure in a community. The young age population, relatively more vulnerable, spends most of the day time in schools. Moreover, these structures in many regions are also used as shelters for the community people during the disasters. Many school buildings of unreinforced masonry construction worldwide are old and were designed and constructed before the development of seismic design codes. Furthermore, in rural areas of developing countries, the construction practice is still informal and school buildings are built locally by local masons without any input from seismic design professionals. In many cases, the seismic performance of these school buildings is not clearly understood, a necessary step for planning appropriate retrofitting interventions for risk reduction.

In the past, many earthquakes have caused destructive damage to school facilities and many young

[1]PhD Student, Department of Civil Environmental and Geomatic Engineering, University College London, London, United Kingdom, rohit.adhikari.15@ucl.ac.uk

[2]Professor, Department of Civil Environmental and Geomatic Engineering, University College London, London, United Kingdom, d.dayala@ucl.ac.uk

[3]Disaster Risk Management Specialist, The World Bank, Washington DC, United States of America, cferreira2@worldbank.org

[4]Senior Disaster Risk Management Specialist, The World Bank, Washington DC, United States of America, framirezcortes@worldbank.org

students as well as teachers have lost their lives, as summarized in Table 1. More recently, the 2015 Nepal earthquakes caused collapse or significant damage to more than 7,000 school facilities but luckily the main shock occurred on a holiday in Nepal.

Table1. Damage to school buildings and fatalities to school children due to some of the past major earthquakes. (Modified from Petal et al., 2015)

Earthquake: Location, Magnitude, Year	**School buildings/classrooms damaged**	**Fatalities (school children)**
Tangshan, China, M7.8, 1976	Most school buildings destroyed	2,000 students killed in a dormitory
Spitak, Armenia, M 6.8, 1988	380 children institution destroyed	Thousands of school children killed.
Ardekul, Iran, M 7.3, 1997	Elementary school collapsed	110 young girls were killed
Gujrat, India, M 7.6, 2001	1,884 school buildings collapsed	971 children and 31 teachers killed
Kashmir, Pakistan and India, M 7.6, 2005	More than 10,000 schools collapsed	More than 18,000 school children died
Wenchuan, China, M 7.9, 2008	157 schools were destroyed	More than 5,300 school children died
Port-au-Prince, Haiti, M 7.0, 2010	Estimated 4,992 schools severely affected	Estimated 1.3 million children and youth affected
Gorkha, Nepal, M 7.8, 2015	More than 7,000 schools significantly damaged	Luckily the earthquake occurred on Saturday, on which schools are closed

Studies of seismic damages in past events show that some types of construction tend to be more vulnerable than others. In general, old school buildings constructed using masonry materials, e.g. stone, brick, mud etc., are inherently more vulnerable than modern engineered constructions. Figure 1 shows damages to stone masonry school building during the 2015 Nepal earthquake. These represent a large proportion of school buildings in Nepal and many other South-Asian countries and their response varies, depending on a number of construction solutions. Thus, the preparation of a catalogue of school building types, valid across many nations and using such catalogue to conduct seismic vulnerability assessment and define strengthening strategies is a fundamental step towards disaster risk reduction (D'Ayala et al., 1997, Coburn and Spence, 2002).

a) b)

Figure 1. a) Heavily damaged dry rubble stone masonry school building and b) non-structural (gable) damage to a stone in mud mortar masonry school building in 2015 Nepal earthquake (Photo credit: The World Bank)

For the seismic vulnerability analysis of these school buildings at regional level, the first step is the identification of the recurring construction typologies in the region. As it is not feasible to analyze each single building in a region to determine its seismic performance, seismic analysis of some characteristic buildings, in the following referred to as index buildings, representative of each construction type, is a second essential step in defining the seismic vulnerability following an analytical approach (D'Ayala et al. 2015). These two fundamental purposes in seismic vulnerability assessment are served by a comprehensive structural classification system by which the buildings having similar construction characteristics are grouped into distinct structural typologies of buildings.

1.1 Available Structural Classification Systems

Several structural classification systems for buildings structures have been developed and in use, some being developed considering global construction types and hence globally applicable (e.g. Coburn and Spence, 2002; Jaiswal and Wald, 2008; Brzev et al., 2013) and some being of national or regional reference (e.g. ATC, 1985; Grünthal, 1998; FEMA, 2015). The structural characteristics used in the early classification systems such as ATC-13 (ATC, 1985) or EMS scale (Grünthal, 1998) are very limited, and the corresponding building typologies are very broad. In ATC-13, for instance, developed by the Applied Technology Council for the seismic vulnerability assessment of buildings in California, USA, the classification of building structures is based on construction material, height of building, structural load bearing system and design and construction quality. The EMS scale building typology catalogue classifies buildings into construction types and sub-types based on the construction material. Similarly, Coburn and Spence (2002) have developed a classification system in which structures are broadly grouped into non-engineered building and engineered buildings and are further classified into several types based on the construction materials used.

Table 2. PAGER building classes with label LBM buildings. (modified from Jaiswal and Wald, 2008)

Label	**Description (according to construction/structure type)**	**Average no. of stories**
RM	REINFORCED MASONRY	All
RM1	Reinforced Masonry Bearing Walls with Wood or Metal Diaphragms	All
RM1L	Low-Rise	1-3
RM1M	Mid-Rise (4+ stories)	4-7
RM2	Reinforced Masonry Bearing Walls with Concrete Diaphragms	All
RM2L	Low-Rise	1-3
RM2M	Mid-Rise	4-7
RM2H	High-Rise	8+
RM3	Confined Masonry	All
A	ADOBE BLOCKS (UNBAKED DRIED MUD BLOCK) WALLS	1-2
A1	Adobe Block, Mud Mortar, Wood Roof and Floors	1-2
A2	Same as A1, Bamboo, Straw, and Thatch Roof	1-2
A3	Same as A1, Cement-Sand Mortar	1-3
A4	Same as A1, Reinforced Concrete Bond Beam, Cane and Mud Roof	1-3
A5	Same as A1, with Bamboo or Rope Reinforcement	1-2
RS	RUBBLE STONE (FIELD STONE) MASONRY	All
RS1	Local Field Stones Dry Stacked (No Mortar). Timber Floors. Timber, Earth, or Metal Roof.	1-2
RS2	Same as RS1 with Mud Mortar.	1-3
RS3	Same as RS1 with Lime Mortar.	
RS4	Same as RS1 with Cement Mortar, Vaulted Brick Roof and Floors	1-3
RS5	Same as RS1 with Cement Mortar and Reinforced Concrete Bond Beam.	1-3
DS	RECTANGULAR CUT STONE MASONRY BLOCK	All
DS1	Rectangular Cut Stone Masonry Block with Mud Mortar, Timber Roof and Floors	1-2
DS2	Same as DS1 with Lime Mortar	1-3
DS3	Same as DS1 with Cement Mortar	1-3
DS4	Same as DS2 with Reinforced Concrete Floors and Roof	1-3
UFB	UNREINFORCED FIRED BRICK MASONRY	All
UFB1	Unreinforced Brick Masonry in Mud Mortar without Timber Posts	1-2
UFB2	Unreinforced Brick Masonry in Mud Mortar with Timber Posts	1-2
UFB3	Unreinforced Fired Brick Masonry, Cement Mortar, Timber Flooring, Timber or Steel Beams and Columns, Tie Courses	1-3
UFB4	Same as UFB3, but with Reinforced Concrete Floor and Roof Slabs	1-3
CB	UNREINFORCED CONCRETE BLOCK MASONRY, LIME/CEMENT MORTAR	All

However, recently developed classifications systems have included several other important parameters as indicative of the specific typology seismic response, such as diaphragm flexibility, structural irregularities, openings, etc. The PAGER classification system (Jaiswal and Wald, 2008), for instance, developed by the USGS to provide a global inventory of building structural types, includes material and type of load bearing structure, lateral resisting system, diaphragm type, height of the structure. It has been used widely in different regions across the world, to calculate forecast of level of damage in the immediate aftermath of main shocks. Table 2 shows the different structure types of load bearing masonry buildings according to PAGER classification system. These classification systems do not explicitly rank the typology parameters in terms of their influence on the seismic response.

On the other hand, the Global Earthquake Model (GEM) (Brzev et al., 2013) global taxonomy system is based on the concept of ordering the parameters from the more generic to the more specific, so that for each additional parameter considered, the resulting class is a subset of the one determined without that parameter. The system has two main categories: primary parameters describing general building characteristics (e.g. height) and secondary parameters (e.g. height above grade, story height etc.) describing the characteristics in more detail. This classification system results in a unique taxonomy string to each building structure. The attributes and the attribute levels for various parameters are shown in Table 3.

Table 3. GEM building taxonomy attributes. (Brzev et al., 2013)

#	Attribute	Attribute levels
1	Direction	Direction of building
2	Material of the Lateral Load-Resisting System	Material type (Level 1) Material technology (Level 2) Material properties (Level 3)
3	Lateral Load-Resisting System	Type of lateral load-resisting system (Level 1) System ductility (Level 2)
4	Height	Height
5	Date of Construction or Retrofit	Construction completed (years)
6	Occupancy	Building occupancy class – general (Level 1) Building occupancy class – detail (Level 2)
7	Building Position within a Block	
8	Shape of the Building Plan	Plan shape (footprint)
9	Structural Irregularity	Regular or irregular (Level 1) Plan irregularity or vertical irregularity (Level 2) Type of irregularity (Level 3)
10	Exterior Walls	Exterior walls
11	Roof	Roof shape (Level1) Roof covering material (Level 2) Roof system material (Level 3) Roof system type (Level 4) Roof connections (Level 5)
12	Floor	Floor system material (Level 1) Floor system type (Level 2) Floor connections (Level 3)
13	Foundation	Foundation system

Although above discussed classification systems include a wide variety of construction types and parameters, some have insufficient parameters and others are too broad to be applied directly to load bearing masonry school buildings. Moreover, these classification systems are primarily focused on residential buildings, and school buildings have typical construction characteristics different to residential buildings such as the need for large classrooms, the presence of several openings among others (see Rodgers, 2012). Some typical construction types of school buildings (e.g. masonry infilled steel framed schools in Nepal) cannot be precisely categorized using these classification systems. Thus, a need for a comprehensive structural classification system specific for Load Bearing Masonry (LBM) schools is identified for the seismic vulnerability analysis of these structures at regional level.

1.2 Methodology for the Development of Structural Classification System

As an initial step towards the development of a globally applicable structural classification system, the current study is primarily based on the information and data on the school buildings from 3 different countries i.e. one from Asia (Nepal) and two from South America (El Salvador and Peru).
An analysis of existing construction type and characteristics, typical vulnerability parameters and the variations of these parameters is prerequisite for the development of a comprehensive structural classification system. Figure 2 shows the overall methodology for the development of the structural classification system. The first step is to understand the construction types and overall construction characteristics along with similarities and differences at regional level (i.e. national level typology identification). Then, with this information and existing knowledge, a number of seismic vulnerability parameters for LBM school buildings are identified so that they completely define the vulnerability of these structures. Finally, considering the variations in the attributes of these vulnerability parameters, a

comprehensive structural taxonomy is developed. A comprehensive description of this work is reported in Adhikari and D’Ayala (2017).

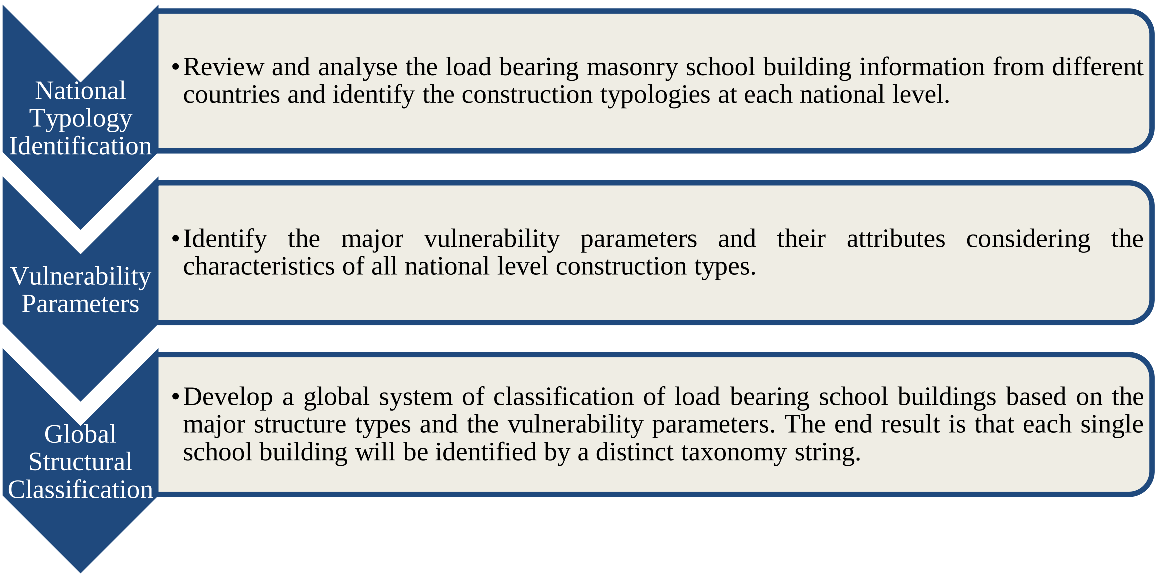

Figure 2. Overall process of development of structural classification system.

2. NATIONAL TYPOLOGY IDENTIFICATION

Identification and comparison of national level construction types from different regions is an important step to develop an internationally applicable structural classification system. Country-wise construction types of LBM schools and corresponding PAGER classes and GEM taxonomies are briefly presented in the following sections. A detailed discussion on the construction characteristics of the LBM school buildings from the three countries are available in a World Bank report by the authors (Adhikari and D’Ayala, 2017).

2.1 Nepal

The main structural typologies of LBM school buildings present in Nepal (national level) are identified from the SIDA survey report (SIDA, 2016) and are listed in Table 4. Most of the load-bearing structures of these school buildings are unconfined/unreinforced masonry walls. The masonry units vary from field stone, dressed stone, bricks to concrete blocks while the mortar is either mud or cement sand mortar. The corresponding PAGER labels and GEM taxonomy strings for each typology are also included in the same table, for comparison.

Table 4. Major structure types of LBM school buildings in Nepal.

ARUP		PAGER	GEM
Structural typology category	**Sub-category**	**Label**	**Taxonomy string**
Adobe	Earth blocks in mud mortar (1 story, 2 – 3 stories)	A	MUR+ADO+MOM/LWAL
	Compressed stabilized soil blocks in mud mortar (1 story, 2 – 3 stories)	A	MUR+ETR+MOM/LWAL
Unconfined/ Unreinforced Masonry	Dry field stone masonry (1 story, 2 – 3 stories)	RS1	MUR+STRUB+MON/LWAL
	Field stone in mud mortar (1 story, 2 – 3 stories)	RS2	MUR+STRUB+MOM/LWAL
	Field stone in mud mortar with minor seismic enhancement (1 story, 2 – 3 stories)	RS2	MUR+STRUB+MOM/LWAL
	Rectangular blocks (bricks, concrete blocks) in mud mortar (1 story, 2 – 4 stories)	UFB1	MUR+CLBRS+MOM/LWAL MUR+CBS+MOM/LWAL MUR+STDRE+MOM/LWAL
	Rectangular blocks in cement mortar (1 story, 2	UFB4,	MUR+CLBRS+MOC/LWAL

	stories, 2 – 4 stories)	UCB	MUR+CBS+MOC/LWAL MUR+STDRE+MOC/LWAL
	Rectangular blocks in mud mortar with traditional tying elements (2 – 4 stories)	UFB2	MUR+CLBRS+MOM/LWAL MUR+CBS+MOM/LWAL MUR+STDRE+MOM/LWAL
	Rectangular blocks in mud mortar with seismic enhancements (2 – 4 stories)	UFB2	MUR+CLBRS+MOM/LWAL MUR+CBS+MOM/LWAL MUR+STDRE+MOM/LWAL
	Rectangular blocks in cement mortar with seismic enhancements (2 – 4 stories)	UFB4, UFB5, UCB	MUR+CLBRS+MOC/LWAL MUR+CBS+MOC/LWAL MUR+STDRE+MOC/LWAL
Steel Framed with Masonry Infill Walls	Light Gauge Steel Frame with locally built stone walls in mud mortar (1 story)	S3, S5L	S+SL+WEL/LFINF
	Light Gauge Steel Frame with locally built brick walls in mud mortar (1 story)		
	Light Gauge Steel Frame with locally built stone walls in cement mortar (1 story)		
	Light Gauge Steel Frame with locally built brick walls in cement mortar (1 story)		

2.2 El Salvador and Peru

The information and data from the El Salvador is limited geographically to San Salvador city, while the data reviewed from Peru is at national level. Major structural typologies of LBM school buildings from these two countries are identified and listed in Table 5. Most of the load-bearing structures of these school buildings are confined/reinforced masonry walls, while a very small percentage of school buildings are unconfined/unreinforced masonry structures. The masonry units are mostly burnt clay bricks and concrete blocks.

Table 5. Major structure types of LBM school buildings in El Salvador and Peru.

Building Category		**PAGER**	**GEM**
Structural typology category	**English name**	**Label**	**Taxonomy string**
Adobe (A)	Adobe	A, RE	MUR+ADO+MOM/LWAL
Construccciones Precarias	Vernacular Constructions	M	ER/LWAL
Paredes de mampostería sin refuerzo (El Salvador) Albañilería sin confiner (Peru)	Unconfined/Unreinforced Masonry	UFB, UCB	MUR+CLBRS+MOC/LW AL
Paredes de mampostería reforzada (confinada y/o con refuerzo integral) (El Salvador) Albañilería confinada o armada (Peru)	Confined and/or Reinforced Masonry	RM1L, RM1M RM2L, RM2M, RM3	MCF+CLBRS+MOC/LWA L MR+CLBRS+RS+MOC/L WAL

This initial analysis of national typologies reveals that there is relatively little overlap of typologies between school buildings in the two regions analyzed. Hence an approach of generic typology classes such as the EMS 98 or the PAGER approach, would not be readily applicable in different geographical context, without the need to create new typologies for each case. A more flexible approach is the one proposed by GEM through an expandable taxonomy, which allows to consider buildings form different regions as belonging to a broad class, for instance URM, while by choosing specific attributes of primary, secondary or tertiary level is possible to capture the specific features of regional building types. This allows direct comparison of corresponding vulnerability, and hence quantification and comparison of risk.

3. SEISMIC VULNERABILITY PARAMETERS

A number of important construction characteristics of LBM school buildings which collectively define the seismic performance and vulnerability of load bearing masonry construction are identified and described in this section. Load bearing wall type is the main construction characteristic that highly governs the seismic performance of these structures. Building height controls the dynamic behavior during seismic loading and hence is another important characteristic of any building structure. Similarly, seismic design level, structural irregularity and diaphragm flexibility influence the seismic performance of load bearing masonry buildings significantly, depending on the construction characteristics in a locality. Other minor parameters (e.g. wall panel length, wall openings etc.) also alter the seismic vulnerability depending on their attributes but are often hard to generalize and prioritize for relative significance. However, in this proposed classification system, the selection and prioritization of these parameters is completely flexible for a specific scenario, by omitting or skipping or rearranging the attributes of the vulnerability parameters in the taxonomy string as shown in section 4.

i) Load Bearing Wall Type

The units and bonding material of masonry (e.g. field stone in mud mortar, bricks in cement mortar etc.) in a LBM structure greatly affect its seismic performance as well as its vulnerability. For example, a stone in mud mortar masonry has a poor shear capacity compared to brick in cement mortar masonry. Mud mortar is generally weaker than cement sand mortar and the failure mechanisms of masonry walls with mud mortar and cement mortar are different. Both bricks and concrete blocks have regular rectangular shape and size, thus these two are placed under same sub-category (i.e. rectangular block) unlike dressed stone which has varying shape and size and is placed into separate sub-categories. The seismic vulnerability also depends on the workmanship, type of bond used, solid or multi-leaf walls etc., which can be considered as second or third level attributes.

ii) Building Height

Building height affects the dynamic behavior of a building during earthquake. LBM school buildings are mostly single or two storied while few 3 – 5 storied school buildings are also present. There is a wide variation in the definition of low-rise and mid-rise masonry structures in existing classification systems. The vulnerability of unreinforced masonry construction tends to be more sensitive to additional stories in comparison to reinforced or confined masonry constructions which have relatively better structural integrity and ductility. Also, the seismic behavior of a single-story building is entirely different compared to that of a multi-story building.

Thus, adobe and unconfined/unreinforced masonry (UCM/URM) buildings are classified as low-rise (single story), mid-rise (2 – 3 stories) and high-rise (4+ stories); while confined/reinforced masonry (CM/RM) buildings as low-rise (single story), mid-rise (2 – 4 stories) and high-rise (5+ stories).

iii) Seismic Design Level

The seismic design level highly affects seismic performance. If seismic design codes are followed and/or seismic enhancements (lintel bands, through stones etc.) are included during the construction, the vulnerability decreases. Date of construction can be considered as a simple indication of seismic design codes followed (if any) in the design of structures. In many cases, it has been found that buildings are not designed following a seismic code although one might be existing in the country or region (e.g. in Nepal). Other factors such as code enforcement capacity in the country, workmanship and level of quality control during construction etc. also influence the seismic design level. It is often hard to define and assign the seismic design level to a building as not easily identifiable on site.

iv) Structural Irregularity

Structural irregularities (horizontal, vertical) tend to make structures more vulnerable than simple and regular structures. Horizontal (plan) irregularity describes the building's irregular (e.g. rectangular long, T-, C- or H-shaped) foot prints or unsymmetrical positioning of lateral load resisting elements, openings whereas vertical irregularity includes the variation in story height or mass over the building height.

v) Floor/Roof Diaphragm Flexibility

Since the floors or roof are the key horizontal components of lateral load resisting system, the seismic performance of a building is influenced by the flexibility of these elements. If the floors/roof are lighter, stiffer and properly connected to the walls so that they can transfer the lateral load to all the load bearing walls at that level, it is considered to be stiff or rigid (e.g. reinforced concrete floors). On the other hand, if the floor/roof is just sitting over the load bearing walls which is not well connected to the walls, the floor is considered to be flexible (e.g. timber floors).

vi) Wall Panel Length

The unrestrained wall panel length in a masonry structure is an important indicator of vulnerability of masonry structures as longer walls are more susceptible to out-of-plane collapse during lateral loading. Masonry walls can be restrained by cross-walls or piers or buttresses. In general, for unreinforced masonry, the wall panel lengths are recommended to be less than 12 times the thickness i.e. walls having unrestrained length less than 12 times the thickness are short panel walls while more than 12 times the thickness are long panel walls. Similarly, for confined masonry, it is recommended to be less than 6 m (Brzev and Meli, 2012).

vii) Wall Openings

If there are large and/or many openings in the load bearing walls, seismic capacity decreases and hence vulnerability increases. Moreover, the cornice of opening is where the cracking initiate and keep on widening as the load increases. The opening is considered small if the combined width of the openings on a wall between two cross walls is less than 35% and 25% of total wall length in single- and multi-story building, and large if the combined width of the openings on a wall between two cross walls is equal to or more than 35% and 25% of total wall length in a single- and multi-story building respectively, following the NBC 203 (1994). The seismic performance is better if the openings are smaller, fewer, located far from corners or wall ends and regularly/symmetrically distributed.

viii) Foundation Type

The type of foundation influences the seismic performance of a building by controlling the settlement, cracking and overturning of masonry walls. The walls of the masonry building are laid on continuous stone masonry, brick masonry or reinforced concrete foundation. A building on concrete foundation is comparably stiffer (thus controls the settlement) and performs better than on a brickwork foundation or stone foundation.

ix) Seismic Pounding Risk

Seismic pounding is the phenomenon in which two adjacent building structures having different vibration characteristics collide with each other during earthquakes. Although this is not a serious issue in case of low-rise building structures, if the gap between the buildings is very small, it can cause damage to non-structural or even structural elements of a building due to hammering. The minimum gap is recommended to be at least 4% of the building height (FEMA 273, 1997).

x) Effective Seismic Retrofitting

If a structure has been intervened before in order to increase the overall seismic resistance (e.g. wall strengthening, improvements of connections, floor/roof strengthening etc.) the seismic vulnerability decreases. Seismic strengthening is categorized as applied to horizontal structures or to main load bearing walls.

xi) Structural Health Condition

Non-structural elements hazards (poor connection quality, heavy self-weight etc.), material deterioration and existing damages (e.g. building out of plumb, delaminated walls, corner separation, cracks in the walls) increase the vulnerability of masonry structures. Falling of non-structural elements during earthquake can cause serious injuries or even death. This is a qualitative indicator that can be rated as poor, fair or good on the basis of the whole building conditions.

4. STRUCTURAL CLASSIFICATION SYSTEM (TAXONOMY)

The proposed comprehensive global structural classification system for LBM school buildings considering the three case study countries (i.e. El Salvador, Nepal and Peru) is presented in Table 6. A Microsoft Excel format of the same can be obtained from the authors.

Table 6. Proposed Structural Taxonomy for LBM School Buildings (Adhikari and D'Ayala, 2017).

<table>
<tr><th>Building Category</th><th>Load Bearing Wall Type</th><th>Height Range (No. of Story)</th><th>Structural Irregularity</th><th>Diaphragm Action</th><th>Wall Panel Length</th><th>Wall Opening</th><th>Foundation Type</th><th>Seismic Design Level</th><th>Seismic Pounding Risk</th><th>Seismic Retrofitting</th><th>Structural Health Condition</th></tr>
<tr><td rowspan="2">Adobe (A)</td><td rowspan="2">Earthen blocks or compressed stabilised soil blocks in mud mortar (A)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td><td rowspan="29">SP or LP</td><td rowspan="29">SO or LO</td><td rowspan="29">SF or BF or CF</td><td rowspan="23">ND or LD or MD</td><td rowspan="29">NP or PR</td><td rowspan="29">OS or RS</td><td rowspan="29">PC or FC or GC</td></tr>
<tr><td>MR (no.)</td><td>NO or HI or VI or HV</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td rowspan="17">Unconfined /Unreinforced Masonry (UCM/URM)</td><td rowspan="2">Dry rubble (or field) stone masonry (UCM/URM1)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td>NO or HI or VI or HV</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td rowspan="2">Rubble (or field) stone in mud mortar (UCM/URM2)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td>NO or HI or VI or HV</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td rowspan="2">Dressed stone in mud mortar (UCM/URM3)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td>NO or HI or VI or HV</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td rowspan="3">Rectangular block (brick, concrete block) in mud mortar (UCM/URM4)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td rowspan="2">NO or HI or VI or HV</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td>HR (no.)</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td rowspan="2">Rubble stone in cement mortar (UCM/URM5)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td>No or HI or VI or HV</td><td>FF + FR or RF + RR or RF + FR</td></tr>
<tr><td rowspan="3">Dressed stone in cement mortar (UCM/URM6)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td rowspan="2">No or HI or VI or HV</td><td rowspan="2">FF + FR or RF + RR or RF + FR</td></tr>
<tr><td>HR (no.)</td></tr>
<tr><td rowspan="3">Rectangular block in cement mortar (UCM/URM7)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td rowspan="2">No or HI or VI or HV</td><td rowspan="2">FF + FR or RF + RR or RF + FR</td></tr>
<tr><td>HR (no.)</td></tr>
<tr><td rowspan="4">Steel Framed with Masonry Walls (SFM)</td><td>SFM with stone in mud mortar (SFM1)</td><td rowspan="4">LR (no.)</td><td rowspan="4">NO or HI</td><td rowspan="4">FR</td></tr>
<tr><td>SFM with rectangular block in mud mortar (SFM2)</td></tr>
<tr><td>SFM with stone in cement mortar (SFM3)</td></tr>
<tr><td>SFM with rectangular block in cement mortar (SFM4)</td></tr>
<tr><td rowspan="3">Confined Masonry (CM)</td><td rowspan="3">Rectangular block in cement mortar with confinement (CM)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td><td rowspan="6">LD or MD or HD</td></tr>
<tr><td>MR (no.)</td><td rowspan="2">NO or HI or VI or HV</td><td rowspan="2">FF + FR or RF + RR or RF + FR</td></tr>
<tr><td>HR (no.)</td></tr>
<tr><td rowspan="3">Reinforced Masonry (RM)</td><td rowspan="3">Rectangular block in cement mortar with reinforcement (RM)</td><td>LR (no.)</td><td>NO or HI</td><td>FR or RR</td></tr>
<tr><td>MR (no.)</td><td rowspan="2">NO or HI or VI or HV</td><td rowspan="2">FF + FR or RF + RR or RF + FR</td></tr>
<tr><td>HR (no.)</td></tr>
</table>

Notes:
Height Range: LR = Low Rise (1 story), MR = Mid Rise (2 - 3 stories), HR (4+ stories) [For Adobe and UCM/URM]; LR = Low Rise (1 story), MR = Mid Rise (2 - 4 stories), HR (5+ stories) [For CM/RM]
Structural Irregularity: NO = No Irregularities, HI = Horizontal Irregularity, VI = Vertical Irregularity, HV = Horizontal + Vertical Irregularity
Diaphragm Action: FR = Flexible Roof, FF = Flexible Floor, RR = Rigid Roof, RF = Rigid Floor
Wall Panel Length: SP = Short Panel, LP = Long Panel
Wall Opening: SO = Small Opening, LO = Large Opening
Foundation Type: SF = Stonework Foundation, BF = Brickwork Foundation, CF = Concrete Foundation
Seismic Design Level: ND= No Seismic Design, LD = Low Seismic Design, MD = Medium Seismic Design, HD = High Seismic Design
Seismic Pounding Risk: PR = Yes, NP = No
Seismic Retrofitting: OS = Original Structure, RS = Effectively Retrofitted Structure
Structural Health Condition: PC = Poor Condition, FC = Fair Condition and GC = Good Condition
Seismic Enhancements include lintel band beams (e.g. RC, wooden), gable bands for buildings with sloped roof, through stones in stone masonry walls, wooden stiches/ties etc.

Five major construction categories are identified: adobe (A), unconfined/unreinforced masonry (UCM/URM), steel frame with masonry walls (SFM), confined masonry (CM) and reinforced masonry (RM); each of them is further classified based on 11 different structural vulnerability parameters. The system produces 14 possible sub-sets of LBM school buildings depending on load bearing wall type (e.g. dry-stone (UCM/URM1), rubble stone in mud mortar (UCM/URM2) etc.).

Thus, for a typical LBM school building (e.g. single story adobe building with no structural irregularity and flexible roof), the structural classification ultimately results in a taxonomy string given as A//LR(1)//NO//FR//….. The length of the string depends on the extent of information on the structural characteristics; the more the information, the longer the string and vice-versa. Further, any element in the string can be omitted or truncated depending on the availability of the information or priorities given to different vulnerability parameters.
Although the parameters and their attributes in the proposed structural classification system (Table 6) are based on the LBM school building information from three countries (i.e. El Salvador, Nepal and Peru), this classification system is equally applicable for the structural classification for seismic risk assessment purpose of LBM schools in any other countries/regions where the construction types are similar. Furthermore, the methodology used in this classification system can be applied for developing structural classification systems for other school construction types (e.g. RC framed structures, timber framed structures etc.) by changing the parameters and their attributes as necessary.

5. APPLICATION TO NEPALESE URM SCHOOL BUILDINGS

This section presents an illustrated application example of the proposed structural classification system for brick masonry in mud mortar school building and typical taxonomy of different typologies of LBM school in Nepal.
For a brick in mud mortar school building from Nepal, the application of proposed structural classification system which finally results in a unique taxonomy string is shown in Figure 3.

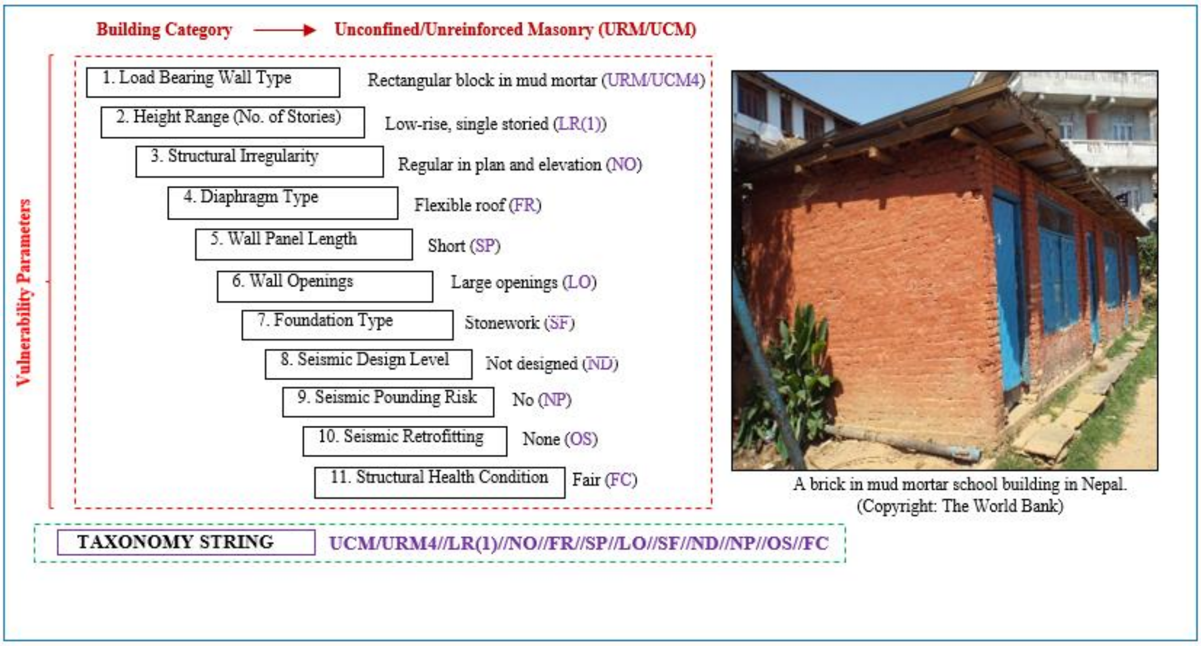

Figure 3. Application example of the proposed structural classification system.

As shown in the photo in Figure 3, rectangular block in mud mortar buildings (UCM/URM4) are typically low- to medium-rise (LR to MR) rectangular plan buildings, with no horizontal or vertical irregularity (NO). These structures mostly have flexible floors (FF) and roof (FR) structure. Unrestrained wall panels are generally short (SP) and these buildings in general have large and many openings (LO). Foundation is usually continuous stonework (SF). Seismic design level of these structures is none (ND). Some structures may have seismic enhancement features, such as timber tying elements, horizontal lintel band etc., in which case the seismic design level can be considered as low (LD). These buildings usually are not strengthened (OS) after the construction. In general, there is no risk of seismic pounding (NP). Most of these schools have fair structural health condition (FC).
In Nepal, nearly 60% of the total school buildings are unreinforced masonry construction which

includes rubble/dressed stone or burn clay brick in mud or cement mortar. Based on the typical construction characteristics of these school buildings (SIDA, 2016), typical taxonomy strings for different typologies of unreinforced masonry school buildings in Nepal as per the proposed structural classification system are listed in Table 7. These strings represent the characteristics of representative index buildings of the respective typologies. The seismic analysis of index buildings is useful in predicting the seismic behavior of the typologies for the seismic vulnerability assessment of LBM school buildings at regional level.

Table 7. Application of proposed classification system to Nepalese unreinforced masonry school building to identify index buildings per typologies.

Building Category	**Sub-Category**	**Height Range**	**Typical Taxonomy**
Unconfined/Unreinforced Masonry (UCM/URM)	Dry stone masonry (UCM/URM1)	Low-rise	UCM/URM1//LR(1)//NO//FR//SP//LO//SF//ND// NP//OS//PC
	Rubble stone in mud mortar (UCM/URM2)	Low-rise	UCM/URM2//LR(1)//NO//FR//SP//LO//SF//ND//NP//OS//PC
		Mid-rise	UCM/URM2//MR(2)//NO//FF+FR//SP//LO//SF//ND//NP//OS//PC
	Dressed stone in mud mortar (UCM/URM3)	Low-rise	UCM/URM3//LR(1)//NO//FR//SP//LO//SF//ND//NP//OS//PC
		Mid-rise	UCM/URM3//MR(2)//NO//FF+FR//SP//LO//SF//ND//NP//OS//PC
	Rectangular blocks in mud mortar (UCM/URM4)	Low-rise	UCM/URM4//LR(1)//NO//FR//LP//LO//SF//ND//NP//OS//PC
		Mid-rise	UCM/URM4//MR(2)//NO//RF+RR//LP//LO//SF//LD//NP//OS//PC
	Rubble stone in cement mortar (UCM/URM5)	Low-rise	UCM/URM5//LR(1)//NO//FR//SP//LO//SF//ND//NP//OS//FC
		Mid-rise	UCM/URM5//MR(2)//NO//RF+RR//SP//LO//SF//LD//NP//OS//FC
	Dressed stone in cement mortar (UCM/URM6)	Low-rise	UCM/URM6//LR(1)//NO//FR//SP//LO//SF//ND//NP//OS//FC
		Mid-rise	UCM/URM6//MR(2)//NO//RF+RR//SP//LO//SF//LD//OS//NP//FC
	Rectangular blocks in cement mortar (UCM/URM7)	Low-rise	UCM/URM7//LR(1)//NO//FR//LP//LO//SF//LD //NP//OS//FC
		Mid-rise	UCM/URM7//MR(2)//NO//RF+RR//LP//LO//SF//LD//NP//OS//FC

6. CONCLUSIONS

Based on the construction types and several structural vulnerability parameters, a simple yet comprehensive global structural classification system for LBM school buildings is developed. The application of proposed structural classification system is also discussed and clarified by applying to typical Nepalese LBM school buildings. This classification system is flexible to include more typologies of LBM schools and moreover, the methodology can be applied to develop taxonomy for other structure types such as RC or Steel framed structures. This classification system is based on the review of LBM school building information from three countries (viz. Nepal, El Salvador and Peru) and is in the process of revision to include more typologies and variations in construction characteristics from other regions.

6. ACKNOWLEDGMENTS

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