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GLOSI taxonomy: A tool for 'seismic risk assessment' oriented classification of school buildings

Rohit K. Adhikari [a,*], Dina D'Ayala [a], Rafael Fernandez [b], Luis Yamin [b], Arash Nassirpour [a], Ahsana P Vatteri [a], Carina Ferreira [c], Fernando Cortes [c]

[a] Department of Civil, Environmental & Geomatic Engineering, University College London, United Kingdom
[b] Departamento de Ingeniería Civil y Ambiental, Universidad de Los Andes, Bogota, Colombia
[c] Disaster Risk Management Specialist, The Global Program for Safer Schools, The World Bank, Washington, United States

A R T I C L E I N F O

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A B S T R A C T

For the seismic vulnerability and risk assessment of school infrastructure in a region, it becomes necessary first to identify and classify these constructions into a distinct number of structural typologies characterised by their vulnerability features. This enables us to rank the expected vulnerability of different typologies at the initial screening stage as well as to characterise the representative index buildings of different typologies for detailed vulnerability quantification. Currently, a systematic and comprehensive taxonomy tailored for the school buildings is not available. The present paper thus develops a globally applicable structural taxonomy to be used in the seismic risk assessment of school infrastructure within the framework of the Global Program for Safer Schools (GPSS) of the World Bank. Application as well as verification of the proposed taxonomy is tested to a range of school construction types from different countries across the world.

1. Introduction

Ensuring access to quality education in a safe environment for all children worldwide is the fourth of the Sustainable Development Goals (SDGs) [1]. Structural safety of school infrastructure against natural and manmade hazards is prerequisite to ensure a safe environment for children's learning activities. Thus, the structural safety of school infrastructure remains a high priority on the agenda of the UN Office for Disaster Risk Reduction (UNDRR), and it is reflected in the structure of the recently revised Comprehensive School Safety (CSS) framework [2]. The CSS framework has been formulated to achieve the education sector targets set out by the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015–2030 [3]. Key targets of the Sendai Framework related to the education sector are: i) minimize the deaths and injuries on schools due to hazard impacts; ii) substantially reduce the number of school children affected by disaster impacts; iii) reduce hazard related investment losses in education sector; iv) minimize the loss of school days due to hazard impacts. Moreover, school infrastructure and associated contents exposed to natural hazards, collectively sum up to an asset value of $13.6 trillion, representing the scale of the potential economic losses to educational systems [4], without including the cultural and social losses associated to it.

Through the Global Program for Safer Schools (GPSS), The World Bank aims to encourage large-scale investments to improve the disaster safety and resilience of school infrastructure and to enhance the quality of learning environments for children in low- and

* Corresponding author.
E-mail address: r.adhikari@ucl.ac.uk (R.K. Adhikari).

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middle-income countries. The GPSS has produced a Roadmap for Safer and Resilient Schools (RSRS), providing guidance for designing intervention strategies and investment plans to make school infrastructure safer and more resilient in the face of natural hazards, as well as encompassing the recovery and reconstruction of school facilities affected by disasters. As the essential technical foundation for the RSRS, the Global Library of School Infrastructure (GLOSI), developed jointly by teams at University College London, UK, and Universidad De Los Andes, Colombia, and freely available online [4], provides a repository of evidence-based knowledge and statistics on school infrastructure, quantitative metrics evaluating the performance of school buildings affected by natural hazards, and scalable solutions to improve their resilience. The GLOSI framework includes a full methodological approach including data collection, classification using the GLOSI taxonomy, seismic analysis for fragility and vulnerability assessment to underpin location specific risk assessment studies. Based on the analysis of a wide collection of school building types, the GLOSI repository includes a library of fragility and vulnerability functions as well as risk reductions solutions for 38 commonly found school *index buildings* [4,5].

A global approach to school infrastructure safety and resilience is justified by the increasing interest worldwide on this theme, as testified by the number of recent publications with focus on national portfolios, such as Iran [6], Italy [7], Pakistan [8], Mexico [9], Indonesia [10] along with increasing evidence of vulnerability of school buildings to even moderate earthquakes. In the recent M5.6 earthquake of November 21, 2022 in Indonesia, at least 342 schools and educational facilities were damaged, causing even death of the school children [11]. The Resilience Development Initiative [12] recorded that more than 52,000 school buildings across Indonesia were prone to earthquakes, with about 60 million students at risk. The prevalent typology of these buildings (estimated 60%) is one story poorly confined masonry (see further in §4). As emerges from global surveys, most school buildings worldwide are built of Load Bearing Masonry (LBM) or Reinforced Concrete (RC) structural systems. The LBM category can include Unreinforced Masonry (URM), Confined Masonry (CM) or Reinforced Masonry (RM) while the RC category can include RC Moment Resistant Frames (MRFs) with or without masonry infills or RC MRFs combined with RC shear walls [4]. Other construction types such as steel frames, timber frames, mixed constructions, prefabricated structures are also present in some countries/regions or in specific emergency situations with a modest incidence worldwide [4].

Several building classification systems are in use [13–20] to aid the seismic vulnerability assessment of existing assets and structures, with different level of definition and precision as to the *building class* represented. These rely on rather general taxonomies and there is no ranking of the descriptors in terms of how each of these influences the seismic performance. They allow to classify large portions of the building stock, but do not provide accurate description of real exposure and therefore pose severe limitation on the accuracy of the vulnerability estimates carried out on this basis. A faceted and more detailed taxonomy system is provided by the Global Earthquake Model (GEM) [18] based on the idea of arranging the parameters from generic to more specific ones. While in theory this allows to apply the same taxonomy to large exposure data sets as well as to highly detailed surveys of individual buildings, applications so far are confined to limited sets of parameters and the attribution to corresponding vulnerability functions is still rather generic [21].

A further limitation for the application of existing taxonomy systems to school infrastructure is the substantial difference in architectural and structural layout with respect to residential buildings [22–24], leading to specific features that affect fragility, and therefore needing specific descriptors. On the other hand, the school infrastructure within a country often comprises a limited number of typologies, as specific design prototypes of schools are adopted by education authorities, and large number of buildings are constructed under the umbrella of national or regional implementation programmes, in different time periods. Such construction programmes are usually triggered by new education policies, identifying specific educational needs, while the construction standard and quality will depend on the development of the national building safety framework of the time [25], and the level of enforcement of building standards. In many low-to middle-income countries however, school classrooms are also financed and built through direct community engagement or NGOs involvement, often delivering buildings with limited structural robustness [26].

Therefore, a thorough taxonomy tailored for school buildings should focus on the specific structural, architectural and functional details which determine the relevant structural characteristics and therefore their resulting seismic vulnerability. The GLOSI Taxonomy, which represents one of the key resources developed within the GLOSI framework [4], is based on the following tenets.

- Having a universal language for the understanding and communication of seismic risk posed by the school infrastructure. Given their specific function, school buildings often follow standard architypes, yet it is still challenging to categorize buildings with similar vulnerability, within a country and among countries. This is mainly due to the lack of a hierarchical classification system and a consistent framework for vulnerability assessment.
- Identification and description of the parameters that affect vulnerability and their range of attributes, should be complete and unequivocal, so that the assignment of a building to a class is independent of the assessor and its vulnerability completely defined.
- Ranking of the parameters should be from the generic to the specific, according to their relative significance in defining and characterizing the seismic behaviour. This allows the taxonomy to be collapsible, and flexible, i.e. it can be applied to set of data of different details, without losing meaning.
- It should be as much as possible exhaustive and expandable, i.e. it should be possible to classify any building types, even ones for which it has not been designed, by considering appropriate attributes of the parameters.
- Parameters and their attributes should be easy to identify and observable. This ensures that a wide range of users can apply the taxonomy and classify school buildings.

In turn, the creation of the taxonomy is functional to the need of determining the fragility and vulnerability of a given building typology using analytical vulnerability approaches as defined in D'Ayala et al. [27]. Therefore the taxonomy should provide sufficient information to: i) devise for each typology identified, representative *index buildings* to be used in the seismic risk assessment of school buildings portfolios [28]; ii) to provide insight valid at global level, thus saving time and resources as well as accelerating the process of seismic risk assessment of school infrastructure by utilising the already available results; and iii) to underpin the development and adoption of possible economic retrofitting options, thus providing solutions at scale.

The paper is organized as follows. The methodology for the development of the comprehensive taxonomy is presented in §2, based on a structure for organic growth as evidence of building typologies emerges from countries engaged with the GPSS program of the World Bank. §3 presents the databases used as the basis for developing the GLOSI taxonomy while §4 presents the distinct taxonomy parameters and the range of their attributes. Then in §5, the application and validity of the taxonomy is discussed with example application to a number of LBM and RC school building cases from different countries, in terms of their taxonomy string and analytical vulnerability functions. Finally, §6 presents the conclusions, use of the taxonomy and future works on expanding the taxonomy to wider construction types of school buildings.

2. Methodology for the development of the GLOSI taxonomy

Rather than moving from theoretical archetypes, the GLOSI taxonomy takes advantage of the basis of the data on schools available from GPSS and other engagements in selected countries: El Salvador, Dominican Republic, Peru, Nepal, Philippines, Colombia, and India. The steps followed for developing the GLOSI taxonomy are shown in Fig. 1.

The first step deals with detailed analysis of school infrastructure databases in order to identify the similarities and differences in construction types and characteristics of school buildings at global level, as detailed in §3. This allows the identification of distinct construction types, their specific construction characteristics and their corresponding vulnerabilities, identified on the basis of expert knowledge. By studying these datasets of real structures, it is ensured that the parameters chosen are relevant and meaningful, and that they can be identified from desktop studies on the basis of different sources of documentation available. Once the parameters are identified, the next step is determining their attributes, specifically, whether these should be of qualitative or quantitative nature and what thresholds define their distinct attributes. The parameters and their attributes are discussed in §4. To ensure that the resulting taxonomy is versatile enough to be applicable to diverse classes of construction technologies and practices and that it is exhaustive in its classification of building types, two checks are performed: firstly, ensuring that the parameters' set is complete, i.e., parameters are necessary and sufficient, and secondly, to ensure that across classes, parameters have analogous structural meaning and role in describing their seismic performance. Such application examples in terms of the taxonomy string and validations in terms of analytical vulnerability functions are presented and discussed in §5.

This approach has two elements of novelty with respect to available taxonomies: i) it focuses strongly on non-engineered typologies, and typologies that are not compliant with seismic standards, most common in low-middle- income countries and whose vulnerability is largely unquantified and ii) parameters and attributes are chosen so as to identify structural deficiencies leading to recurring failure modes. This is important as it support quantification of fragility by means of analytical approaches. It also aids the identification of strengthening needs, in turn providing rational support for financial decision on risk mitigation.

3. School databases used for developing the GLOSI taxonomy

Analysis, comparison and identification of similarities and differences in the construction types and features of school buildings is necessary for the development of a comprehensive and globally applicable taxonomy. This section thus presents a summary of the databases and statistical distribution of construction features of public-school infrastructure from different parts of the world (Fig. 2). Table 1 presents the details of the public-school infrastructure databases used as the basis for the development of the GLOSI

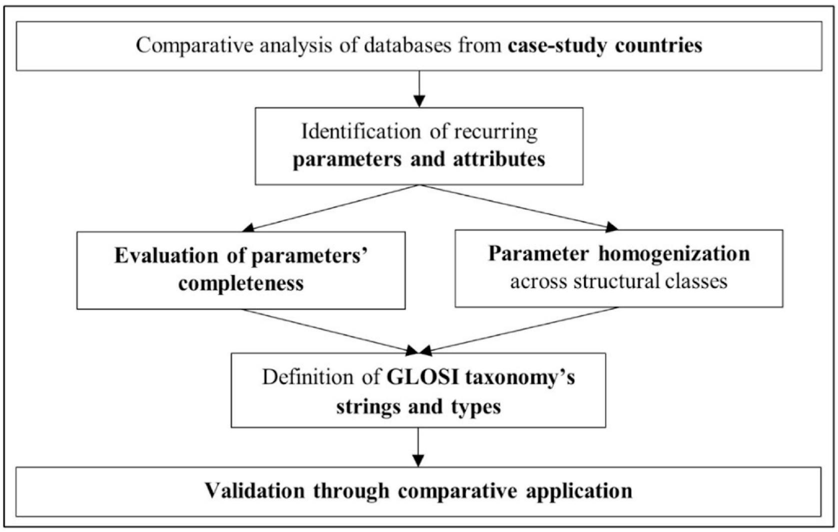

Fig. 1. Methodology for the development of the GLOSI taxonomy.

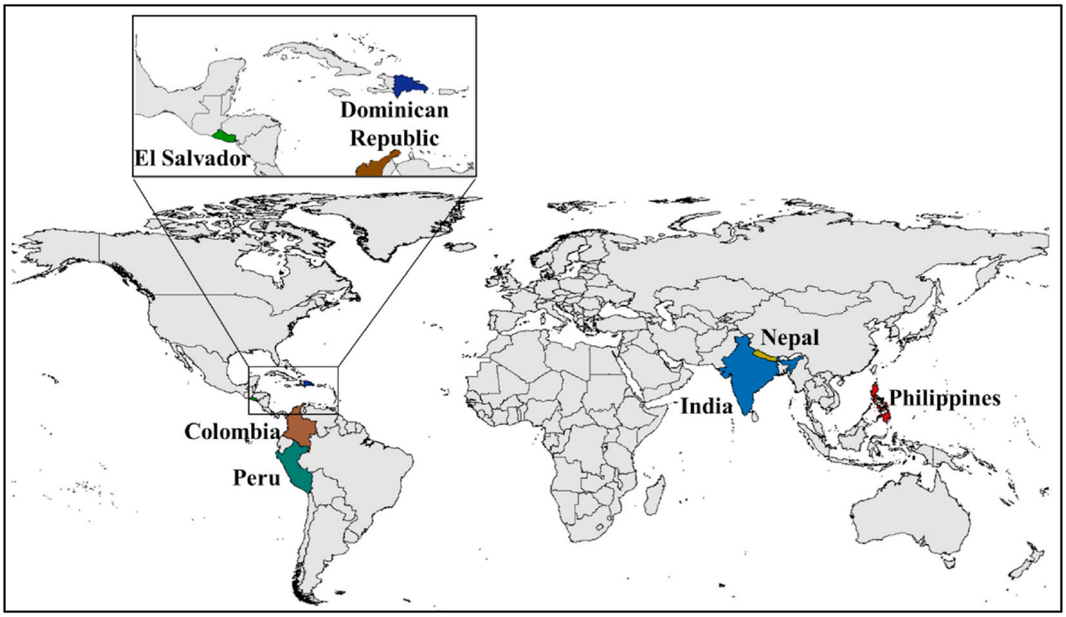

Fig. 2. Countries from which school infrastructure databases were studied in the development of the GLOSI taxonomy.

Table 1
Database of school infrastructure from different countries used in the development of the GLOSI taxonomy[1].

Country	Number of schools	Data level	Field survey[1]	References
Peru	~50,000	country-wide data	Yes	[4,31]
Nepal	~5750	represents country-wide data	Yes	[4,30]
Philippines	~84,000	country-wide data	Yes	[4,32]
El Salvador	~5180	country-wide data	Yes	[4]
Dominican Republic	~6000	country-wide data	Yes	[4]
Colombia (Cali)	~400	city level data (Cali municipality)	Yes	[4,33]
Kirgiz Republic	~78	representative sample from high seismic risk areas	Yes	[4,34]
India (Guwahati)	~500	representative sample from Guwahati city	Yes	[35]

taxonomy. In each of the database presented, detailed information at school building level is available, including photographs, plan and elevation sketches as well as other relevant construction features. The first four databases (i.e. from Peru, Nepal, Philippines and El Salvador) were used for the initial development of the taxonomy, while the next four were used for its testing and refinement. The reliability of the information in these databases was cross-checked and validated by the authors by carrying out field surveys of representative sample of school facilities in each country. For example, a field visit [29] was carried out in April 2018 in the Kathmandu valley and Kavre district in order to verify the reliability of the information in the SIDA (Structural Integrity and Damage Assessment) school database in Nepal [30]. Desk studies of the information in these databases were conducted in order to identify prevalent typologies, as presented in Figs. 3 and 4.

As evident from Fig. 3a, LBM and RC construction types together represent more than 80% of the school building portfolio in each of the case-study countries. For this reason, the GLOSI taxonomy is currently developed to be applicable to these two major construction types. Construction types in LBM school buildings include unreinforced, reinforced to confined masonry. In country such as Nepal, LBM school buildings are mostly unreinforced, with a range of masonry fabric types (see Fig. 3b) while in other countries such as El Salvador or Dominican Republic, modern masonry constructions, i.e. confined and reinforced masonry represents more than 80% of the portfolio [28]; 2020). Where the official databases allow, the proportion of different materials/structural systems found in school buildings is further disaggregated, for masonry structures in Nepal (Fig. 3b) and for RC frames in Peru (Fig. 3c). In both cases, significant presence of different materials/structural systems with substantially different level of expected vulnerability justifies the inclusion of the sub-types in the GLOSI taxonomy (see further in §4.1).

All case studies show a prevalence of single stories buildings (Fig. 4a). While LBM school buildings across the world are mostly single storied (see data for Nepal and El Salvador, more than 90% of the LBM schools are single storeyed [4], RC school buildings are commonly 2–3 storeys [30]. However, the available databases are not sufficiently detailed to allow reliable cross-correlation between structural typology and number of storeys. This is one of the reasons for a systematic approach such as the GLOSI taxonomy, whose application would allow to create comparable database/statistics at country level with respect to significant typologies.

As the seismic design codes are updated with time, the year of construction of a building has been usually considered as an

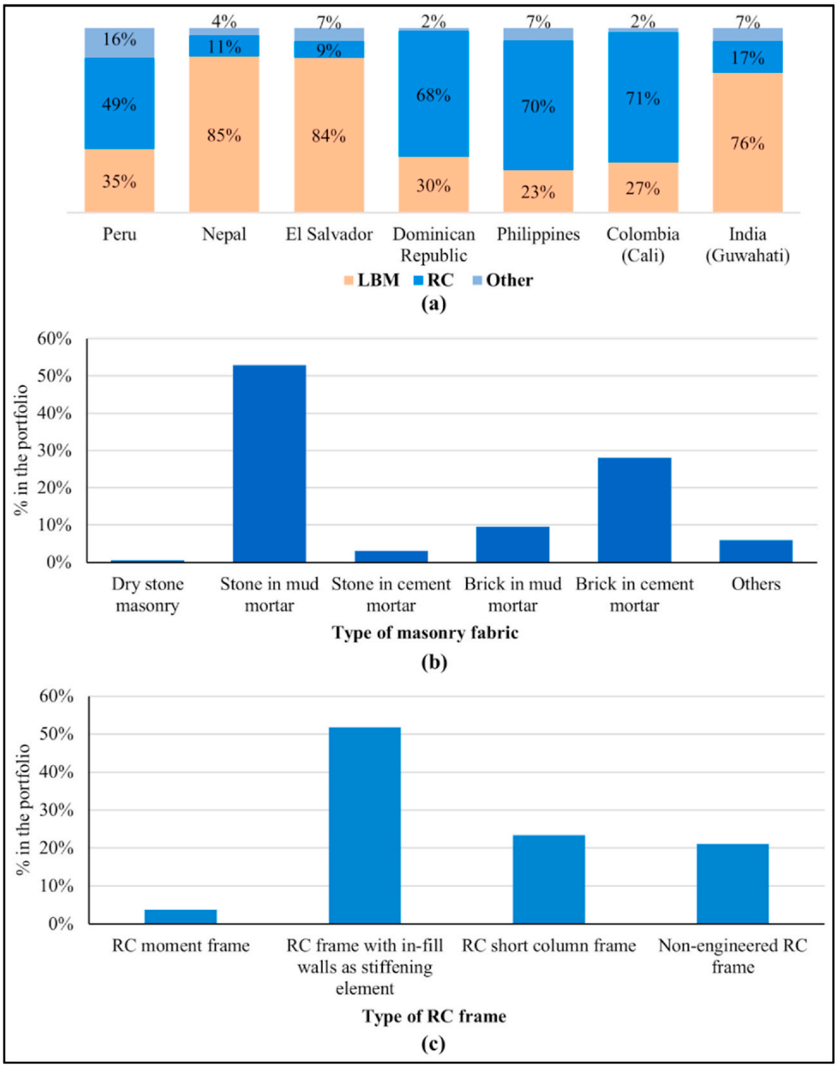

Fig. 3. Material and construction types: a) material of structural system across different countries, b) type of masonry fabrics in LBM school buildings from Nepal [30] and c) type of RC frames in school building in Peru [31].

indication of the seismic design level (Fig. 4b). Numerous revisions of the Uniform Building Code (UBC), first drafted in 1927, occurred during the two decades between 1970 and 1990, incorporating the theoretical and experimental advancements made during this period. As many national codes in low- and middle-income countries are based on the UBC code, these advancements were reflected in respective national codes, with some years of delay. Despite this, the code compliance in building construction also depends on the level of enforcement and knowledge/awareness of earthquake resistant design, which is seen lacking in community-led school building construction. For example, although the first versions of modern seismic design codes were drafted in 1994 in Nepal, as many as 70% of both RC as well as LBM school buildings in Nepal are non-engineered [30]. Thus, the use of year of construction is a useful guidance but not sufficient to categorize the seismic design level across different countries, and therefore the assessment of seismic design level requires explicit reference to the construction features present in the building, as elaborated further in §4.3.

As seen from Figs. 3 and 4, the three construction features i.e. material and structural system, building height and the seismic design level can be mapped for school buildings in most countries using the existing databases and literature. However, detailed information related to more technical construction features such as diaphragm type, irregularity, structural spans, openings' distribution, are not generally available in existing national databases, apart from few cases, e.g. the SIDA database for Nepal [30].

Based on the above discussion, the range of material types and construction features within and across different countries demand distinct and clearly defined parameters to completely identify the taxonomy of these school buildings. Thus, a number of distinct parameters and their attributes are presented and discussed in §4, also identifying the relative importance of these parameters on the

[1] The authors conducted detailed survey of a representative sample of the schools in selected locations of the case-study countries.

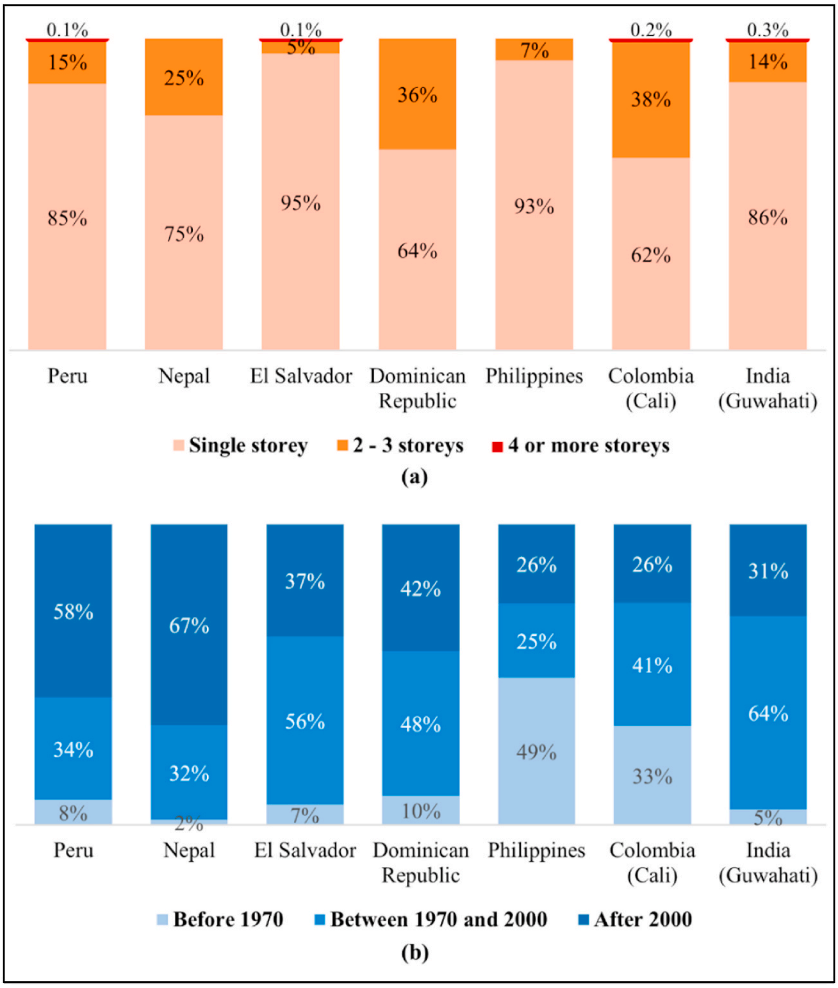

Fig. 4. Distribution of construction features of school buildings across different countries: a) number of storeys and b) year of construction.

vulnerability characteristics of school buildings.

4. Identification and definition of taxonomy parameters

Constructing a taxonomy is the process of identifying the materials, structural elements, layout, etc., that characterise a building's response to a natural hazard. For a taxonomy to be of global value, such parameters should be chosen so that they can equally describe any type of lateral load resisting system, whether frame or walls systems, but also able to correctly classify the details of the characteristics that determine difference or similarity in seismic response. The parameters should also be arranged in a hierarchical structure, from the more generic to more specific ones, so that specific typologies, described by a larger number of parameters, can be nested within classes described by a smaller number of key parameters. To achieve this and reflect the level of effort required in the data collection, Table 2 shows the parameters of the GLOSI taxonomy, subdivided in primary parameters (**in bold**) and secondary parameters. The significance of each parameter in characterising a building's seismic response is also provided. The primary parameters are the ones affecting and governing the anticipated seismic behaviour of a school building i.e. its main structural system, height range and the overall seismic design level. The relevant attributes of these parameters jointly define a *building class*. Furthermore, since the information required to identify these three parameters at school building level are usually available in the existing databases (see Fig. 4), the identification of *building class* at national level is usually straightforward.

The secondary parameters are a group of construction features, some specific to school buildings, which can modify the usual expected behaviour of a *building class* characterised by the three primary parameters. As listed in Table 2, these are differentiated in definition between frame structural systems and wall structural systems, although their role in the lateral response is the same. From the brief descriptions in Table 2, it can be noted that the parameters are mostly comparable to other globally used taxonomies, such as the GEM, HAZUS or SYNER-G [18–20]. However, there are two major differences with respect to the above references: the first is to consider in detail the constitutive elements of the masonry as well as the specific vulnerability indicators in masonry buildings. The second is the way in which the seismic design level is approached. Rather than referring to the year of construction, which in

Table 2
Taxonomy parameters identified for the GLOSI building taxonomy.

SN	Parameter	Description
P1	**Main structural system**	Identifies the construction materials and lateral load bearing system
P2	**Height range**	Identifies the number of storeys in the building that controls the dynamic response, vibration properties of the structure
P3	**Seismic design level**	Reflects the compliance with seismic codes if relevant and the quality of construction, including detailing, workmanship and material quality
P4	Diaphragm type	Identifies the roof/floor diaphragm behaviour (horizontal structures and their connection to lateral load resisting elements)
P5	Structural irregularity	Identifies variations of stiffness and strength properties in plan as well as elevation
P6	Wall panel length/Span length	*Wall panel length* - determines the typical unrestrained length of a wall panel between the cross-walls/buttresses/confining elements in LBM construction *Span length* - determines the typical clear span of a bay in RC construction
P7	Wall openings/Column type	*Wall openings* - determines the extent/distribution of openings within a typical wall panel in LBM construction, hence defining the relative stiffness between pier and spandrels *Column type* - determines the relative stiffness and strength between vertical and horizontal structural elements in RC construction
P8	Foundation type	Identifies the type and material of foundation structure as well the soil type of the site
P9	Seismic pounding risk	Identifies the damage susceptibility due to the difference in height of adjacent buildings
P10	Effective seismic retrofitting	Identifies the history of structural retrofitting on the structure (if any)
P11	Structural health condition	Identifies existing damage or deterioration in structures which can affect the seismic response
P12	Non-structural components	Identifies the hazardousness/vulnerability of non-structural elements

classification systems is taken as an indicator of compliance with the national seismic code of the time, in the GLOSI taxonomy, the design seismic level is explicitly defined through the analysis of specific construction details. This strategy is followed to account for cases in low- or middle-income countries, where school buildings might be built by communities or local builders, without technical support and reference to national structural building codes. A comparative discussion of the robustness and efficacy of the GLOSI taxonomy and the GEM taxonomy is presented in §5.

The three primary parameters along with their attributes are further discussed in §4.1, §4.2 and §4.3. This is followed by the discussion on 'failure mode determinant' secondary parameters in §4.4.

4.1. P1 – Main structural system

The main structural system depends on both the material and construction system and hence determines the stiffness, strength, and

Table 3
Attributes for *P1 – Main structural system* for LBM school buildings (Photos: GLOSI Repository [4].

		
A - Adobe	**URM4** - Brick in mud mortar	**CM** – Confined masonry
		
URM1 - Dry stone masonry	**URM5** - Rubble stone in cement mortar	**RM** – Reinforced masonry
		
URM2 - Rubble stone in mud mortar	**URM6** - Dressed stone in cement mortar	**SFM** - Steel framed with LBM walls
		
URM3 – Dressed stone in mud mortar	**URM7** - Brick in cement mortar	

the extent of ductility of the structure. The attributes of main structural system (P1) for LBM constructions are presented in Table 3.

In LBM constructions, the unit type and binding material (e.g., rubble stone in mud mortar, brick in cement mortar) and the resulting masonry fabric greatly affect the seismic performance [36–39]. Compared to lime or cement-based mortar, mud mortar is weaker, exhibiting poor bond, cohesion and frictional strength; essential in determining resistance to lateral forces together with the level of connection among walls [29,37,40,41]. Similarly, bricks or dressed stone provide better workmanship hence integrity as well as improved frictional resistance compared to irregular shaped rubble units [29]. Therefore, different combinations of units and mortar lead to different typologies [17] and consequently different fragility and vulnerability functions and hence is reflected in the GLOSI taxonomy, by considering seven distinct masonry fabric types of URM (URM1 to URM7) as listed in Table 3.

Compared to URM, seismic performance is substantially improved if the masonry is confined or reinforced. Therefore, confined masonry (CM) and reinforced masonry (RM) are considered as distinct *building classes*, as shown in Table 3. In CM construction [42], the walls are confined with tie-beams and tie-columns, and the walls are generally built of brick units in cement mortar. Similarly, in RM construction, the walls are reinforced in vertical and horizontal directions for improved flexural and shear capacity [43]. There is another category of LBM buildings which are built along with a light steel frame, named as steel framed masonry (SFM). In these buildings, the light steel frame is built mainly for supporting the roof structure and the frame-wall connection is poor. As high as 28% of the national portfolio of school buildings in Nepal belong to SFM category with URM walls [30]. SFM school buildings are also found in El Salvador but with RM or CM walls [28]. Accordingly, different sub-attributes of SFM category can be classified, resulting in distinct fragility and vulnerability functions. More details on these can be found in the GLOSI repository [4].

The attributes of main structural system (P1) for RC constructions are presented in Table 4. The seismic response of RC framed structures is governed by the relative capacity of columns to beams and also by the stiffness of the infill walls. Based on the information in the databases across several countries (refer to §3), the GLOSI taxonomy identifies five different basic configurations of structural systems for RC school buildings, as shown in Table 4. RC1 represents the buildings with RC moment resisting frames without masonry infill walls or with isolated infill walls that are separated from the columns by expansion joints and therefore do not interact with the RC frame behaviour. RC2 is the category in which the infill walls act with the frame as stiffening elements as the infills are not separated from the RC frames. In RC2 structures, the masonry infill walls run full storey height (no horizontal window below the upper beam). The RC3 type includes the buildings where the infills walls are partial (usually forming a horizontal window) without reaching the full storey height, resulting in a configuration that generates captive column or short column effect [44]. The next category, RC4 are combined or dual systems which include mixed lateral load resisting systems, usually a reinforced concrete MRF stiffened with steel braces or RC walls. Finally, RC5 represents RC construction types without standard structural system i.e. non-engineered community-led constructions.

Besides building with dual systems, as classified in RC4, it is possible to find school buildings with a combination of RC3, presenting window openings in the long direction, and RC2 in the short direction. In such cases, the initial classification can consider the more vulnerable typology, or alternatively provide a classification for each of the two principal directions of the structure.

4.2. P2 – height range

The number of storeys affects the vibrational modes and periods of a building under earthquake excitations. Compared to low-rise buildings, buildings with more storeys are more flexible and therefore subjected to greater lateral displacement. Moreover, higher

Table 4
Attributes for *P1 – Main structural system* for RC school buildings (Photos: GLOSI repository [4]).

RC1 – Bare RC frames

RC2 – RC frames with masonry infill walls

RC3 - RC frames with masonry infill walls generating short column effect

RC4 - Combined or dual systems

RC5 – RC non-engineered

Table 5
Attributes for *P3 – Height range.*

Taxonomy parameter	Attributes	Commentaries
Height Range	**LR** - Low Rise **MR** - Mid Rise **HR** - High Rise	- LR: single storey - MR: 2 to 3 storeys - HR: 4+ storeys (Exact number of storeys to be given in the bracket)

mode effects also contribute to seismic vulnerability as the building height increases. Since single-storied school buildings are most common (refer to Fig. 4) and distinct to multi-storied buildings in terms of seismic demand and damage [45], this study uses three uniform categories for both LBM and RC school buildings: low-rise (single-storeyed), mid-rise (2–3 storeys) and high-rise (4+ storeys) including up to 6 storeys (Table 5).

4.3. P3 – seismic design level

In the GLOSI taxonomy, the seismic design level is defined as the ensemble of structural solutions and details which characterise the basic lateral response of the structure. These might be as a result of the compliance with a specific seismic code or guidelines in force in the country or determined by good construction practices not explicitly codified. Hence, the quality of the construction including workmanship, material quality, connectivity among structural elements as well as at global building level collectively define the seismic design level which is one of the key parameters affecting the lateral seismic capacity. For the URM class, irrespective of the masonry constituents, a building is well-designed if it meets the following requirements: it has a strong masonry bond pattern (e.g. English bond) and workmanship in walls construction; the cross-walls are well connected to each other and also to the horizontal structures; the latter have adequate in-plane stiffness. The design at wall level involves the use of good quality units and mortar, provision of strong masonry bond pattern, proper connection between wythes [46]. Similarly, the seismic design at global building level is governed by the provision of corner quoins/stone and horizontal seismic bands such as lintel band, sill band and roof bands [47]. These details, which can be observed on site, are reflected in the attributes chosen for this parameters, which identifies four levels of seismic design, from poor design level (PD), when minimum integrity is not assured, to high design level (HD) when proper connections and seismic bands are present (Fig. 5). Knowledge of the seismic resistant construction culture in the country of interest and its evolution are also vital to determine the presence of some of these details in the school building portfolio.

In CM buildings, the density and arrangement of confining elements is the major driver of seismic performance as discussed in detail in [48]. For example, in CM schools in El Salvador [28], the density of RC confining element includes elements around the openings; while in India and Indonesia, confined masonry school have lower confinement density and openings are not confined [48,49]. Three major features generally affect the seismic design level of CM buildings: 1) the distribution and density of confining elements, 2) the quality of connections between masonry and confining elements and 3) the density of the walls in two orthogonal directions. The specific threshold of the three criteria defining each design level is chosen so that the deficiencies of partially confined masonry constructions (Fig. 6a) are accommodated in the taxonomy, as well as code-conforming CM constructions (e.g. Fig. 6b) around the world. Similarly, in RM buildings, the presence and layout of vertical and horizontal steel reinforcement affect the seismic design level. The issue however in the RM case is the difficulty of identifying the reinforcement details from visual observation only unless structural drawings are available.

In case of RC buildings, common expectation is that these would have been designed to the national code of the time. Therefore, the seismic design level is considered poor for structures designed for gravity loads only. These are common in several seismic prone countries, either because built prior to the enforcement of seismic codes, such as in Perú and Nepal or because of being community-led construction [30,31]. Following ACI 318–19 [50], low design level detailing will be comparable with ordinary moment frames provisions, medium design level with intermediate moment frames provisions and high design level to special moment frames provisions. Also, structures designed for low seismic hazard zones would commonly be low design level, structures designed for medium hazard zone would be medium design level and structures built in high seismic hazard zones would be high design level (PGA values follow ASCE 7–16 seismic categories). The poor and low design cases are most likely to have low lateral capacity and brittle collapse mechanism, compared to medium design and high design cases which have better lateral capacity and ductile collapse mechanisms. To illustrate this, Fig. 7 shows two pictures of RC school buildings, one with poor design (PD) and the other with high design (HD). The PD case (Fig. 7a) is a non-engineered building with column dimensions less than 20 cm while the HD case (Fig. 7b) is an engineered building as per the prevailing codes, column dimensions are greater than 30 cm and masonry infill walls are well isolated from the RC structure.

The definition and details which identify the four attributes of seismic design level for URM, CM and RC buildings are summarised in (Table 6).

For large portfolio of school buildings, the assignment of the attributes for the seismic design level might require engineering expertise and time. In the first instance, the seismic design level could be defined from the age of construction or the seismic hazard zone, for compliant structures. However, as the application experience of the taxonomy for the classification and seismic risk assessment of school buildings in El Salvador and Dominican Republic [28,51] shows, desktop study of prevalent typologies as per

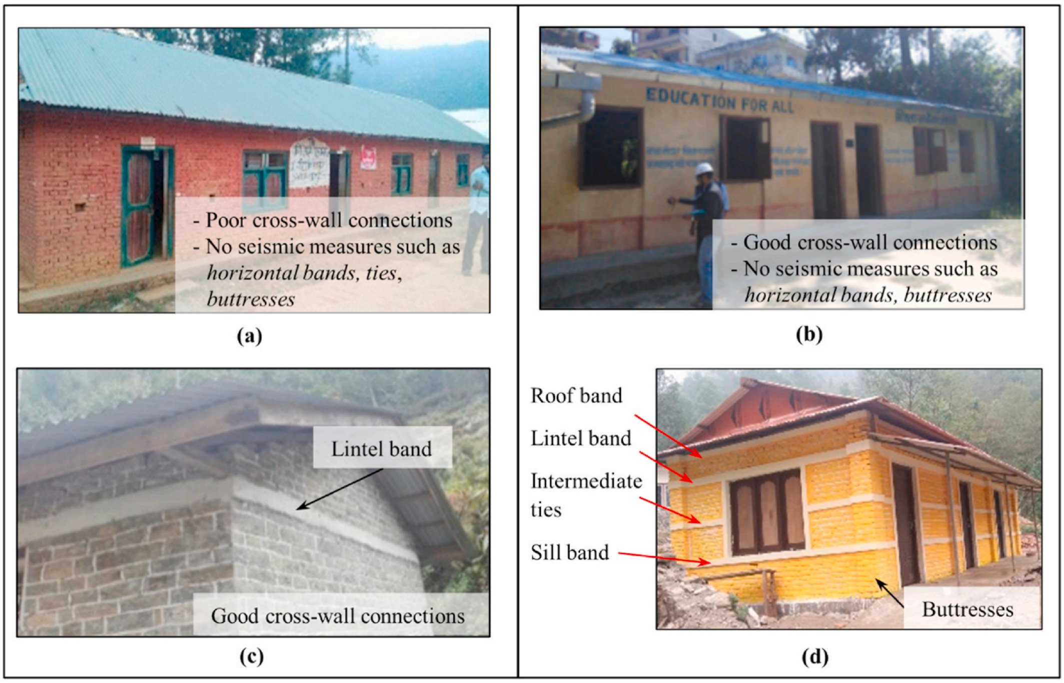

Fig. 5. Example photographs of URM school buildings with a) 'Poor', b) 'Low', c) 'Medium' and d) 'High' seismic design levels. (Photos from Nepal [30]).

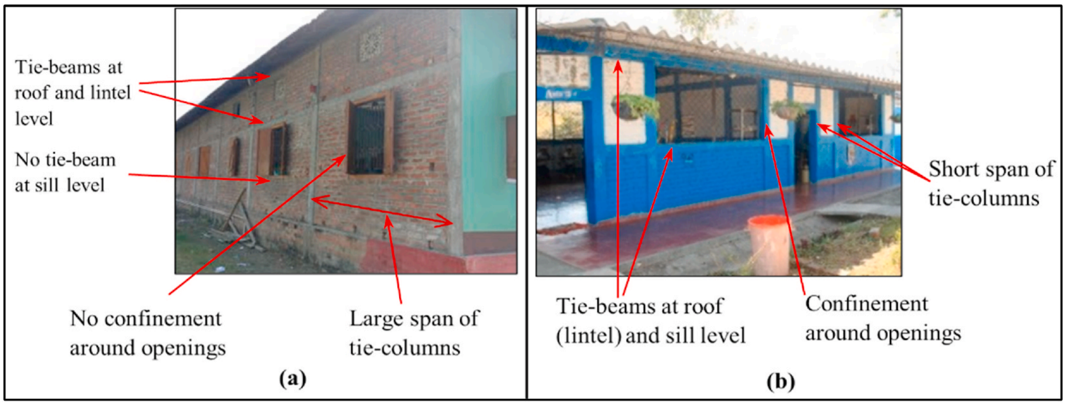

Fig. 6. Example photographs of CM school buildings with a) 'Poor' seismic design level (Photo from India [48] and b) 'High' seismic design level (Photo from El Salvador[28].

specific country level educational infrastructure programmes, together with targeted field surveys of representative buildings, and local expertise of the national construction practices are sufficient to reliably assign correct design levels.

4.4. Secondary parameters

The nine secondary parameters (P4 – P12) listed in Table 2 play important roles in modifying the expected seismic behaviour of a *building class* defined by the primary parameters and consequently completely defining the *index buildings* which are representative models of a particular *building class*. Being of particular relevance to school architecture, a discussion on two of these parameters is included here: the 'Wall panel length/Span length' and the 'Wall openings/Column type'. These parameters, although differently defined for URM, CM and RC typologies, have similar role, and their geometric dimensions determine the structural behaviour of the resisting elements, failure modes as well as the global lateral response. Consequently, as their attributes require engineering judgement and calculations, these are briefly described in §4.4.1 and §4.4.2. The other secondary parameters (included in Appendix A) are explicit and their attributes selection straightforward. Nonetheless, it is noted that the parameter 'P10 – Effective seismic retrofitting' needs in-depth assessment of the details of the retrofitting and its contribution to seismic resistance, if its attribute is 'Yes'. Moreover, it can influence several parameters including 'P1 – Main structural system', 'P3 – Seismic design level' and possibly others. In this case such scoring outcome would then trigger a more detailed review of the typology corresponding to the taxonomy string. Similarly, the

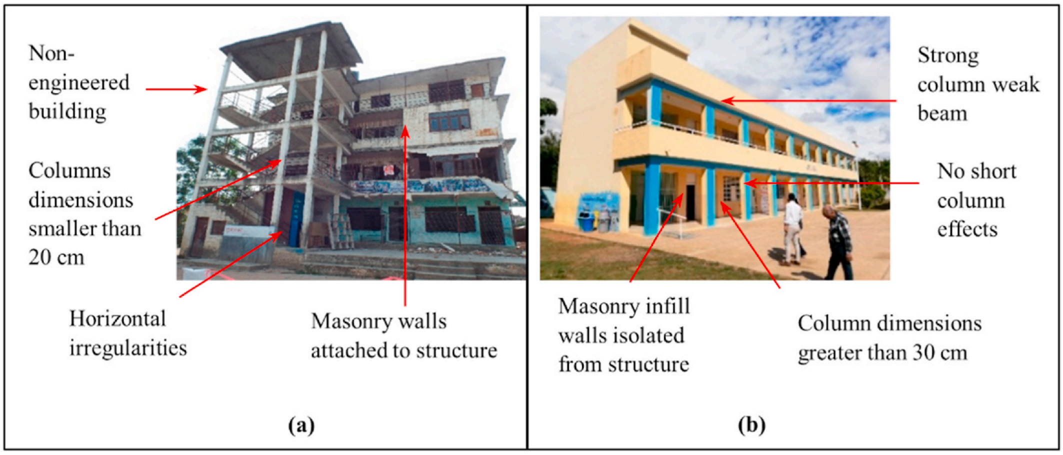

Fig. 7. Example photographs of RC school buildings with a) 'Poor' seismic design level (Photo from Nepal [30]) and b) 'High' seismic design level (Photo from Dominican Republic [51].

Table 6
Attributes for *P3 – Seismic design level.*

Taxonomy parameter	Attributes	Commentaries
Seismic design level	**PD** - Poor Design **LD** - Low Design **MD** - Medium design **HD** - High design	For URM buildings - **PD**: Community led non-engineered constructions without any seismic enhancement measures (see Fig. 5a). - **LD**: Minor seismic improvement measures (i.e. through stone, corner stone or ties) mainly at wall level (see Fig. 5b). - **MD**: Minor (e.g. through stone, corner stone or ties) and few major seismic improvement measures (i.e. buttresses, lintel band above openings) (see Fig. 5c). - **HD**: All minor and major seismic improvement measures (lintel band above openings, roof band, gable band, intermediate ties) (see Fig. 5d). For CM buildings: - **PD**: Minimum confinement ratio, including plinth and floor band, is satisfied but there is poor connection between walls and confining elements and poor wall density (see Fig. 6a). - **LD:** Minimum confinement ratio and the wall density are sufficient, but there is poor connection between walls and confining elements. - **MD**: Minimum confinement ratio and wall density are sufficient and there is good toothing between walls and confining elements. - **HD**: Toothing, wall density and confinement are in compliance with international guidelines and best practice, including full vertical confinement of opening and sill and lintel bands (see Fig. 6b). For RC buildings: - **PD:** Community led non-engineered construction mainly built to withstand gravity loads and have low resistance to lateral loads (see Fig. 7a). - **LD:** Designed for low seismic loads; joints not seismically detailed; spacing of stirrups $\geq d/2$, d being the distance from the extreme fibre in compression to the centroid of the longitudinal reinforcement in tension; dimensions in structural elements >20 cm; low seismic capacity and brittle failure mechanism. - **MD:** Designed for a medium seismic hazard zone; joints seismically detailed, spacing of stirrups $\leq d/2$; minimum dimensions in structural elements >25 cm; better lateral capacity and ductility, hence ductile collapse mechanism expected. - **HD: D**esigned for a high seismic hazard zone; joints seismically well detailed; spacing of stirrups $\leq d/4$; minimum dimensions of structural elements >30 cm; high lateral capacity as well as ductility, hence ductile collapse mechanism expected (see Fig. 7b).

assessment of parameter 'P11 – Structural health condition' while expressed in a qualitative manner, responds to the need of identifying further vulnerability associated with existing damage and deterioration. Presence of cracks, spalling of concrete or exposed rebars; obvious signs of further deficiencies, are easy to identify on site or from photographs.

4.4.1. P6 – Wall panel length (LBM)/Span length (RC)

4.4.1.1. URM buildings. In URM buildings, the out-of-plane vulnerability of a wall panel is directly proportional to its unrestrained length. This is because of their low bending moment capacity in out-of-plane direction [52,53], which is more pronounced when the

Table 7
Attributes for *P6 – Wall panel length* (LBM) and *Span length* (RC) parameters.

Taxonomy parameter	Attributes	Commentaries
LBM: Wall panel length	**SP** – Short panel **LP** - Long panel	- SP when the wall length is ≤ 12 times the wall thickness, otherwise LP
CM: Wall panel length	**SP** - Short panel **LP** - Long panel	- SP when the wall length between confining columns (l) ≤ 3 m for wall thickness ≤110 mm, l ≤ 4 m for wall thickness ≤250 mm, otherwise LP
RC: Span length	**SS** - Short span **LS** - Long span	- SS when the span length is up to 6 m, otherwise LS

building lacks box-like global behaviour [54]. As an example, during the 2008 Wenchuan earthquake in China, a dormitory with smaller rooms i.e. shorter panel lengths survived while the adjacent main classroom building of a primary school, of same construction type but with larger rooms, collapsed [22]. Thus, the wall panel lengths are classified into two categories: long panels and short panel (see Table 7).

4.4.1.2. CM buildings. In CM buildings, the tie-columns' spacing determine the wall panel length, which assume the same role of restraint as cross-walls in URM structures, to limit out-of-plane failure mechanisms. Different national codes recommend different upper limits for the CM panel length: the Peruvian code [55] recommends 5 m spacing whereas the Chilean code [56] allows up to 6 m. Guidelines from Mexico [57], Colombia [58] and Indonesia [59] restrict spacing to 4 m. The Indian Code [60] provides rules related to the thickness of the wall, which are somewhat more conservative, and these have been assumed as reference in the GLOSI taxonomy, as summarised in Table 7.

4.4.1.3. RC buildings. The span length between columns in RC buildings is an indicator of general dimensions and vulnerability. It measures the distance between successive columns and identifies the flexibility of the frame. Studies have shown that larger spans (more than 6 m) influence the fragility of the building, increasing the exceedance probability of extensive and collapse damage states [61]. Although larger spans mean larger structural elements in recent designs, the elements are often undersized and three-dimensional effects are not taken into account in the design of older structures [24], generating high deflections and collapse mechanisms when spans are too large. Therefore, span length up to 6 m is categorised as short span while more than 6 m is considered long span, as shown in Table 7.

4.4.2. P7 – Wall openings (LBM)/Column type (RC)

4.4.2.1. URM buildings. The size, amount and layout of opening in walls govern the size of piers and spandrels, which in turn affect the lateral strength and seismic behaviour of masonry buildings. Openings in LBM walls reduce its in-plane capacity and stiffness and promote crack initiation and propagation at the corners of the openings. Large openings also result in weak and slender piers and spandrels (Fig. 8). To minimize the seismic damage, seismic codes usually recommend the openings to be located at a minimum clear distance from the top and ends of the wall and if unavoidable, to be reinforced [62].

For the GLOSI taxonomy, the openings are classified as either small or large opening, depending on the extent of openings within a typical wall panel (see Fig. 8). For URM buildings, the opening is small if the total width of the openings in a restrained wall panel is less than 50% of the panel length and it is large when the combined total width of the openings is equal to or more than 50% of the panel length. This is based on the study of the opening characteristics in the URM school buildings from the case study countries (refer to §3).

4.4.2.2. CM buildings. In CM wall panels, the size of masonry piers plays key role in the seismic response, and presence of openings reduces the pier width. National building codes usually prescribe thresholds on the opening size beyond which confinement of the openings is necessary in order to compensate the reduction in lateral capacity. For example, the Colombian code [58] recommends that an unconfined opening area of up to 35% of the wall area is acceptable, whereas the Peruvian code [55] allows the total length of unconfined opening to be up to half the length of the wall panel. The Mexican code [57] recommends confinement of the opening if the opening's horizontal or vertical dimension exceeds 25% of the wall length, or 600 mm. Thus, in the GLOSI taxonomy, following a more stringent criteria, an unconfined combined area of openings less than 10% of the wall panel is considered as small Opening (SO) which can be left unconfined without any significant impact in the seismic capacity. In addition to this, horizontal and vertical dimensions of the openings shall be limited to no more than one third of the respective dimensions of the CM wall panel. Nevertheless, it is usually required to have larger openings for ventilation and natural lighting in school buildings. Hence, to recognise such architectural requirements in schools, large openings are further classified into two sub-classes: Large Opening with Confinement (LOC) (see Fig. 9) and Large Opening with No confinement (LON), as summarised in Table 8.

4.4.2.3. RC buildings. In RC buildings, the columns being equivalent to the piers in LBM buildings, play a vital role in the lateral capacity of the building. Seismic design codes usually recommend minimum dimensions for columns and beam [50,63] and also recommend the relative capacity of columns with respect to beams. Considering this, the 'Column Type' parameter helps to understand

Fig. 8. Definition of opening percentage in URM buildings.

Fig. 9. Example CM building with LOC type of openings.

Table 8
Attributes for *P7 – Wall openings* (LBM) and *Column type* (RC) parameters.

Taxonomy parameter	Attributes	Commentaries
URM: Wall openings	**SO -** Small Opening **LO -** Large Opening	- SO if the combined total opening width in a wall panel <50% of the panel length; otherwise, LO
CM: Wall openings	**SO** - Small Opening	- SO if the combined total area of openings in a wall panel ≤10% of the CM panel area
	LOC - Large Opening with Confinement	- LOC if the total area of confined openings in a wall panel >10% of the CM panel area
	LON - Large Opening with No confinement	- LON if the combined total area of openings without confinement in a wall >10% of the CM panel area
RC: Column type	**WC -** Weak Column **SC -** Strong Column	- For RC frames, SC criteria is met when: * The column depth ≥ the beam depth * $\frac{h_c}{0.3\,x\,d_c} \leq 22$ (ACI 318–19), where h_c and d_c are the height and depth of the column

the RC structures if the weak-storey collapse mechanism can be triggered. When there are Weak Columns (WC) i.e. cross-section of columns is smaller than the cross-section of beams, this can lead to a weak- or soft-storey failure mechanism. Conversely, when the column cross-section is larger than that of the beam, it is Strong Column (SC) relative to the beam and the RC frame is expected to comply with the strong-column weak-beam requirement [64] where the failure mechanism involves the beams in the upper storeys thus a more ductile type of failure is expected. Fig. 10 presents two different column-beams connections for illustrative purpose. Table 8 presents the attributes of wall openings for URM and CM buildings and the column type for RC buildings.

5. Application and verification of the GLOSI TAxonomy

To demonstrate the ease of use and the consistency in identifying appropriate levels of vulnerability, this section presents the application of the GLOSI taxonomy to a range of construction types and their construction features from different countries. This also

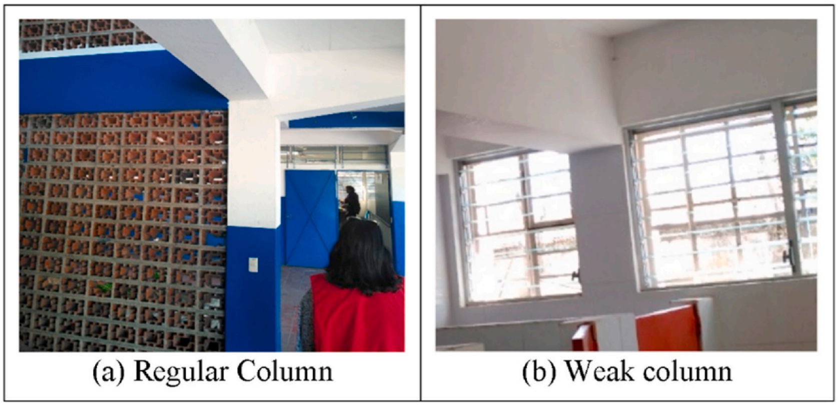

Fig. 10. Column types in RC buildings.

provides an indirect proof that the vulnerability curves for school buildings derived for one country are applicable to other countries, given the construction typologies have similar taxonomic strings. This can become a valuable resource when producing country level seismic risk profile, common practice for the global financial institutions when deciding on support for disaster risk reduction projects. More examples of applications of the taxonomy are included in the GLOSI repository [4].

Table 9 presents a comparison of the GLOSI taxonomy strings of URM buildings from Nepal, CM buildings from El Salvador and India, and RM buildings from El Salvador and Dominican Republic. With respect to the URM typology (first row in Table 9), the URM2 typology has a 'rubble stone in mud mortar' fabric, while the URM7 typology has a 'brick in cement mortar' fabric. Both are single storied and have low seismic design level (LD) because of the lack of any horizontal seismic bands, as these are community-led non-engineered constructions. Moreover, both typologies have the same attributes for all secondary parameters: flexible diaphragm (FD) i.

Table 9
Application of the GLOSI taxonomy to LBM school buildings from different countries (Photos: GLOSI Repository [4].

Unreinforced masonry (Nepal)
URM2/LR/LD/FD/NI/SP/SO/RF/NP/OS/PC/VN

Unreinforced masonry (Nepal)
URM7/LR/LD/FD/NI/SP/SO/RF/NP/OS/PC/VN

Confined masonry (India)
CM/LR/MD/FD/NI/SP/LON/RF/NP/OS/GC/NN

Confined masonry (El Salvador)
CM/LR/HD/FD/NI/SP/LOC/RF/NP/OS/GC/NN

Reinforced masonry (Dominican Republic)
RM/LR/LD/FD/NI/SP/LO/RF/NP/OS/PC/NN

Reinforced masonry (El Salvador)
RM/LR/HD/FD/NI/SP/LO/RF/NP/OS/GC/NN

e. light and poorly connected timber roof structure; no irregularity (NI) i.e. rectangular plan shape; short wall panels (SP); small wall openings (SO); stonework in foundation extending more than 0.5 m deep, hence rigid type foundation (RF); no presence of nearby buildings within a meter distance, hence no pounding risk (NP); no retrofitting, i.e. original structure (OS); poor structural health condition (PC), due to material deterioration; both buildings present unsecured gables i.e. vulnerable non-structural components (VN). Therefore, the relative vulnerability of these two typologies is entirely related to their difference in masonry fabric. As brick in cement mortar, URM7, has better shear capacity than rubble stone in mud mortar, URM2, the latter can be expected to be more vulnerable [37]. The qualitative comparison of taxonomy strings is confirmed by their vulnerability functions analytically derived using the GLOSI methodology [4] based on the modified N2 method [27] (Fig. 11a). For the URM2, $PGA_{50\%\ MDR}$, defined as the Peak Ground Acceleration (PGA) capacity for 50% Mean Damage Ratio (MDR), is 40% less than the corresponding for the URM7. This shows how the different masonry fabric type i.e. the attribute of the first GLOSI taxonomy parameter result in significantly distinct vulnerability functions.

Similarly, CM building types from India and El Salvador are compared in the second row of Table 9. While both are single storied i.e. LR buildings, there is difference in their seismic design level. The Indian CM school building has satisfactory level of confinement, but the flexible diaphragm does not have bracing, so it belongs to the MD category, while the CM building in El Salvador has better confinement of the panels and stiffening of the diaphragm, so that it can be classified as High Design (HD).

Furthermore, the secondary parameters reveal differences in the confinement of the openings: the Indian CM case has large openings without confinement (LON) while the El Salvador CM case also has large openings but with confinement (LOC). These differences highlight lesser vulnerability of the El Salvador case than the Indian case. Such qualitative conclusion is confirmed by computing their vulnerability functions, as compared in Fig. 11b, the $PGA_{50\%\ MDR}$ capacity for the CM/LR/HD building type from El Salvador being 25% more than that of the CM/LR/MD building type from India.

Finally, two different RM buildings from Dominican Republic and El Salvador are compared in the third row of Table 9. Both of these RM buildings are single storied. The RM building from El Salvador is constructed as per the prevalent seismic design codes i.e. the walls are reinforced vertically (600 mm c/c) and horizontally (400 mm c/c) at regular spacing, and the building has an RC ring beams at the roof level. Hence the seismic design level is high (HD). On the other hand, the RM building from Dominican Republic has masonry walls with a vertical reinforcement spacing of 800 mm, and no horizontal reinforcements. Furthermore, there is no ring beam at the roof level, hence the seismic design level of this building is low (LD). In terms of the secondary parameters, the attributes for both buildings are the same except for the structural health condition: the one from the Dominican Republic has deteriorated material quality (PC). Hence, the seismic performance of the RM/LR/HD building type from El Salvador is expected to be significantly better than that of the RM/LR/LD building type from Dominican Republic. This is shown by quantitative comparison of their vulnerability functions in Fig. 11c: the $PGA_{50\%\ MDR}$ capacity of the RM/LR/HD *building class* from El Salvador is 140% more than that of the RM/LR/LD *building class* from Dominican Republic.

Table 10 presents the application of the GLOSI taxonomy to RC school buildings typologies from different countries. In terms of diaphragm type, the most common attribute is rigid diaphragm as the floors/roof are RC slab constructions. Based on the taxonomies presented in Table 10 and the structural characteristics of each building, the GLOSI approach [4] was implemented to derive the corresponding vulnerability function for each *index building*, as presented in Fig. 12 for all the six *index buildings*. In contrast to the representation of the intensity measure (IM) by PGA in the LBM cases, IM in the RC cases is represented by the first mode spectral acceleration Sa (T1). This is because of the longer first mode period of RC buildings, compared to those of the masonry buildings, making Sa(T1) for RC buildings considerably higher than PGA. Since Sa(T1) values are structure dependant, it is noted here that the RC vulnerability functions are not directly comparable unless a location specific risk assessment study is conducted.

First, the vulnerability functions for two different RC1 MRFs from the Dominican Republic (first row Table 10), without masonry infills are compared: a single-storey (LR) and a two storeys (MR) typology. From Fig. 12a, it is evident that the vulnerability functions for low-rise and mid-rise RC1 buildings are similar, with slightly increased vulnerability (10%) of the mid-rise building as expected. The RC MRFs with masonry infills (RC2) are represented by a case in Colombia and another in the Philippines with similar scoring except for the 'Column type' parameter. For RC2, Fig. 12b shows the effect of this parameter, with a greater level of vulnerability for the Philippines typology, the $PGA_{50\%\ MDR}$ capacity for the Colombia case being almost 100% higher compared to the Philippines case. This is influenced by the relative quality of the infill masonry as well, producing initially stiffer but more fragile behaviour for the Philippines case, leading to a soft storey mechanism.

Finally, the vulnerability functions for the two different RC MRFs with masonry infills and short column effect (RC3), one each from Dominican Republic and El Salvador, are classified in the third row of Table 10 and their vulnerability curves are compared in Fig. 12c. While the quality of masonry infills also affects this category, the difference in vulnerability functions noted for these two typologies (the $PGA_{50\%\ MDR}$ capacity for the El Salvador case being almost 100% higher compared to the Dominican Republic case) is due to the different levels of seismic design, LD for Dominican Republic, compared to MD for El Salvador, attributed to the substantial difference in dimension of the columns, the level of shear reinforcement detailing and the presence of cantilever elements.

Thus, the comparison of the taxonomy strings as well as the results of detailed vulnerability assessment on similar building types from different countries provides clear evidence of the applicability, significance, and reliability of the GLOSI taxonomy. Readers are referred also to other published works by the authors [5,29,48], where thorough sensitivity analyses for most of the taxonomy parameters can be found.

Furthermore, in order to show the distinct features, robustness and efficiency of the present GLOSI taxonomy compared to taxonomies in the literature, a comparative discussion of the application of GLOSI taxonomy and the widely used GEM taxonomy [18] is presented. The confined masonry school buildings from El Salvador as shown in Table 9 is considered for this comparison. The strings obtained from the application of GLOSI taxonomy and GEM taxonomy for this building are given in Table 11. An apparent observation

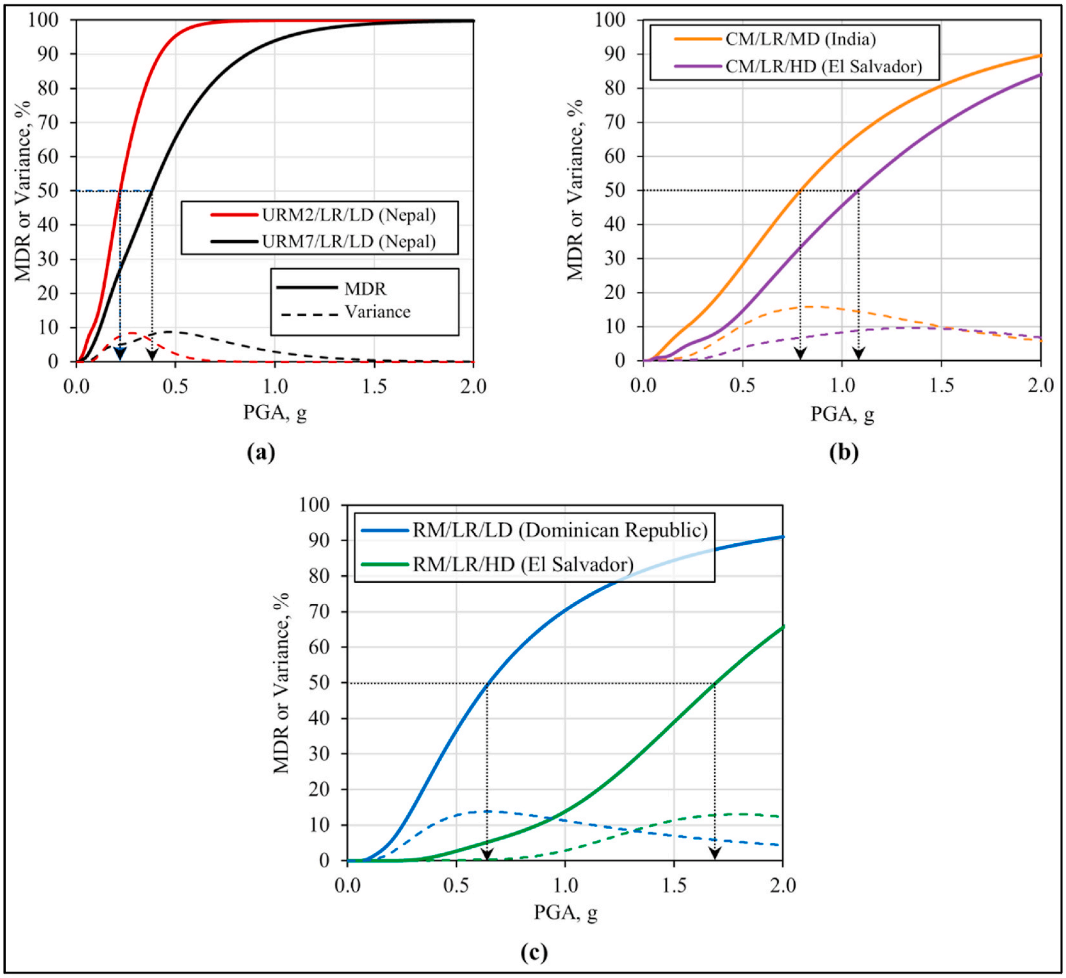

Fig. 11. Comparison of seismic vulnerability functions for LBM school *building classes* from different countries: a) URM, b) CM and c) RM. The continuous line and dotted line represent the MDR and its variance, respectively.

is the length of the string: the GLOSI taxonomy only yields a 12-attribute string while the GEM taxonomy produces a string with more than 20 attributes. This is because the GOLSI taxonomy articulates well several relevant attributes nested into distinct parameters. For example, a single parameter 'Diaphragm type' is used in the GLOSI taxonomy to accommodate the roof/floor material and structure as well as the connection roof/floor to vertical structure. On the contrary, the GEM taxonomy considers all of these elements as individual attributes.

Also, as identified in §4.1, each main typology (i.e. URM, RC) is divided into several structural sub-types, as it is widely recognised that each of these exhibit distinct seismic behaviour and vulnerability. Such detailed account of structural systems is not considered in the GEM taxonomy. With respect to the seismic design level, a key parameter controlling the seismic performance, GEM taxonomy does not account for the relevant construction features and refers to the year of construction or retrofit as a measure of seismic design level. However, the seismic design level in school buildings is not always the direct reflection of the seismic design codes available in the country, as evidenced in several countries such as Perú and Nepal [30,65]. Moreover, in the GLOSI the presence of retrofit is treated as a separate parameter, to identify the original design level and the possible improvement as discussed in §4. Specific to the CM building shown in Table 11, the seismic design level is affected by the construction features such as wall density, amount/spacing of RC tie-columns and tie-beams, provision of toothing at RC-masonry interface; which are collectively represented by the 'HD' attribute of the 'Seismic design level' parameter in the GLOSI taxonomy string in Table 11 (see also Table 6), while the construction year '1990' in the GEM taxonomy string does not provide any details of the seismic detailing in the structure. Moreover, the specific parameters that readily identify vulnerability in school buildings such as the 'Wall panel length' for out of plane vulnerability in masonry buildings or the size of 'Wall openings' has not been considered in the GEM taxonomy. Hence, it can be concluded that, while the GEM taxonomy is flexible and applicable for many structural types and at different scales, it does not have the resolution and direct link to seismic vulnerability assessment achieved through the GLOSI taxonomy.

Thus, the GLOSI taxonomy allows uniform and coherent understanding as well as quick comparison of reliable vulnerability characteristics of school buildings worldwide, by synthetically identifying similarities and differences. Moreover, the taxonomy can

Table 10
Application of the GLOSI taxonomy to RC school buildings from different countries (Photos: GLOSI Repository [4].

RC1 (Dominican Republic)
RC1/LR/HD/RD/NI/SS/WC/RF/NP/OS/GC/VN

RC1 (Dominican Republic)
RC1/MR(2)/HD/RD/NI/SS/WC/RF/NP/OS/GC/NN

RC2 (Colombia)
RC2/MR(2)/MD/RD/NI/SS/SC/RF/PR/OS/GC/VN

RC2 (Philippines)
RC2/MR(2)/MD/RD/NI/SS/WC/RF/NP/OS/PC/VN

RC3 (El Salvador)
RC3/MR(2)/MD/RD/NI/SS/SC/RF/NP/OS/FC/VN

RC3 (Dominican Republic)
RC3/MR(2)/LD/FD/NI/SS/SC/RF/NP/OS/FC/VN

directly help ranking the vulnerability of different school buildings, which can be used as a guidance for prioritising data collection, initial screening for detailed vulnerability evaluation and strengthening and so on. In particular, countries can benefit from the globally shared information about the vulnerability and risk reduction measures, such as the GLOSI repository [4] developed adopting the GLOSI taxonomy. For example, the retrofitting system proposed in Perú for RC3 buildings [31] can be used in similar RC3 buildings in El Salvador, or the retrofitting alternatives for URM schools in Nepal [65] can be replicated to Colombian URM school buildings. A collection of seismic vulnerability data and risk reduction measures for several global *building classes* of school buildings as per the GLOSI taxonomy can be found in the GLOSI repository [4].

It is however worth mentioning that the successful use of a taxonomy scheme depends on the burden of the data collection necessary to complete the classification, especially for application to large portfolios. When detailed school databases are not available in a country/region, the data collection process is best approached by applying a number of strategies such as secondary data collection, remote data collection and field data collection. Useful data and information on school buildings can be extracted from a range of secondary resources such as government database, published works from past projects on schools, literature on construction practice and seismic design codes, seismic damage in past earthquakes. Remote data collection using maps or satellite imagery can also help to collect large-scale general data such as number of buildings in each school, plan shape of building etc., useful to a first level classification. Field visits can be useful to validate the secondary data by conducting field survey to a representative sample of schools and for consulting local experts. Such data collection strategies were followed in the seismic risk assessment of school infrastructure in El Salvador, Dominican Republic and Kyrgyz Republic [28,34,51]. Data collection activities can be carried out by non-expert civil or structural engineers if proper training and guidance is provided. Readers are referred to the GLOSI repository [4] for detailed practical guidance on the data collection for the application of the GLOSI taxonomy, where a detailed data collection form (also available as a mobile/tablet/web application) along with a user manual is available.

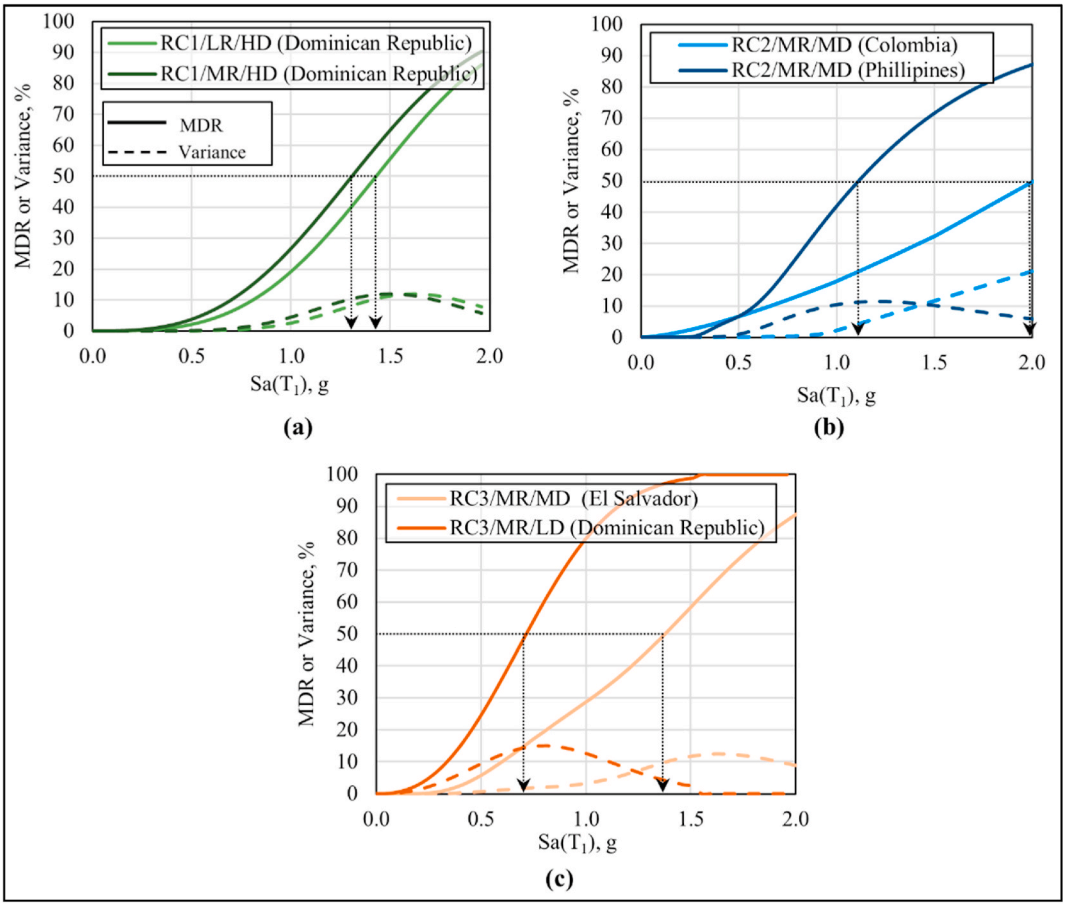

Fig. 12. Comparison of seismic vulnerability functions for RC school *building classes* from different countries. The continuous line and dotted line represent the MDR and the variance, respectively.

Table 11
Application of the GLOSI and GEM taxonomy for a confined masonry school building (Photo: GLOSI Repository [4].

School building	 *Confined masonry (CM) (El Salvador)*
GLOSI taxonomy string	CM/LR/HD/FD/NI/SP/LOC/RF/NP/OS/GC/NN
GEM taxonomy string	DX + D99/MCF + CLBRS + MOC/LWAL + DNO/DY + D99/MCF + CLBRS + MOC/LWAL + DNO/HEX:1+HBEX:0+HFEX:3 + HD99/YEX:1990/EDU + EDU2/BPD/PLFR/IRRE/EWMA/RSH2+RMT6+RWO + RWO1+RWCP/FN + FWC99/FOSSL

6. Conclusions

The GLOSI taxonomy presented in this paper is developed on the basis of real data and information of school buildings from different countries across different continents, considering the similarities and differences in their construction characteristics. Besides, the taxonomy can be understood as a systematic classification system and consistent vulnerability assessment framework to identify buildings with similar vulnerability. Several additional applications may be derived from the taxonomy system such as the ranking of vulnerability parameters, the development of generic retrofitting solutions. In relation to the latter, 14 LBM and 24 RC *index* *buildings* from global school building database have been identified and their detailed vulnerability information as well as retrofitting options are available in the GLOSI repository of the World Bank. These can enable the exchange and use of technical information at global scale. This paper also presents the application of the GLOSI taxonomy in several countries, highlighting the potential problems and challenges in the process of gathering information and creating the exposure database for the portfolio of school infrastructure. The taxonomy presented in this paper can be used together with machine learning techniques such as a clustering procedure to identify buildings with similar characteristics to develop large scale interventions programs.

Although the taxonomy would have been more robust and reliable with the analysis of whole country level datasets on schools, such were not available in all the considered countries. Moreover, in future, the GLOSI taxonomy needs to be updated so as to accommodate other construction types (such as steel or timber framed construction) as well as construction features in newly built schools, by collecting data from more countries. This is important because the GLOSI taxonomy's main objective is to have a uniform language for communicating seismic vulnerability and risk to school infrastructure at global level so that it can contribute to global initiatives such as achieving the fourth UN SDG.

The work presented in this paper is focused on the seismic risk to school infrastructure, but school buildings are also subject to other perils such as hurricane, floods or climate change effects. Thus, it is necessary to develop and implement new taxonomy classification systems or improve the presented taxonomy with the aim of identifying the critical parameters for each hazard in a holistic manner. In addition, in light of COVID-19 pandemic, further taxonomy systems should be developed in the future for functional aspects in school facilities, including parameters such as student density, bathrooms density and quality, illumination, ventilation and energy efficiency among others in order to ensure healthy functionality of the school infrastructure.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

This appendix presents the attributes and commentaries of the secondary parameters that are not discussed in the main text of the paper. More discussion on these parameters and the choice of the attributes and their valuation can be found in The World Bank [4].

Table A1
Attributes for *P4 – diaphragm type*.

Taxonomy parameter	Attributes	Commentaries
Diaphragm type	**RD:** Rigid type diaphragm **FD:** Flexible type diaphragm	A rigid diaphragm should meet both of the following two requirements: 1 . Floor and roof structure with adequate in-plane stiffness, e.g.: - RC flat slab - Traditional slab supported by concrete joists - Composite deck (steel and RC) - Two-way braced timber or steel framework 2 . Good connection of the floor and roof structure to the vertical structural elements, e.g.: - Monolithic connection to the vertical structural elements (column, wall) - Adequate anchorage (e.g. fastened with the reinforcing bars) - A diaphragm is considered to be flexible type if it does not meet both of the above-mentioned criteria.

Table A2
Attributes for *P5 – structural irregularity*.

Taxonomy parameter	Attributes	Commentaries	
Structural irregularity		HI includes:	VI includes:

(*continued on next page*)

Table A2 (*continued*)

Taxonomy parameter	Attributes	Commentaries	
	NI - No irregularities HI - Horizontal irregularities VI - Vertical irregularities HV - Both horizontal and vertical irregularities	- Re-entrant corner - Torsional irregularity - Diaphragm discontinuity - Out-of-Plane offset - Non-parallel system	- Mass irregularity - Soft storey - Vertical geometric irregularity - In-plane discontinuity in vertical structural elements

Table A3
Attributes for *P8 – Foundation type.*

Taxonomy parameter	Attributes	Commentaries
Foundation type	FF - Flexible foundation RF - Rigid foundation	Following two factors govern the foundation type. 1 Materials, structure and geometry of the foundation. - The material can be brick masonry, stone masonry or RC - The structure type can be isolated footing, combined footing, strip foundation, Mat Foundation etc. - Depth can be deep, medium or shallow. 2 The site soil type: hard, medium or soft type. For example, a RC mat foundation in a hard type of soil is considered as a rigid foundation (RF).

Table A4
Attributes for *P9 – Seismic pounding risk.*

Taxonomy parameter	Attributes	Commentaries
Seismic pounding risk	**PR -** Pounding risk **NP -** No pounding	When the seismic gap between adjacent buildings <4% of the critical height, then there is pounding risk (PR). Critical height is the level where the expected collision occurs i.e. height of the shorter building.

Table A5
Attributes for *P10 – Effective seismic retrofitting.*

Taxonomy parameter	Attributes	Commentaries
Effective seismic retrofitting	**OS -** Original structure **RS -** Retrofitted structure	- When a structure has been effectively retrofitted so that the seismic resistance has considerably improved, it is a retrofitted structure (RS). - This parameter might influence other parameters in the taxonomy, such as the P1 – Main structural system, P3 – Seismic design level and others. - Minor non-structural maintenance works do not count as 'effective retrofitting'.

Table A6
Attributes for P11 – *Structural health condition.*

Taxonomy parameter	Attributes	Commentaries
Structural Health Condition	**PC -** Poor Condition **GC -** Good Condition	- It represents the conditions such as deteriorated material quality, existing damage or cracks. - Engineering judgement is required. - See FEMA P-58 [66] for further information.

Table A7
Attributes for *P12 – Non-structural components.*

Taxonomy Parameter	Attributes	Commentaries
Non-Structural Components	**VN -** Vulnerable Non-Structural Components **NN -** Non-Vulnerable Non-Structural Components	- Non-structural components such as parapets, ceilings, tiles, HVAC components, infills can cause injuries/casualties and economic losses - This is a qualitative parameter and the choice of the attributes depend on the evaluation of the location, self-weight, connection of the different non-structural elements.

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