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STRUCTURAL AND NON-STRUCTURAL SEISMIC VULNERABILITY ASSESSMENT FOR SCHOOLS AND HOSPITALS BASED ON QUESTIONNAIRE SURVEYS: CASE STUDIES IN CENTRAL AMERICA AND INDIA

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ABSTRACT

As numerous earthquake disasters in recent years have shown, the integrity of schools and hospital buildings is of utmost importance. For hospitals and health centers this holds especially true since these facilities have to remain fully operational in order to protect the lives of patients and health workers as well as to provide emergency care and medical treatment in the aftermath of the disaster.

Even though possible direct economic losses caused by earthquake damage to school buildings are comparably low, every effort should be made to increase the seismic safety of schools in order to prevent damage and to protect pupils from harm.

A fast and cost-effective procedure is proposed in order to assess the structural and non-structural seismic vulnerability of hospitals and schools. Through the application of standardized questionnaires, both a structural and non-structural vulnerability index are derived which allow a priority ranking and an identification of the most vulnerable features so that responsible authorities are able to conduct a more targeted investigation using more advanced investigation methods. In contrast to other available approaches, structural and non-structural vulnerability are treated separately. While the structural vulnerability index is generated taking into account main design failures as well as the age of the building and its general state of maintenance, the non-structural vulnerability index covers all types of installations, secondary structural elements as well as their impact on the functionality of the building. To optimize a realistic selection of survey questions, the questionnaires have been applied to numerous hospitals and school buildings in Northern India and the Central American countries Guatemala, Nicaragua and El Salvador. Based on these results and the experiences gained during these case studies, a calibration of the questionnaires was done through the definition of reliable weighting factors for the different vulnerability-affecting aspects.

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Introduction

Among other infrastructure systems, the integrity of schools and hospital buildings during an earthquake disaster is of utmost importance. For hospitals and health centers this holds especially true since these facilities have to remain fully operational in order to protect the lives of patients and health workers as well as to provide emergency care and medical treatment in the aftermath of the disaster. In addition to other particularities, the importance of a hospital to suffer as little damage as possible is increased by the 24 hour–7 day occupancy, a high percentage of immobile and highly vulnerable occupants, and the presence of highly sensitive and expensive installations and medical instruments. Damage to these equipments automatically leads to high direct economic losses. On the other hand, direct economic losses caused by earthquake damage to school buildings are comparably low. Nonetheless, every effort should be taken to increase the seismic safety of schools in order to prevent damage and to protect pupils from harm.

In the framework of institutional cooperation projects in Central America and Northern India which are founded by Norwegian government, a comprehensive investigation of the seismic vulnerability of local schools and health facilities is underway. The studies are conducted under close cooperation with local research institutions as well as with the national governmental authorities which are in charge of these facilities.

The detailed structural analysis of any building requires a multitude of input information on the buildings layout, its detailing (e.g. reinforcement) or construction material properties. In most cases, these data can only be obtained if sufficient construction drawings are available and material testings are conducted which derive reliable estimates of material properties. Since these investigations cannot be performed for a larger number of buildings, an alternative procedure which allows a rapid assessment of the structure's actual vulnerability is proposed. Through the application of standardized questionnaires, structural and nonstructural vulnerability indices are derived which allow a priority ranking of those facilities which are potentially susceptible to damage in case of an earthquake. Based on the screening results, responsible authorities are able to conduct a more targeted investigation of the respective structures using more advanced investigation methods.

Rapid Visual Survey Procedure

In 1988, FEMA published its "rapid visual screening" (RVS) procedure whose goal was to identify, inventory and rank buildings that are potentially dangerous in case of an earthquake (FEMA 1988). The RVS procedure, which was updated in 2002 (FEMA 2002) has been widely used throughout the United States in order to identify the structural vulnerability without considering non-structural components or the structural peculiarities of hospitals and schools. Recently, an enhanced RVS methodology, called the E-RVS method, was presented by (Wang and Goettel 2007) which they applied to school buildings in Oregon, U.S. (Wang and Goettel 2006). In contrast to these initiatives, the World Health Organization (WHO) and the Pan American Health Organization (PAHO) developed over the years screening procedures for health facilities within their "Safe Hospitals" program (http://safehospitals.info). These efforts led to the development of the "Hospital Safety Index", a multi-hazard screening procedure for health facilities in terms of structural safety, non-structural safety, and safety based on functional capacity (PAHO 2000; PAHO 2008a; PAHO 2008b).

Questionnaire Development

In consideration of these procedures and by reviewing available documents (e.g. WHO, 2007), a visual survey procedure has been developed in order to rapidly assess the structural and non-structural vulnerability of schools and hospitals. The procedure is based on standardized questionnaires that are customized to the distinct characteristics of these facilities.

In contrast to other approaches, e.g. the Hospital Safety Index, the developed method is constricted in terms of the following aspects:

1. Only the vulnerability of buildings under earthquake loading is addressed (single-hazard approach). An extension of the procedure to other natural hazards, in principle, is possible.
2. Only structural and non-structural vulnerability is addressed disregarding operational (functional) vulnerability. This because an objective assessment of functional features is more difficult and requires sophisticated interviews with various personnel groups of a hospital or school.
3. Structural and non-structural vulnerability are treated separately. Hence, separate vulnerability indices are derived.
4. Only the building's vulnerability is investigated irrespective of its topographic situation, geological conditions, or seismic hazard. Including these features would lead to a risk assessment which should not be the issue of the current procedure.

Furthermore, the following principles have been considered for the screening methodology:

1. Simplicity: The questions can only be answered by stating 'yes' or 'no' so that any personal (subjective) opinion of the screener is avoided.
2. Feasibility: In certain cases, the screener may not be able to reliably answer questions that require detailed technical knowledge or that address installations which are not accessible. It was tried to exclude/reduce these questions from the questionnaires.
3. Practicability: The number of questions has been limited to a certain number so that interviews with hospital and school personnel lasting for several hours are avoided.

As for any building, the assessment of the structural vulnerability is of utmost importance in order to get an idea about the building's exposure to suffer structural damage as a direct effect of earthquake shaking. However, especially for high-priority structures, like hospitals and schools, the vulnerability in terms of non-structural or functional features can lead to severe follow-up losses in the direct aftermath of an event and in the weeks or months to follow which may exceed the losses caused by structural characteristics by far.

For the questionnaires developed and applied in the present context it was solely concentrated on the vulnerability caused by structural and non-structural components. The questionnaires consequently consist of three parts addressing (1) general information, (2) structural vulnerability, and (3) non-structural vulnerability. While the part on structural vulnerability is the same for hospitals and schools, the parts on general information and non-structural vulnerability are customized to the peculiarities and differences of hospitals and schools and consequently are different from each other. The final decision on the questions that are included in the questionnaires was made after applying previous versions of the questionnaires to numerous schools and hospitals in developing countries. During that process a revision of the questionnaires took place which excluded those questions that were believed to be irrelevant or not suitable for the entire procedure.

When applying the questionnaires to any school or hospital, vulnerability indexes *SVI* and *NVI* are derived representing a measure of the structural and non-structural vulnerability, respectively. Each question addressed in the questionnaire has a certain level of importance (low, moderate, high) that is dependent on how large its impact is on the overall vulnerability of the building. To calculate either of the two vulnerability indexes *SVI* or *NVI*, the single scores are summed up and divided by the number of answered questions. Questions that are not applicable to a particular building are excluded from the calculation of a vulnerability index.

Structural Vulnerability

Table 1 lists the 15 questions on structural vulnerability and their levels of importance. The levels of importance depend on the building typology (reinforced concrete or masonry) and were assigned based on expert opinion. It should be noted that this part of the questionnaires is the same for the vulnerability assessment of both hospitals and schools. A distinction is solely made in terms of the building's typology, i.e. whether reinforced-concrete or masonry structures are concerned. A later extension of the questionnaires to other building typologies, e.g. steel structures, is in preparation.

In order to account for the building's age and its actual state of preservation, the structural vulnerability index *SVI* is modified by age factor *AF* and actual state factors *ASF*, respectively. Since age and the actual state of a building have large impact on its vulnerability (EMS-1998; Grünthal, ed. 1998) but not automatically addressed in the questions, it was decided to consider both features by separate factors. Table 2 list the decided values for both factors and the percental increase of structural vulnerability factor *SVI*. The vulnerability index amplified by the factors AF and ASF will be called $(SVI)^*$. Both indexes *SVI* and $(SVI)^*$ are kept in order to see the change of structural vulnerability with and without considering age and actual state.

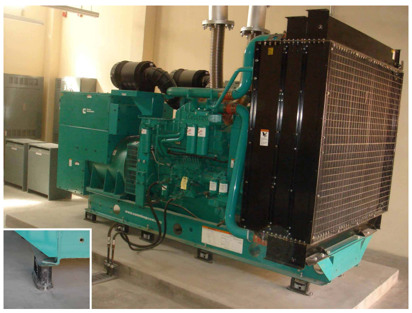
The selection of the questions addressing structural vulnerability was done with regard to existing screening procedures and provisions (e.g. FEMA 154; PAHO 2000; PAHO 2008b) complemented by questions which target peculiar structural features.

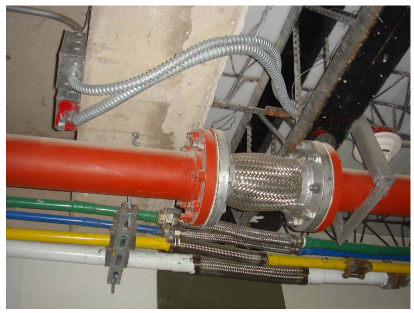
Table 1. Questions addressing the structural seismic vulnerability and their levels of importance.

No.	**Question**	**Level of importance**	
		reinforced concrete	**masonry**
1	Is the building irregular in plan?	moderate	moderate
2	Are the columns regularly distributed?	low	*not applicable*
3	Are both building directions adequately braced?	high	high
4	Does the ratio between the building's length and width is > 2.5?	low	moderate
5	Does the building possess eccentric cores (staircases or elevators)?	moderate	moderate
6	Does the building have a soft storey?	high	*not applicable*
7	Is the building irregular in elevation caused by setbacks of upper stories?	moderate	high
8	Does the building have cantilevering upper stories?	moderate	moderate
9	Does the building possess a heavy mass at the top or at roof level?	low	low
10	Are pounding effects possible?	low	low
11	Does the building have short columns?	moderate	*not applicable*
12	Are strong beams–weak columns available?	high	*not applicable*
13	Does the building possess shear walls?	low	*not applicable*
14	Did the building suffer any significant structural damage in the past?	low	low
15	Does the building possess seismic retrofitting or strengthening measures?	moderate	low

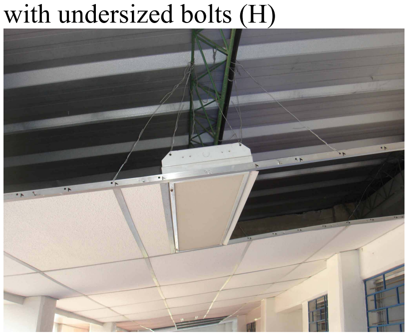
Table 2. Suggested values for age factor *AF* and actual state factor *ASF* and the percental increase of structural vulnerability index *SVI*.

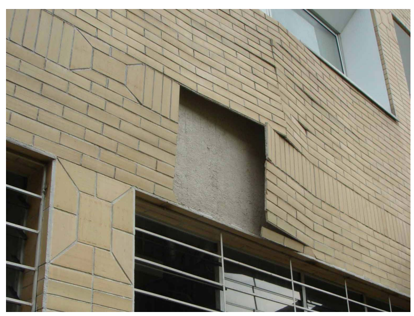
			Actual state			
			good (new)	recently renovated	in need of renovation	bad (decayed)
			ASF = 1.00	*ASF* = 1.05	*ASF* = 1.10	*ASF* = 1.20
Age	< 10 years	*AF* = 1.000	0 %	5 %	10 %	20 %
	10–20 years	*AF* = 1.025	2.5 %	7.6 %	12.8 %	23 %
	20–40 years	*AF* = 1.050	5 %	10.3 %	15.5 %	26 %
	> 40 years	*AF* = 1.100	10 %	15.5 %	21 %	32 %


(a) Emergency generator mounted with undersized bolts (H)


(b) Flexible connection of pipes (H)

(c) Non-maintained hose-reel cabinet (H&S)


(d) Insufficient securing of suspended ceilings (H&S)


(e) Loosened façade claddings (H&S)

(f) Inadequately secured gas cylinders (H)


(g) Wrong storage of chemicals (H)


(h) Barred classroom windows of ground floor (S)


(i) Tables are missing where pupils could hide from falling objects (S)

Figure 1. Examples of non-structural features that affect the non-structural vulnerability of hospital (H) and/or school facilities (S).

Non-structural Vulnerability

In contrast to other screening procedures, non-structural features are treated separately from the structural characteristics of the building. While the structural vulnerability index *SVI* or *(SVI)** is generated taking into account main design failures as well as the age of the building and its general state of maintenance, a non-structural vulnerability index *NVI* is derived that covers all types of non-structural elements such as secondary structural elements, equipment, furniture or installations that may put people and contents at risk during evacuation after a seismic event. Some examples of non-structural features that affect a school's and/or hospital's non-structural vulnerability are given in Figure 1.

To optimize a realistic selection of survey questions, the questionnaires have been tested on numerous hospitals and school buildings in the Central American countries Guatemala, Nicaragua, El Salvador and Panama. Based on the results of these pre-studies and the experiences gained during these case studies, a calibration of the questionnaires was done through the introduction of reliable importance factors for the different vulnerability-affecting aspects.

Table 3 gives an overview of those categories which are addressed in the non-structural parts of the questionnaires for hospitals and schools. For schools, electrical facilities and propane pipes are disregarded. Within each of these categories, a number of questions are posed that are interdependent and thus logically connected.

In addition to non-structural vulnerability index *NVI*, a pie-chart diagram is generated for each facility that allows a better overview of the different non-structural features and their respective vulnerabilities (Figure 2). A separate pie-chart diagram is given for hospitals and schools. Each piece of the pie-chart represents one of the non-structural categories while their size is a measure of its importance. A tripartite color code is applied for each piece of the pie-chart in order to graphically illustrate the vulnerability level of the single categories and the facility as a whole. The coloring of a pie-chart piece (into red, yellow or green) that represents a certain non-structural category, is a measure of how vulnerable the facility is with respect to that particular category.

While the shape of a pie-chart is fixed and remains unchanged, the coloring of the single pieces directly reflects the survey results and thus will be different for each observed facility. In addition to the derived non-structural vulnerability index (*NVI*) that joins these results into a single value, the colored pie-chart diagram provides a rapid visual identification of the most deficient non-structural components. Moreover, an easy comparison between the non-structural vulnerability of different facilities is supplied.

Structural versus Non-structural Vulnerability

The concept of deriving separate structural and non-structural vulnerability indexes *SVI* and *NVI*, respectively, points to the authors' opinion that structural and non-structural vulnerability are not automatically connected. Needless to say that a building which is in very bad structural condition due to age or carelessness and thus exhibits high structural vulnerability will most probably not excel with respect to the condition of its non-structural components. On the other hand, a building that is of high capacity and does not allow for large deformations may be crucial to many acceleration-sensitive non-structural components.

Table 3. Categories of the non-structural questionnaire parts for hospitals and schools. The percental values represent the importance levels of the respective category on the final non-structural vulnerability index *NVI*.

No.	Category	Components	Level of importance	
			Hospital (H)	School (S)
1	Electrical facilities	emergency generator, fuel tank, service lines and pipes, bus ducts and cables	18 %	*not applied*
2	Fire fighting	smoke detectors, alarms, fire extinguishers, hose-reel cabinets, (H: emergency water tank)	10 %	6 %
3	Propane or other gas (e.g., oxygen) pipes	shut-off valve, wrench tool, pipe installations	18 %	*not applied*
4	Elevators	maintenance, motors, control cabinets	3 %	6 %
5	Non-structural infill walls and partitions	protection of infill brick walls against out-of-plane failure, movement joints available	5 %	8 %
6	Ceilings	securing of suspended ceilings	2 %	8 %
7	Emergency exits and escape routes	exit doors, automatic doors, glazing of windows, safety glass, designation and illumination of escape routes	25 %	44 %
8	Appendages	parapets, façade cladding, roof tiles, chimneys, external AC machines	2 %	4 %
9	Movable equipment	H: gas cylinders, chemicals, hazardous materials S: wardrobes, lockers, bookshelves, blackboards, desks	6 %	8 %
10	Appurtenant structures	open spaces, neighboring structures, road access to the facility	9 %	16 %

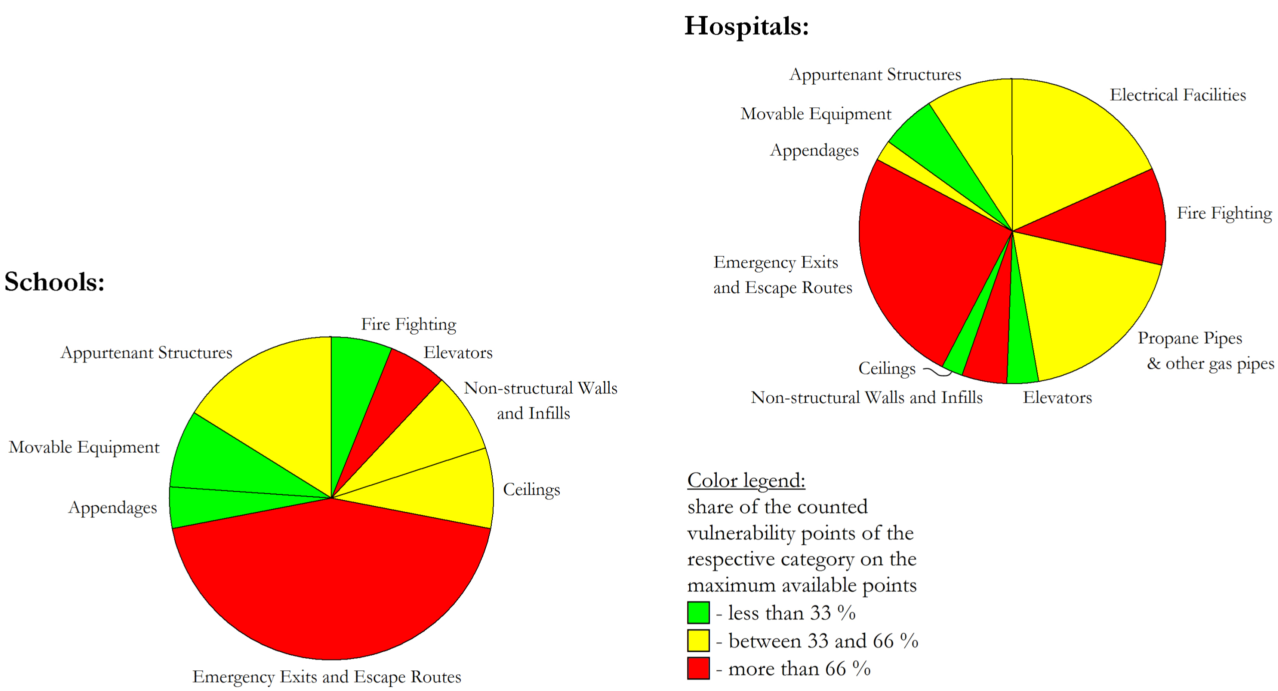
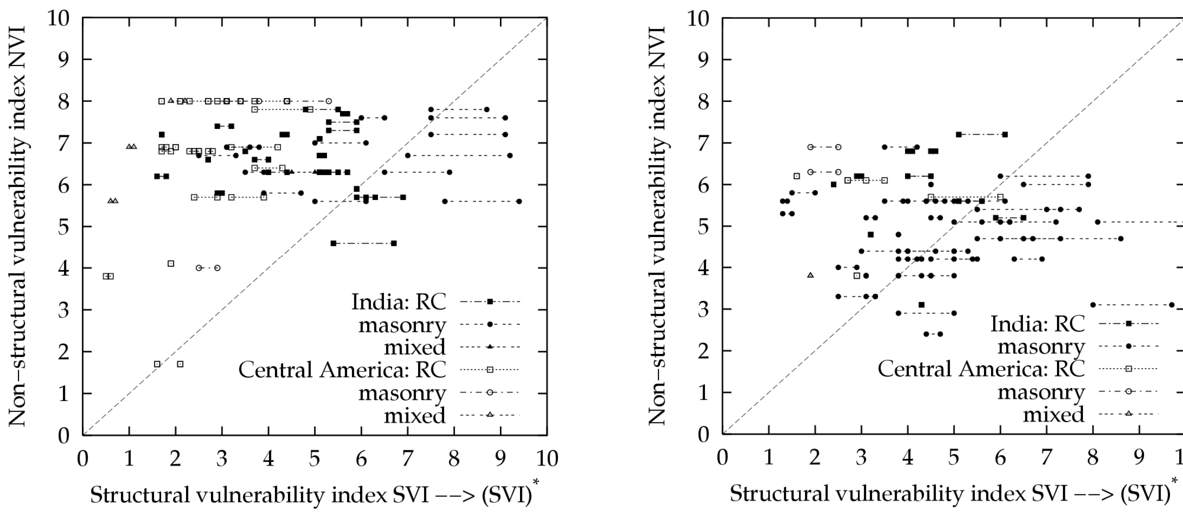


Figure 2. Pie-chart diagrams for hospitals and schools representing of the different categories of nonstructural vulnerability. The sizes of each pie chart are according to the percental values given in Table 3.

To investigate whether any correlation exists between structural and non-structural vulnerability, Figure 3 compares the vulnerability indices, respectively. This is done separately for schools and hospitals that were investigated in Central America (i.e. Guatemala, El Salvador, and Nicaragua) and Northern India (Dehradun). From Figure 3 no direct correlation can be observed between the structural and non-structural vulnerability indexes, which endorses the decision to separately treat the different vulnerabilities. Further, no general differences in the vulnerabilities between facilities in Central America and India can be observed.



(a) hospitals *(b) schools*

Figure 3. Comparison between structural and non-structural vulnerability indices which were derived for (a) hospitals and (b) schools located in Central America and Northern India. [Each pair of points connected by a horizontal line represent the indexes *SVI* and *(SVI)**, respectively.]

Case studies in Central America and India

The development and calibration of the questionnaires was done while applying them to a considerable number of hospitals and school facilities in Central America and India. Even though differences in building execution, material qualities or building regulations (codes) naturally exist between these different regions, similarities in the structural typologies can be observed. This holds true for building typologies (RC frames, clay brick and stone masonry), as well as story numbers *N*. Table 4 represents the statistical analysis of the structural vulnerability part of the questionnaires. These results clearly show that the structural vulnerability of both hospitals and schools in India are higher than those investigated in Central America. It should be stated that the distribution in terms of building age and actual state of maintenance is comparable between the analyzed facilities in Central America and India. Principle features that obviously depend on the region and not on the type of occupancy, are e.g. a much higher percentage of inadequately braced buildings as well as of strong beams–weak columns at buildings in India than in Central America. Other features, as e.g. slender plan shapes with L/W ratios > 2.5 are more often prominent at school buildings than at hospitals irrespective of the region concerned.

With respect to non-structural vulnerability, a direct comparison of single features is of course difficult so that this is limited to a comparison of the respective non-structural vulnerability indexes *NVI*. Again, similarities in the non-structural vulnerabilities between schools and hospitals in India and Central America could be observed. On average, higher *NVI* were derived for hospitals where even new and/or well-maintained buildings revealed severe deficits of non-structural issues. In terms of schools, it needs to be stated that many of the observed buildings are of smaller size, single-storied and of light construction, and thus expose only lower structural vulnerabilities. The majority of observed schools facilities are characterized by severe non-structural deficits especially in terms of fire protection, escape routes and movable equipment.

Table 4. Statistical analysis of the questionnaire parts addressing structural vulnerability. Given numbers represent percentages of total investigated buildings that confirm the respective vulnerability-affecting feature.

No.	Factor affecting structural vulnerability	Hospitals		Schools	
		Central America	India	Central America	India
1	irregularity in plan	37	67	13	44
2	irregularly distributed columns	5	46	0	30
3	inadequately braced building directions	11	92	13	93
4	L/W ratio > 2.5	37	26	75	60
5	eccentric cores	26	72	38	55
6	soft storey	5	17	0	20
7	irregularity in elevation caused by setbacks	22	28	0	7
8	cantilevering upper stories	7	13	50	2
9	heavy mass at the top or at roof level	4	36	0	0
10	pounding effects possible	26	18	25	13
11	short columns	76	46	100	70
12	strong beams–weak columns	19	75	17	80
13	no shear walls	81	100	83	100
14	structural damage in the past	26	23	38	40
15	no retrofitting/strengthening	93	97	100	95

Conclusions

The herein presented procedure to assess both structural and non-structural vulnerability of hospital and school facilities by the application of standardized questionnaires is an attempt to quickly identify existing structural and non-structural shortcomings, to allow a priority ranking of the most vulnerable structures and to provide a basis to compare different structures with each other. However, the proposed rapid sample survey shall rather be seen as a means to identify the most vulnerable structures so that responsible authorities are able to conduct a more targeted investigation using more advanced analysis methods than to substitute these more elaborate procedures.

The questionnaires were applied to numerous hospitals and schools in Central America and India, thereby developed as well as calibrated. However, a more substantiated calibration of the decided importance factors, age and actual state factors, and derived vulnerability indexes with more thorough analytical studies of selected structures is ongoing (Verbicaro et al. 2009) and will be the purpose of future investigations.

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The herein described questionnaires for the vulnerability assessment of schools and hospitals and an elaborate manual (Lang et al. 2009) are currently available in English and Spanish language. All documents can be downloaded from http://www.norsar.no/c-121-Hospitals---Health-Centers-and-Schools.aspx/.

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