SEISMIC EVALUATION AND RETROFIT OF SCHOOL BUILDINGS IN VENEZUELA

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ABSTRACT:

70% of the about 34,000 Venezuelan schools are in high seismic hazard regions; about 1,000 are similar or identical to the four school buildings that collapsed during the 1997 Cariaco earthquake. This paper describes a national program aiming to evaluate and reduce the risk of existing schools. The steps under way include: (1) Development of a nationwide catalog on a GIS basis of the existing schools that includes type and date of construction, location, number of stories and population; (2) Building risk maps and estimating losses and casualties from future events; (3) Inspection of 250 school buildings located in the higher hazard zones, with emphasis on the older ones, using a data collection form specially designed for schools. A structural score that is correlated with seismic risk is assigned to each building; (4) Detailed studies of 10 standard school types, selected as pilot projects, including in situ dynamic tests and soil and foundation surveys; (5) Development of optimal retrofitting projects. The proposed solutions for the standard schools that collapsed in the 1997 Cariaco earthquake add stiff and ductile auxiliary structures to withstand most of the earthquake loads; (6) Installation of accelerometers in four schools to record future events; (7) Development of a guide for reducing non-structural vulnerabilities; (8) Workshops and production of videos to enhance the level of community awareness and preparation for seismic events.

KEYWORDS: schools, vulnerability, retrofitting, reducing risk.

1. INTRODUCTION

School buildings have frequently collapsed during past and recent earthquakes. A few examples are the 2001 Bhuj earthquake (Mw=7.7) in India, where 971 students and 31 teachers died (Jain 2004), the 2005 Kashmir earthquake (Mw = 7.6) in Pakistan where about 19,000 children died, most of them in widespread collapses of school buildings that were affected to a much higher proportion than other buildings (EERI 2006), and the 2008 Sichuan, China, Earthquake (Mw=7,9) that destroyed at least 6,898 schools killing thousands of students and teachers; the China Ministry of Housing and Rural Development has ordered local authorities to investigate the collapses (EERI 2008).

Of the seven reinforced concrete buildings that collapsed during the 1997 Cariaco, Venezuela, earthquake (Mw=6.9), four were school buildings. The collapsed buildings are representative of two school types built several decades ago: The Old-Type and the Box-Type. Failures were primarily the result of structural deficiencies that are common in structures build with old design codes: low strength, stiffness and energy dissipation capacity, and short columns created by infill walls (López et. al. 2007). Four school buildings of the Old-Type had already shown damaged in short columns during moderate earthquakes in 1974 (M_s=6.1), 1981 (mb=5.5), 1986 (Ms=6.1) and 1991 (mb=5.3) (López 2008). It is estimated that there are about 1,000 school buildings in the country of the same types that collapsed in Cariaco. And 70 % of the about 34,000 schools are located in high to very high seismic hazards zones with peak accelerations ranging from 0.25g to 0.40g for 475 years mean return periods; most of these buildings were built several decades ago using old structural design codes, which are known to be insufficient to provide protection against seismic motions.

A national project that aims to reduce the seismic risk in existing school buildings is described in this paper. The three-year project was initiated in 2006 with the participation of IMME (Central University of Venezuela), FEDE (Ministry of Housing and Habitat) and FUNVISIS (Venezuelan Foundation for Seismological Research) with the financial support of FONACIT (Ministry of Science and Technology). The project represents an important step towards ensuring safety to educational spaces for communities. FEDE (The Foundation of Educational Buildings) as the lead agency in addressing the educational physical plant of the nation, is also committed to this goals and gives a high priority to strengthening school buildings for ensuring structural stability and the safety for its occupants, and to the construction of new earthquake-resistant schools. Specific objectives of the project are to identify the structural characteristics of the about 28,000 schools in the country, to develop cost effective and non-disruptive retrofitting solutions and to enhance the level of community awareness and preparation for seismic events.

2. COMPILATION OF BASIC INFORMATION OF SCHOOL BUILDINGS

The goal is to identify construction types, specially the older ones, and to compile basic information regarding the main structural features that influence seismic performance, for the about 34,000 schools in the country. The information is used to develop a nationwide catalog of school buildings attending to earthquake risk features on a GIS basis. The features to compile could be obtained from architectural and structural plans, if they were available for each constructed school type in the country. However, these plans have been found for only a few construction types. Therefore it was decided to develop the information strategies search which is described as follows. In a first stage older school buildings were identified by means of the local State Office of FEDE that is located at each one of the 24 states of the country. Photographs and digital images of older construction types, specially the ones that collapsed in the 1997 Cariaco earthquake, were sent to each local office in order to identify them. This yielded a data base of 701 school buildings with information regarding name, location, construction type, school population and seismic hazard zone.

The Ministry of Education carried out the National Scholar Census in 2006; the information was collected by 4,000 properly instructed high-school students with the intention of compiling educational information as well as basic structural information for all the schools in the country: Year of construction, number of stories, location, school population and construction type; the last is identified with the help of drawings and photographs that describe usual construction types built in the last century. The 2007-2008 Census that yields similar information has been completed using internet and is actually being processed. Based on a GIS developed in recent years by FEDE that contains the geographic location of 18,000 schools, a new system that allows incorporating information from the National Scholar Census and to represent thematic maps is under way. The GIS is intended to generate an integrated tool that simulates the occurrence of earthquakes and estimates damages and losses. This will facilitate the decision making of the local, regional and national authorities for developing plans of prevention, reduction of risk, and attention of seismic emergencies.

3. ESTIMATION OF DAMAGES AND LOSSES

A simplified study of seismic losses is performed. Risk indexes are determined associated to seismic scenarios and to approximate fragility curves The peak horizontal ground acceleration at each school site is determined for a specific seismic event that is described by a given magnitude and a specific location, using appropriate attenuation relationships.

For each school type, the estimated mean value of the yield base shear divided by building weight, the effective vibration period and the ultimate roof displacement of the structure are determined. The yield displacement is obtained from these. Four damaged states are defined: light, moderate, severe and collapse. Yield displacement corresponds to the initiation of the light damage state and ultimate displacement corresponds to the collapse one; moderate and severe damage states are defined by intermediate displacement values. Seismic vulnerability of the school building adopts a lognormal distribution to describe the fragility curve. The probability of exceedance of a given damage state is calculated for each value of the peak ground acceleration (PGA). The mean damage state values are determined from the displacement responses for a given PGA. The standard deviation of ln(PGA) for each damage state is adopted following (Bonett 2003). As an example the fragility curve estimated for an old school is shown in Figure 1.

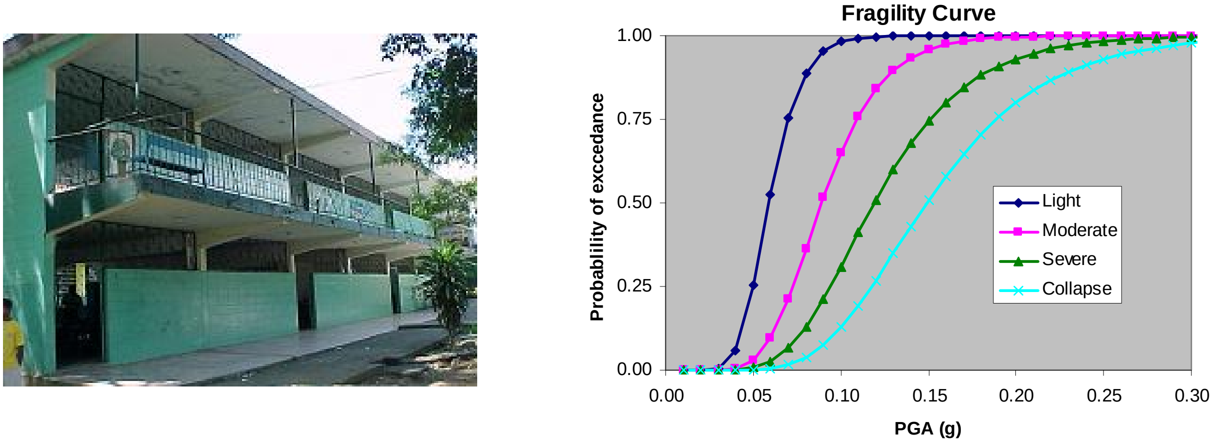


Figure 1. Fragility curve for four damage states, for an old school.

The probability of exceedance of a given damage state is obtained from the fragility curve. The School Damage Factor (SDF) is obtained pondering the damage states probabilities with the damage factors following (Hwang and Lin 2002) (Blondet et. al. 2005). Effects on occupants assume that seismic event take place in activity hours, and casualties are determined in function of the ATC's occupant affectation factor associated with each damage state (ATC 1985). Finally, a repair cost factor will be obtained as the product of school damage factor and the facilities value according to its educational level and social importance. To estimate the seismic risk the damage range associated to an annual probability of exceedance will be determined (Safina 2000).

4. VISUAL INSPECTION OF SELECTED SCHOOLS

Visual inspections of 250 school buildings located in medium to high seismic hazard zones in Venezuela were completed (CENAMB 2008). Special attention was focused on older structure types which showed inadequate behavior during past earthquakes. The collected information will be used to evaluate potential seismic risk for mitigation purposes.

A data collection form was specially designed to collect information considering typical characteristics of school buildings in Venezuela. The data collection form was based in local experience as well as international experience (FEMA 2002; Meneses and Aguilar 2004). The information includes year of construction, number of students, GPS coordinates, schematic horizontal and vertical plans of the building, structural configuration, structural and non-structural details, state of maintenance and a detailed photographic report. The information is directly related to the requirements of Venezuelan design codes (COVENIN 1985; COVENIN 1998; COVENIN 2001).

Visual inspections were performed by inspectors having basic structural and earthquake engineering instruction, such as civil engineering students or firemen. A detailed instruction manual was prepared to facilitate inspectors to perform their activities. A three-day workshop was given to train inspectors to collect the required information and to fill in the data collection form, paying special attention on structural and non-structural details that influence seismic performance. The first day of the workshop included the presentation and description of the data collection form, a detailed explanation about the information to be collected in situ and how to fill the data collection form, and the presentation and discussion of a practical example. The activities for the second and third day of the workshop included a field practice in two actual school buildings and a discussion of the obtained results.

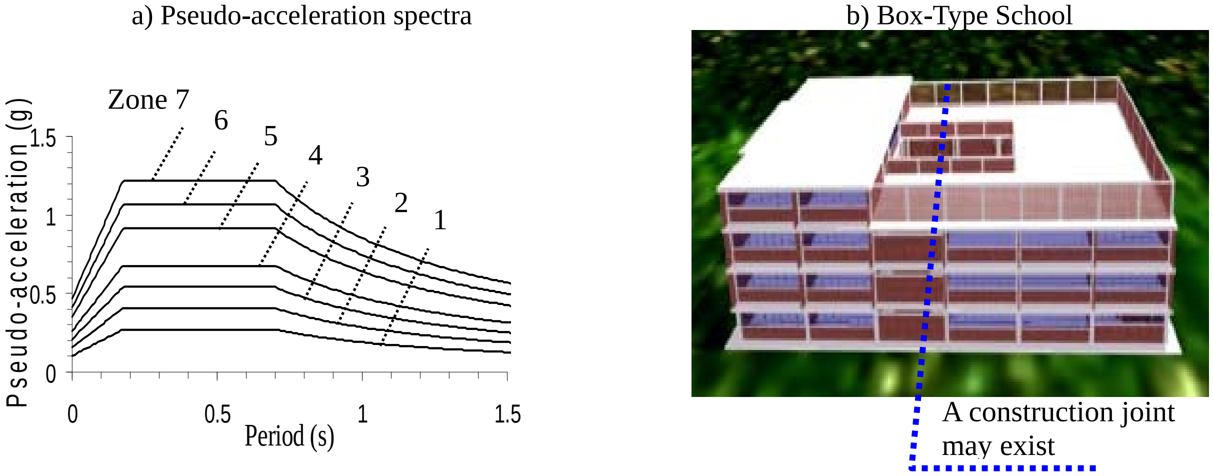
The information collected from visual inspection will be used to estimate a seismic risk index for each school building. The risk index considers the seismic hazard, the seismic vulnerability and an estimate of potential losses. The seismic hazard index is established according to the seismic hazard map of the Venezuelan seismic code (COVENIN 2001). The seismic vulnerability is based on structural and non-structural characteristics, based on local and international experience. Finally, loss estimate will be based on school capacity. The risk index will be used to take sound technical and bureaucratic decisions for mitigation of seismic risk in school buildings in Venezuela.

5. SEISMIC EVALUATION OF SELECTED SCHOOLS

Ten schools were selected as pilot projects for a detailed seismic evaluation. They belong to construction types that were built many times between 1940 and 1980. The study includes in situ dynamic tests, material testing, soil and foundation surveys, and the development of optimal retrofitting projects. Each school is evaluated for the seismic ground motions specified in the national code; peak ground acceleration varies from 0.10g to 0.40g for the seven seismic zones in the country. These values are multiplied by 1.3 for the design of school buildings. Figure 2(a) shows the elastic pseudo-acceleration spectra for 5% damping at each seismic zone, for stiff soil.

Two school buildings that are being evaluated belong to the Box-Type schools that were built in 1970-1980; Figure 2(b) shows an idealization of a typical four-story Box-Type school. They have reinforced concrete frames and masonry infill of hollow clay or concrete blocks. There are two types of these buildings: The Closed-Box-Type and the Open-Box-Type; the latter has a construction joint that gives place to two similar but independent buildings, each with a C-shaped floor plan.

Drift demands are estimated at each seismic zone using the Coefficient Method (FEMA, 2000). The ultimate drift values are taken from the results of a pushover analysis. Figure 3 shows the roof drift ratio for the Closed- and the Open-Box-Type buildings; the ultimate roof drift ratio is exceeded in the high hazard zones for the Open-Box-Type and in most zones for the Closed-Box-Type pointing out the need for a retrofitting.


a) Pseudo-acceleration spectra

b) Box-Type School

A construction joint may exist

Figure 2. (a) Pseudo-acceleration spectra for each seismic zone in the country and stiff soil conditions; (b) Idealization of a Box-Type School (Taboada and Sosa, 2008).

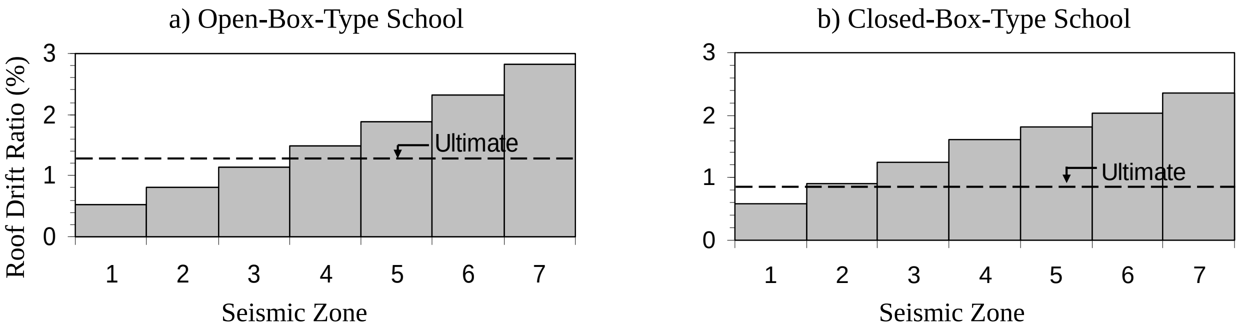


Figure 3. Roof Drift ratio demand and ultimate drift at each seismic zone for two school types.

6. EXPERIMENTAL DETERMINATION OF DYNAMIC PROPERTIES

Natural periods, mode shapes and damping ratios of the first vibration modes were determined for the school buildings selected as pilot projects using ambient vibration tests. The procedure consists on the installation of a previously configured arrangement of seismometers located in selected places of the structure and a data acquisition system. The data is later post-processed to determine the values of interest. The data for each sensor (Guralp Systems, Kinemetrics Inc.) goes to an A/D converter (Iotech, 2002) with a sampling rate set to 200 Hz; frequencies of interest rarely overpass 100 Hz. For each record, the power spectra were calculated using the Welch´s method (Welch, 1967) with 60% overlap and a number of data points of 16384, allowing enough period range to 82.91s and frequency tolerance of ± 0.003 Hz.

The vibration modes were calculated from the cross correlation analysis of two simultaneous records, in which the common frequencies and phase angles are of special interest (Figure 4). The vibration modes were determined for phase angles of 0° or 180° for the common frequencies in the different records. Once calculated the phase angle, the position of each point respect to the equilibrium position was established. And with the vibration amplitude estimated for each frequency at each point, it was possible to draw an approximate vibration mode for the whole structure. The modal damping was calculated from the power spectra by the half power method, assuming that the damping is small. (Craig, 1981; Cunha et al.; 2006, El Borgi et al., 2004; López et al., 1989).

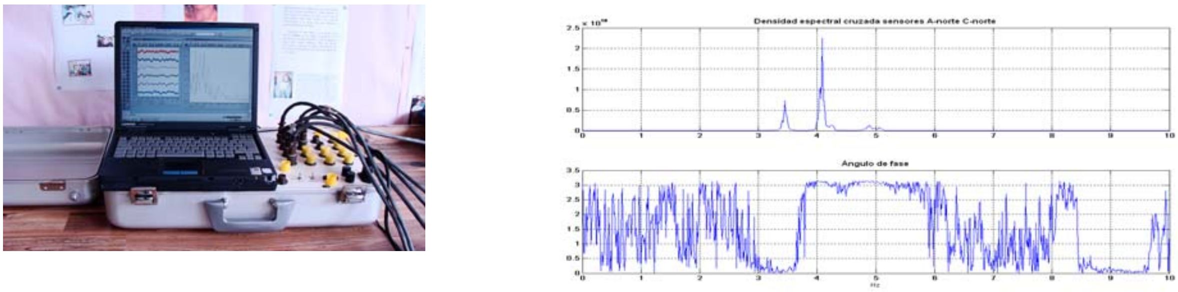


Figure 4. Central data acquisition system and amplitude-phase curves for each frequency.

7. RETROFITTING OF SCHOOLS

Several options of structural retrofitting are studied for each pilot project in order to optimize the relationship between expected performance and economical cost. They take into account the properties of the existing structure, mainly its strength, stiffness and ductility with emphasis on the irregularities and weaknesses like short columns. In a common option auxiliary structures are designed to withstand most of the earthquake loads, connected to the diaphragms of the existing structures, and supported in properly improved foundations. Special attention is given to the deflection compatibility between both structures; drifts are kept below levels that could jeopardize the capacity of the existing structure to support gravity loads.

Preferred solutions are those with an extended international support of structural performance researches. Considering the great importance of warranting the schools safety, is necessary to avoid innovations that lack of a broad and proven support, sometimes called “cookbook approaches” (Perbix & Burke, 1989). Generic documents like FEMA 356 (FEMA, 2000) and several research papers have been examined (Pincheira, 1993; Roeder et al., 1996; Sasani et al., 1999), among others.

Figure 5 shows a designed retrofitted structure (Hernández, 2004) for Old-Type school buildings located in high hazard seismic zones. Concentric steel braced frames form the auxiliary structure, which absorbs almost all lateral loads. In the longitudinal direction braced frames are connected to new RC collector elements, guaranteeing a rigid diaphragm behavior; in the transverse direction they are connected to the existing beams. A quadrilateral ring of reinforced foundations supports the four braced frames to improve the bearing and uplift capacity. Drift limit of 0.7 % was imposed to protect the existing structure, which supports the gravity loads. Design included rigorous detailing of the connections for members overstrength, which compensates the small system redundancy. The masonry walls are separated from the columns where a short column can be developed and are appropriately anchored to avoid out of plane failure. This solution inflicts minor disruptions of school operations.

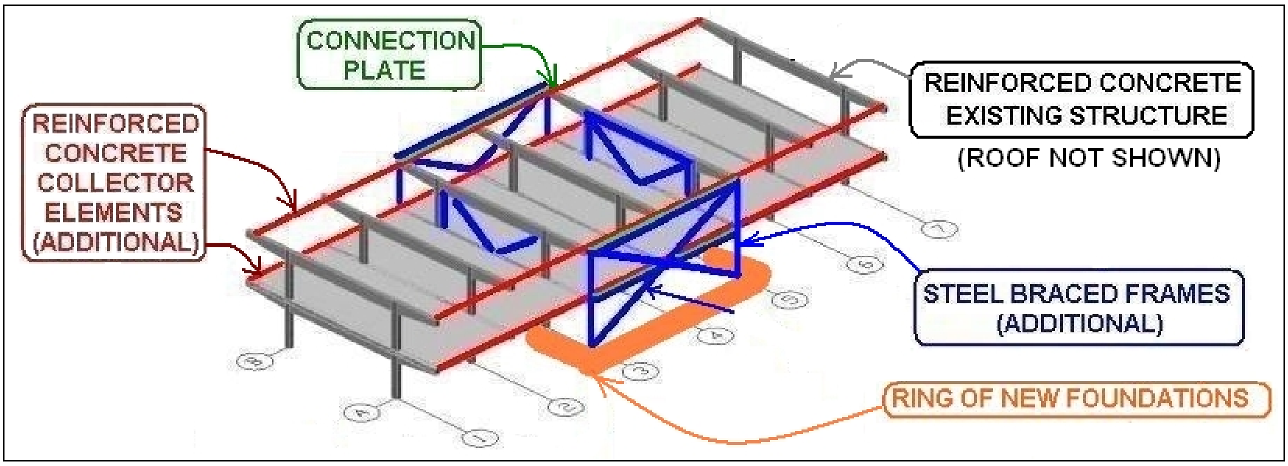


Figure 5. Retrofitted structure for an Old-Type school building.

8. NON-STRUCTURAL HAZARDS

The vulnerability of school buildings can be generated or increased by improperly connection or storage of non-structural components (FEMA 2004). There are three types of risks associated with earthquake damage to non-structural components: people injured or killed by damaged or fallen objects, property loss and difficulty or impossibility to carry out post-earthquake emergency operations. Figure 6 shows the overturning of a masonry infill wall in a school building and the overturning of shelves during the 1997 Cariaco earthquake. The steel structure for the school building was undamaged. This situation is common in rural school buildings where the masonry is not properly connected to the structure. Several dynamic analyses were performed to evaluate the effects of the connections and a proper anchorage to the structure was developed.

A guide for reducing risks generated by nonstructural components is being developed. The higher hazard components are identified by visual inspections of several school buildings. The components are classified according to their sensitive to displacement and/or acceleration. The guide consists of a set of recommendations and drawings addressed to the managers and users of the school building to reduce the seismic hazards.

Figure 6. (a) Overturning of masonry walls and (b) Overturning of shelves (MIDAS, 1997) during the 1997 Cariaco earthquake.

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