Improving Seismic Safety in Venezuelan Schools

O. A. López, A. Marinilli, G. Coronel & R. Bonilla
IMME, Engineering Faculty, Central University of Venezuela

J. Domínguez
Venezuelan Foundation for Seismological Research, FUNVISIS, Ministry of Science and Technology, Venezuela

R. Vielma
Foundation of Buildings and Educational Endowments FEDE, Ministry of Education, Venezuela.

SUMMARY
This paper presents the results obtained in a project that aims to improve seismic safety of schools in Venezuela. At first 19,972 school buildings were identified. About 50% of them are located in high hazard zones and about 46% were constructed before 1982, with less demanding seismic requirements than current ones. The probability that complete damage state occurs for a building designed with older seismic codes is 5 to 42 times greater than in new school buildings. A total of 293 school buildings were inspected using a data collection form specially designed to gather structural and non-structural information. Eleven buildings were selected as pilot projects for seismic retrofitting. First mode vibration periods and damping ratios were determined from ambient vibration. Retrofitting solutions adds auxiliary structures of reinforced concrete walls or columns connected to the existing buildings. Retrofitting costs are between 15% and 25% of the replacement cost.

Keywords: schools, retrofitting, structural reinforcing, vulnerability, seismic safety.

1. INTRODUCTION

Since 1950 there are 16 earthquakes ($5.2 \leq Mw \leq 7.2$) that have caused structural and nonstructural damage to schools in Venezuela. The last one was the 1997 Cariaco earthquake (M_w=6.9) that caused the collapse of four school buildings killing one teacher and several students. This paper presents results obtained in a project that aims to improve seismic safety in Venezuelan schools. Its overall objective was to develop tools that could influence effectively the reduction of the seismic risk in school buildings and therefore in the protection of the lives of students and teachers. The project was developed through the joint efforts of the Institute of materials and structural models (IMME) of the Faculty of engineering of the Central University of Venezuela, the Venezuelan Foundation for Seismological Research (FUNVISIS) and the foundation of buildings and endowments educational (FEDE) of the Ministry of Education, with funding from the Ministry of Science and Technology. Detailed results are presented in (IMME-FUNVISIS-FEDE, 2011).

2. INVENTORY OF SCHOOLS

The collection of information to generate a data base related to the earthquake-resistant characteristics of school buildings was developed in several ways: (a) The national survey carried out by the Ministry of Education, and (b) inspections to schools completed by the research team. As a result, from a total of 19.972 school buildings surveyed, 49.5 per cent are in zones of high seismic hazard (PGA=0.3-0.4g for 475 years return periods), 41.1% in intermediate hazard zones (PGA=0.20-0.25g), and 9.4% in low hazard zones (PGA=0.10-0.15g). Approximately 46% of the buildings were built before 1982, with standards and requirements less demanding than those in modern standards. In a still more unfavorable situation are approximately 21% of those buildings that were built before 1967 when there was a major change in the seismic design requirements motivated by the earthquake of that year in Caracas. A total of 438 buildings were identified belonging to two construction types defined as critical because they correspond to the four buildings collapsed in the Cariaco 1997 earthquake: 104 buildings are of Old-Type (Figure 1) and 334 are of the Box-Type (Figure 2). Of these, 42 Old-Type and 205 Box-Type schools are located in the high seismic hazard zones.

a) The collapsed Valentín Valiente School	b) Cristobal Rojas School (School Nº 4)
	

Figure 1. There are 104 school buildings of the Old-Type, similar to the collapsed buildings in the 1997 earthquake.

a) The collapsed Martínez High School	b) Silverio Córdoba School (School Nº 9)
	

Figure 2. There are 334 school buildings of the Box-Type, similar to the collapsed buildings in the 1997 earthquake.

3. FRAGILITY CURVES AND EXPECTED DAMAGES IN SCHOOLS

A methodology for the determination of school buildings fragility curves which supplies the probability of reaching a specific damage state given the occurrence of a seismic event was developed. The basic hypothesis is that buildings were designed and built in compliance with the seismic code in force at the time of the construction. From 1939 to date, there have been seven national seismic standards. Four damage states were defined: minor, moderate, severe and collapse. The proposed methodology was evaluated and calibrated with field observations on school buildings during the 1997 Cariaco earthquake. School buildings built with old standards are considerably more vulnerable than those built with modern standards, as shown in Figure 3 for a two story standard school building built in Caracas on stiff soil. A school designed with the 2001 code resists on average an earthquake which is about 5 times more intense than a school designed with the 1955 code. For a seismic event with a PGA about 0.30g, the likelihood of achieving the complete damage state of the building designed with standards of 1939, 1947, 1955, 1967 and 1982 is about 33, 34, 42, 10 and 5 times greater than the probability of the same building designed with the actual 2001 code. A sample of 569 school buildings in the metropolitan area of Caracas was exposed to the simulation of the 1967 Caracas earthquake (Mw = 6, 6). It was concluded that at least 13 schools would be severely damaged but not to collapse, which is 2.3 per cent of the total. About 59 people may be slightly injured, 41 severely injured and there could be a few deaths as social losses. Details of the methodology and results are included in a companion paper presented in this conference (Coronel and López, 2012).

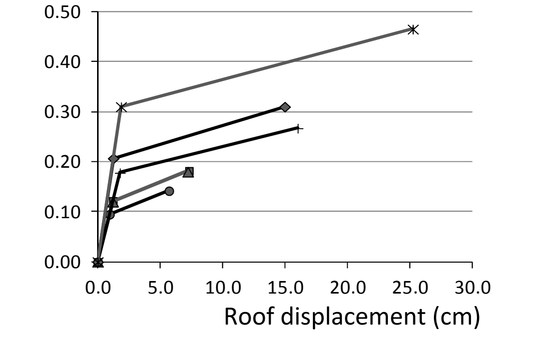
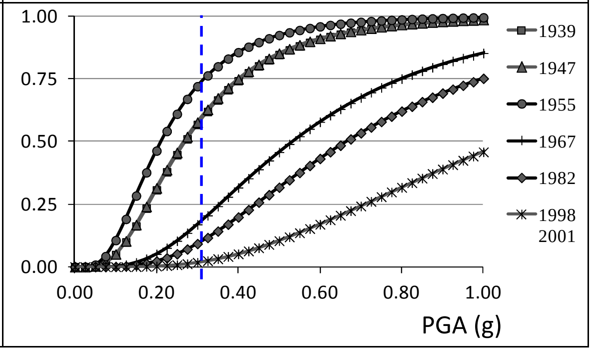
a) Capacity curves: Base shear/weight vs. roof displacement (cm)	b) Fragility curves for the complete damage state. Probability of exceedence vs. PGA (g)
	

Figure 3. Capacity and fragility curves for a standard two-story reinforced concrete school building located in Caracas on stiff soil, for each building code since 1939 to 2001.

4. INSPECTION OF SCHOOL BUILDINGS

An instrument for rapid visual inspection of school buildings that aims to identify those characteristics that most influence their vulnerability to earthquakes was developed. A team of people was trained to carry out inspections. Special attention was aimed at establishing the year of construction and identifying short columns, weak and soft stories and absence of well-defined lines of seismic resistance in one of the two horizontal directions. A methodology for assigning vulnerability, risk, and prioritization indices was established. The risk index is obtained by combining the vulnerability index with a hazard index. The prioritization index is obtained by combining the risk index and a school population index. The prioritization index is intended to be used to select those critical buildings that deserve to go to a later phase of detailed studies. The rapid visual inspection instrument was applied to 293 schools distributed throughout the country. Results point out that about 31% of the inspected buildings showed risk index values equal or greater than that of the Martínez High School (Figure 2). Figures 4 shows the prioritization index; about 41% of the inspected buildings have values greater than that of the V. Valiente School and about 15% greater than the value of the Martínez High school, both collapsed in the 1997 earthquake (Figures 1 and 2). Details of the methodology and results are included in a companion paper presented in this conference (Marinilli et al., 2012).

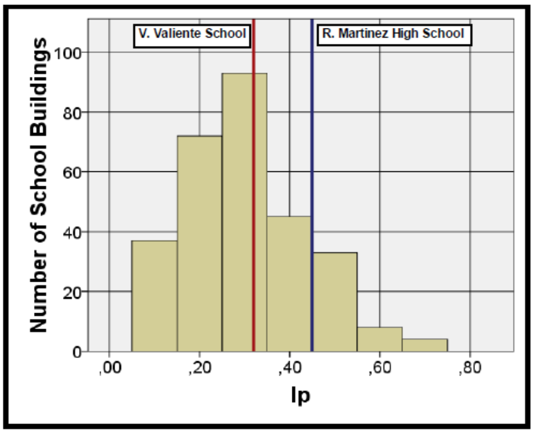


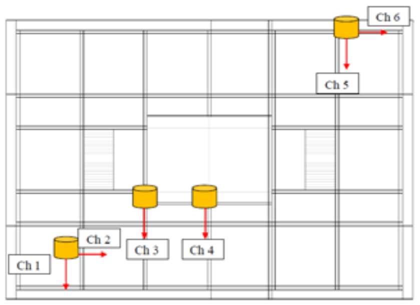
Figure 4. Prioritization index (Ip) for the inspected 294 schools as compared with the collapsed schools.

5. MEASUREMENT OF DYNAMIC PROPERTIES

Natural periods, damping ratios and modal shapes of the first vibration modes were determined for the school buildings selected as pilot projects, using techniques of dynamic response to ambient vibrations. Each building was instrumented with six 1 Hz seismometers placed at the highest floor, as shown for the Box-Type building in Figure 5 (School Nº 5 in Table 1). Non-parametric methods of signal processing were used for the determination of the dynamic properties. The vibration modes were calculated from the cross correlation analysis of two simultaneous records. The vibration modes were determined for phase angles of 0° or 180° for the common frequencies in the different records. With the vibration amplitude for each frequency at each point, it was possible to draw an approximate vibration mode for the building. The modal damping was calculated from the power spectra by the half power method, assuming that the damping is small.

Damping ratios vary between 2% and 10%. The first mode frequencies vary between 5.4 and 7.9 Hz, values that are relatively high due to the contribution of the infill masonry walls that contribute to the dynamic response during low intensity motions. Three schools (Schools Nº 1, 7 and 10 in Table 1) located in the highest hazard zone were selected to install permanent accelerometers to record their responses to future seismic events.

a) Location of accelerometers in plan



b) Power spectral density of Channel 6.

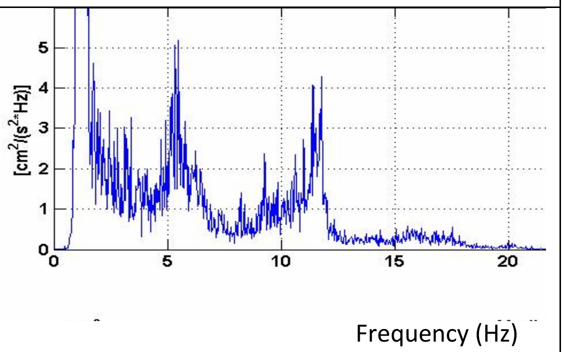


Figure 5. Determination of dynamic properties for low intensity motion in School Nº 5.

6. TRAINING OF TEACHERS TOWARDS SEISMIC PREVENTION

Workshops of seismic prevention were completed in the schools selected as pilot projects (Table 1). The workshop is an educational experience, interactive and participatory, using practical activities for the explanation of the issues, in a pleasant, simple and clear language, to make the information accessible to all kinds of audiences (IMME-FUNVISIS-FEDE, 2011). This workshop provides teaching and learning strategies that can be used as elements that can motivate the reduction of non-structural vulnerability of the school with simple implementing measures, as well as facilitate the organization of the educational community to provide a timely and effective response in the event of an emergency. Also these workshops provide a space to share the details of the project and its significance for the reduction of risk in the educational institutions (Figure 6).

7. DETAILED SEISMIC EVALUATION OF SELECTED SCHOOLS

Eleven schools were selected as pilot projects for a detailed evaluation and seismic retrofitting. The schools listed in Table 1 are located in four different cities, have between two and four stories and were built between 1950 and 1991. They are located in the high seismic hazard zones of the country where peak ground acceleration (PGA) values between 0.30g and 0.40g is required for the design of new buildings at rock sites in the national building code (FONDONORMA, 2001). Since school buildings are considered as essential facilities the above values are increased by 30% and further multiplied by a factor between 0.9 and 1 depending on the soil condition. Table 1 shows the soil condition and the resulting PGA (return periods ~1,000 years) at each school. The elastic response spectra at each school site are plotted in Figure 7.

a) Children in an exercise of preparation

b) Training of teachers

Figure 6. Seismic prevention workshop in a school (courtesy of Aula Sísmica-FUNVISIS).

The structural system of the schools Nº 1 to 11 in Table 1 consists of reinforced concrete space frames. These school buildings have the following structural deficiencies: i) Low ductility capacity; ii) Low stiffness and strength; iii) The absence of well-defined seismic resistance lines in one of the two horizontal directions of the building; iv) The presence of several short columns that increases the brittle behavior.

School buildings Nº 1 to 4 in Table 1 are for practical purposes identical to the two buildings of the Valentín Valiente school that collapsed during the 1997 Cariaco earthquake (M_w=6.9). Figure 1 compares school building N° 4 located in the city of Cúa with of one building of the Valentín Valiente school after the earthquake. These school buildings have a rectangular plan and are very flexible in the longitudinal direction due to the small dimension (20 cm) of the columns and the absence of beams (Figure 9), although in some cases they may have a shallow beams in that direction (Figure 8). School N° 5 is a modified more recent version of older schools Nº 1 to 4 where the column short dimension was increased to 25 cm but the presence of a longitudinal beam below the slab at about 1/3 of the column length from the top introduces short column effects. School buildings Nº 6 (Figure 10) to 9 are similar to the two buildings of the Martínez High School that collapsed in the1997 earthquake. A view of one of the collapsed building is compared in Figure 2 with school building N° 9 (Table 1). These 3- to 4-story buildings have a rectangular plan with an opening at the center and shallow beams in the short plan direction. School N° 10 (Figure 11) is a 2-story building with 25 cm square columns that has no beams in one direction at the central span. The L-shaped plan 4-story school building N° 11 (Figure 12) has a flat slab supported by columns without beams, and most partition walls are terminated at the second story leaving a soft first story. School Nº 12 in Table 1 is a rural school that is located in many places in the country; it has a non-ductile steel frame structure and is very flexible in the longitudinal direction (Figure 13).

Most buildings have partition masonry walls, 12 to 15 cm thick, made of concrete or clay blocks, located inside the frames and generating short columns. Although these walls introduce additional lateral stiffness and strength during low intensity ground motions, they are not included as seismic resistance elements in this evaluation due to its brittle behavior during the large intensity motions that are expected in these buildings.

Table 1. Schools selected for structural retrofitting

School data					Existing structure		Retrofitted structure	
N°	Name	N° of Stories	City Soil	PGA	Vibration Period (s)	Roof Drift (%)	Vibration Period (s)	Roof Drift (%)
1	Rodríguez Abreu	2	Carúpano Stiff soil	0.468g	1.58	6.2	0.07	0.03
2,3	Urbaneja and Reyes	2	Carúpano Stiff soil	0.468g	1.50	10.1	0.27	0.60
4	Cristobal Rojas	2	Cúa Stiff soil	0.351g	2.28	5.9	0.27	0.50
5	Playa Grande	2	Carúpano Stiff soil	0.468g	0.99	3.5	0.14	0.011
6	Faustino Sarmiento	4	Caracas Rock	0.39g	1.70	1.6	0.66	0.62
7	Corazón de Jesús	3	Cumaná Stiff soil	0.494g	1.37	3.3	0.39	0.71
8	Graterol Bolívar	3	Cumaná Soft soil	0.468g	1.25	5.5	0.23	0.25
9	Silverio Córdova	3	Cumaná Soft soil	0.468g	1.21	5.9	0.39	0.78
10	M. Reina de López	2	Carúpano Stiff soil	0.468g	1.24	5.1	0.19	0.24
11	Padre Sojo	4	Caracas Rock	0.390g	1.31	1.4	0.38	0.48
12	Rural School	1	National Any soil	0.494g	2.20	5.0	0.3	0.80

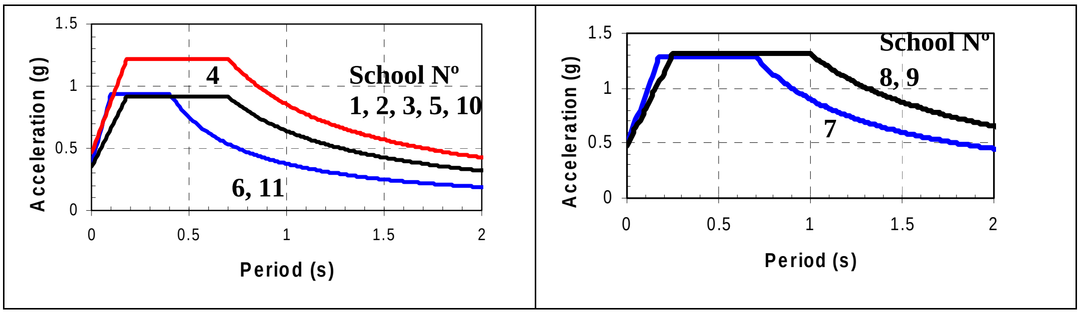


Figure 7. Elastic response spectra for evaluation and retrofitting at each school.

Mathematical models of each school building were developed and the seismic responses to the spectra shown in Figure 5 were calculated by the response spectrum analysis method. Two seismic horizontal components of equal intensity were considered and their effects combined by the SRSS-rule. A vertical seismic component with 2/3 the intensity of the horizontal components was included in the analysis. Table 1 shows the fundamental period of each building considering cracked sections of structural elements and neglecting the contribution of masonry infill walls. The large flexibility of buildings is pointed out by the large period values shown in the table. The roof drift ratios shown in Table 1 vary between 1.4% and 10.1%, exceeding the 1.2% limit specified in the building code and pointing out the need for structural retrofitting. The base shear demands imposed by the seismic motions for ductility values not larger than 3, exceeds the base shear capacity of the buildings.

8. SEISMIC RETROFITTING OF SELECTED SCHOOLS

The seismic retrofitting criteria for the analysis and design was defined as follows: i) An additional structural system is added to the buildings to take most of the lateral seismic loads; the additional structure is separated from the existing structure and attached to the slabs along the perimeter of the building so as to interfere less with the existing structure that takes the gravity loads; ii) The combined existing and additional structural systems should be able to support a seismic motion given by the elastic response spectra shown in Figure 7, by means of inelastic response using reduction factors not exceeding the value of 3; iii) A limit of 0.8% was imposed to the drift ratio in order to protect the existing non-ductile structures.

Retrofitting projects were developed for the 12 school buildings shown in Table 1. Reinforced concrete C-shape shear walls at the corners were designed for school Nº 1, supported on reinforced concrete wall footings (Figure 8). For schools Nº 2, 3 and 5, two shear walls at the middle were added in addition to the corner shear walls, all of them supported on micro-piles. Two concentric steel braced frames in each direction were designed for school Nº 4, supported by a quadrilateral ring of reinforced concrete continuous footing. Figure 9 shows the retrofitting of the building under construction. Reinforced concrete columns connected by beams at the perimeter of the building supported by micro-piles, were designed for school Nº 6 (Figure 10). For schools Nº 7 to 11 the solution uses reinforced concrete shear walls connected by beams at the perimeter of the building and supported by micro-piles (Figures 11 and 12). For schools Nº 1 to 12 slabs were reinforced at the perimeter of the buildings in order to transfer the lateral loads to the additional structure. Figure 13 shows the retrofitting solution designed for the school Nº 12 that consisted of adding steel bracings in the longitudinal direction. The detailed engineering of the retrofitting projects was developed as follows: School building Nº 1 and 5 by (Hernández, 2011), Nº 2 and 3 by (Fernández, 2011), Nº 4 by (Hernández, 2005), Nº 6 to 9 by (Tenreiro, 2011), Nº 10 by (Lee, 2011), Nº 11 by (Rodríguez, 2011) and Nº 12 by (Bonilla and Azancot, 2010).

The effects of retrofitting on the fundamental periods and roof drift ratios are summarized in Table 1. Fundamental periods were reduced by a factor ranging between 2 and 23, leading to a significant reduction of the roof drift ratios. The cost of retrofitting, expressed as a percentage of the replacement cost, varies between 15% and 25% as shown in Table 1.

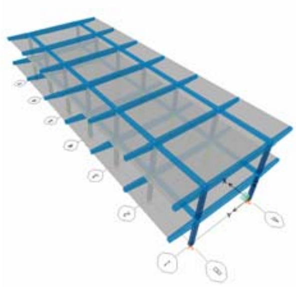
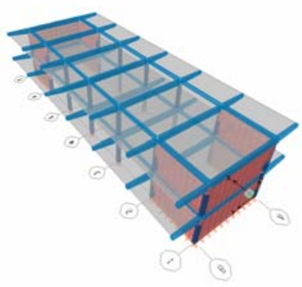
a) General view	b) Existing structure	c) Retrofitted structure
		

Figure 8. Retrofitting of school building Nº 1 (Rodríguez Abreu). (Images courtesy of A. Fernández).

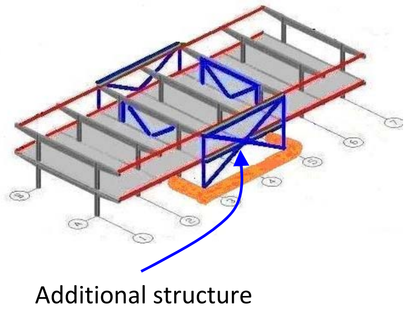
a) General view	b) Existing and additional structures	c) Under construction
		

Figure 9. Retrofitting of school building N° 4 (Cristobal Rojas). (Hernández, 2005).

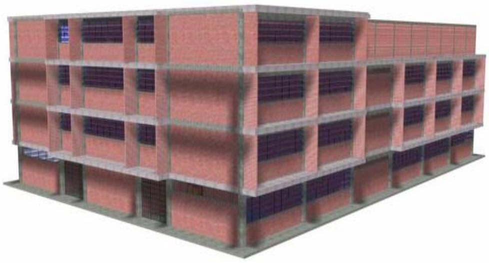
a) First story	b) Existing building	c) Retrofitted building
		

Figure 10. Retrofitting of school building Nº 6 (Faustino Sarmiento). (Images courtesy of A. Taboada).

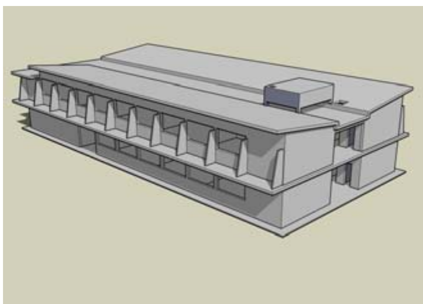
a) General view	b) Existing building	c) Retrofitted building
		

Figure 11. Retrofitting of school building Nº 10 (M. Reina de López). (Lee, 2011).

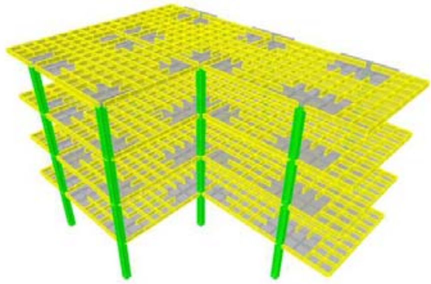
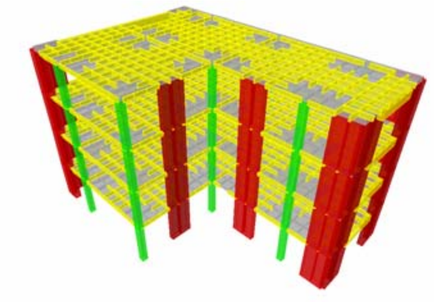
a) General view	b) Existing structure	c) Retrofitted structure
		

Figure 12. Retrofitting of school building Nº 11 (Padre Sojo). (Rodríguez, 2011).

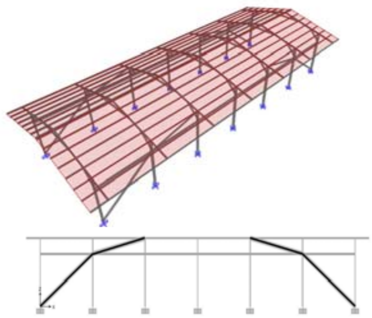
a) General view	b) Existing structure	c) Retrofitted structure
		

Figure 13. Retrofitting of school building Nº 12 (Rural School). (Bonilla and Azancot, 2009).

9. CONCLUSIONS

Results of a project aiming to improve seismic safety in Venezuelan schools have been summarized in this paper. About 49.5 per cent are in zones of high seismic hazard, from a total of 19.972 school buildings surveyed. Approximately 46% of the buildings were built before 1982, with standards and requirements less demanding than those in modern standards. A total of 438 buildings were identified belonging to two construction types defined as critical because they correspond to the four buildings collapsed in the Cariaco 1997 earthquake, from which 247 are located in the high seismic hazard zones. For a seismic event with a PGA about 0.30g, the likelihood of achieving a complete damage state of buildings designed with old seismic codes is between 5 and 42 times greater than for a modern school buildings designed with the 2001 code.

A methodology for rapid visual inspection was developed and applied to 293 schools distributed throughout the country. Results point out that about 41% of the inspected buildings have prioritization index values greater than that of one school that collapsed in the 1997 Cariaco earthquake.

Eleven school buildings were selected as pilot projects for seismic retrofitting. Vibration periods and damping ratios of the first modes were determined from ambient vibration. These school buildings have the following structural deficiencies: low ductility capacity, low stiffness and strength, the absence of well-defined seismic resistance lines in one of the two horizontal directions of the building, and the presence of several short columns that increases the brittle behavior. The seismic retrofitting consist of adding an structural system to the buildings to take most of the lateral seismic loads; the additional structure is separated from the existing structure and attached to the slabs along the perimeter of the building so as to interfere less with the existing structure that takes the gravity loads. A limit of 0.8% was imposed to the drift ratio in order to protect the existing non-ductile structures. Retrofitting costs are between 15% and 25% of the replacement cost. Permanent accelerometers are actually being placed in three school buildings to record dynamic responses during seismic events.

ACKNOWLEDGMENT

This research was funded by FONACIT, Ministry of Science and Technology of Venezuela, Project # 2005000188. The support of FEDE, FUNVISIS, IMME-FI-UCV, is appreciated.

REFERENCES

Beyer M. (2011). Proyecto de Refuerzo Estructural de la U. E. Corazón de Jesús. Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.

Bonilla R. and Azancot R. Vulnerabilidad sísmica de edificaciones escolares tipo R, IX CONVESIS, Caracas 19-22 Mayo 2009.

Coronel G. and López. O. A. (2012). Regional Seismic Risk, Damage and Loss Scenarios of Venezuelan School Buildings, 15 World Conference on Earthquake Engineering. 24-28 September 2012, Lisbon, Portugal.

Fernández N. (2011). Proyectos de Refuerzo Estructural de las escuelas M. Urbaneja y Petrica Reyes de Quilarte. Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.

FONDONORMA (2001). Edificaciones Sismorresistentes. Norma COVENIN MINDUR 1756, Caracas (In Spanish).

Hernández E. (2011). Proyectos de Refuerzo Estructural de la E. B. Playa Grande y de la E. B. Rodríguez Abreu, Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.

Hernández, J.J. (2005). Proyecto de Refuerzo Estructural: Adecuación de la Escuela Básica Cristóbal Rojas. Anexo 3, Informe Técnico IMME No. 81-04, Caracas, Venezuela.

IMME-FUNVISIS-FEDE. (2011). Reducción del Riesgo Sísmico en Edificaciones Escolares de Venezuela. Informe Técnico Final, 05 de Diciembre de 2011. Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.

Lee C. (2011). Proyecto de Refuerzo Estructural de la U. E. M. Reina de López, Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.

Marinilli A., Fernández N., López O. A. and Coronel G. (2012). Inspection of School Buildings in Seismic Prone Areas in Venezuela. 15 World Conference on Earthquake Engineering. 24-28 September 2012, Lisbon, Portugal.

Rodríguez D. (2011). Proyecto de Refuerzo Estructural de la U. E. Padre Sojo, Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.

Tenreiro E. (2011). Proyectos de Refuerzo Estructural de las Escuelas D. Faustino Sarmiento, Silverio Córdova y Graterol Bolívar. Proyecto FONACIT Nº 2005000188, Ministerio de Ciencia y Tecnología. Caracas, Venezuela.