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SEISMIC RISK REDUCTION IN VENEZUELAN SCHOOLS

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ABSTRACT

70% of the about 28,000 Venezuelan schools are in the high hazard zones. This paper describes the results obtained so far in a national program aiming to evaluate and reduce the risk of existing schools. Basic information such as construction type and year of construction was investigated by means of the National School Survey carried out by the Ministry of Education; 46 % of the buildings were built before 1982, using earthquake requirements considerably less demanding than the ones in modern codes. 436 buildings that are similar to the collapsed buildings in the 1997 earthquake were identified. A risk level is determined by means of fragility curves, assuming that the buildings were constructed in fulfillment of the code at the time of construction. By means of a data collection form 284 school buildings were inspected; seismic vulnerability is determined and combined with seismic zone and school population to calculate a risk index. Ten schools were selected as pilot projects for detailed studies; dynamic properties were determined by ambient vibration tests. Most of them have reinforced concrete space frames with masonry infill. Seismic retrofitting is carried out using linear and nonlinear analysis. Auxiliary structures are added to support the seismic loads, connected with the diaphragms of the existing structures and supported on new foundations.

Introduction

Several recent earthquakes have pointed out the high vulnerability of school buildings. About 19,000 children died during the 2005 Kashmir earthquake in Pakistan. The 2008 Sichuan, China, earthquake destroyed several schools killing thousands of children. A significant number of school buildings collapsed during the 2009 L´Aquila earthquake (M=5.8). Since 1950 there have been 16 moderate earthquakes in Venezuela that have caused structural and nonstructural damage to schools; the 1997 Cariaco earthquake ((M_w=6.9) caused the collapse of four school buildings killing 23 people. This paper presents the methodology and general results obtained so far in a national project that aims to reduce seismic risk in school buildings of Venezuela.

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Inventory of School Buildings

The 28,878 schools in Venezuela are distributed at each zone as shown in Table 1 and Figure 1. The PGA values vary at each zone to a maximum of 0.4g in Zone 7, for return periods T=475 years (COVENIN 2001). About 70 % of the schools are in zones of high hazard (0.25g ≤ PGA ≤ 0.40g). The dots plotted in Figure 1 show the location of 18,685 school buildings that have been incorporated in a geographical information system (GIS) aiming to generate an integrated instrument to simulate earthquake occurrence and expected damage and losses.

Table 1. Percent of schools and PGA values at each seismic zone in Venezuela.

Zone	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
PGA, g	-	0.10	0.15	0.20	0.25	0.30	0.35	0.40
Schools (%)	1.4	1.8	7.3	20.1	23.2	40.3	3.9	2.0

The information on the construction type, the year of construction and the number of floors of each school, was investigated in the National School Survey carried out by the Ministry of Education that contains images of the construction types used more frequently in the 20th century. At a first stage a total of 549 buildings that are highly vulnerable to seismic motions were identified; 79% are in the high hazard zones, and 332 of those buildings belong to the Box-Type and 104 belong to the Old-Type I, which are types that collapsed during the 1997 Cariaco earthquake. Those are 2- and 3-story buildings with non-ductile reinforced concrete space frames that were built 30 to 60 years ago and have several short columns created by infill walls.

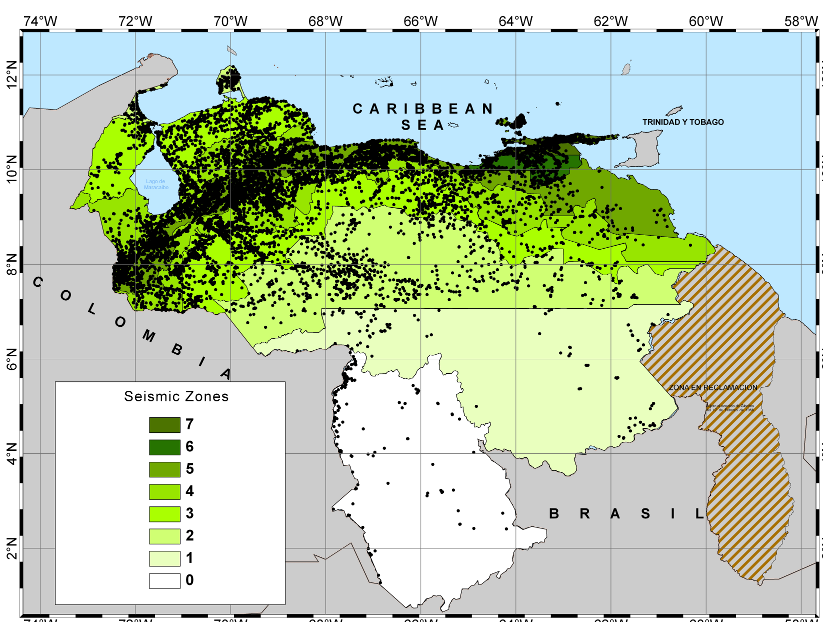


Figure 1. Seismic zone map and location of school buildings in Venezuela.

Six different codes were used in the past for the design and construction of schools, being the first code established in 1939. Seven construction periods are defined in Table 2, from the pre-1939 to the post-1998 periods. From 18,685 buildings identified so far, the percent at each construction period is shown in Table 2; about 46 % of the buildings were built before 1982, using earthquake resistant requirements considerably less demanding than the actual ones.

Table 2. Percentage of school buildings at each construction period.

Construction period	**Pre 1939**	**1939-1947**	**1947-1955**	**1955-1967**	**1967-1982**	**1982-1998**	**Post 1998**
Buildings (%)	1.5	1.8	3.7	14.2	24.8	27.7	26.4

Fragility Curves and Seismic Risk Index

The vulnerability of a school building is characterized by approximate fragility curves that are expressed as a function of the PGA. The goal is to facilitate decision making to develop plans for prevention and risk reduction. The buildings are supposed to satisfy the design code in force at the year of construction. A bilinear capacity curve is developed: i) The yield base shear is estimated from the design shear specified in the code, incorporating an overstrength; ii) The yield displacement is calculated assuming the fundamental period and that the dynamic response is contained in the fundamental mode; iii) The ultimate displacement is estimated assuming a ductility capacity associated with each code (Coronel and López 2009). Four damage states are defined: (1) Slight, (2) Moderate, (3) Severe, and (4) Complete (Figure 2a). Each damage state is represented in the capacity curve selecting the yield and ultimate displacements. The fragility curves are defined using a lognormal distribution, adopting standard deviations recommended in (FEMA-NIBS 2009; Bonett 2003). Figure 2b shows the fragility curves for the complete damage state for 2-story schools in seismic zone 7, for the six codes.

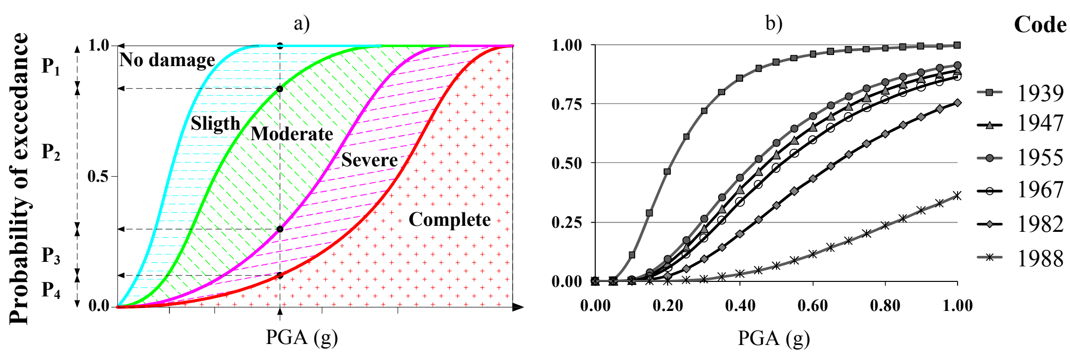


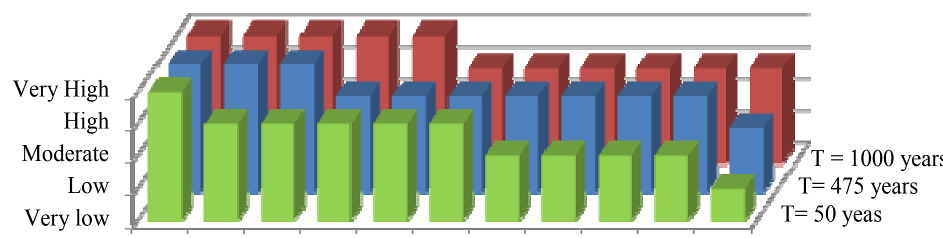
Figure 2: a) Example of the fragility curves for each damage state; b) Fragility curves for the complete damage state for 2-story buildings designed with different codes.

The probability of occurrence (P_i) of each damage state (i) is obtained from the fragility curves for a given PGA value (Figure 2a). The Damage ratio (D_i) is defined for each damage state as a percentage of building replacement cost, as shown in Table 3 (Blondet et al. 2005). The risk index (R_I) is obtained by weighting the probability of occurrence with the damage ratio: $R_I = \Sigma P_i.D_i$. A Risk level is defined associated with ranges of R_I, as shown in Table 3. Four Risk levels are defined: Very low, Low, Moderate, High and Very High. Figure 3 shows the estimated risk levels for a group of 42 school buildings located in the Sucre State of Venezuela, in the seismic zones 6 and 7; the number of stories and the year of the corresponding design code are also indicated. Results are presented for T= 50, 475 and 1000 years, associated with PGA values of 0.20g, 0.40g and 0.50g in Zone 7 and 0.18g, 0.35g and 0.44g in Zone 6, respectively. Figure 4 shows risk levels calculated for 547 school buildings in the Sucre State for T= 475 years. Since 56 % of those buildings were built before 1982, 53 % of them have a risk that is characterized as Very High.

Table 3. Damage state, Damage ratio (D_i), Risk level and Risk index (R_I).

i	Damage state	D_i (%)
0	No damage	0
1	Slight	5
2	Moderate	20
3	Severe	65
4	Complete	100

Risk level	R_I (%)
Very low	< 2.5
Low	2.5 – 12.5
Moderate	12.5 - 30
High	30 - 75
Very High	> 75



Code-year	39	47	55	67	67	67	82	82	82	82	98
Number of Stories	2	2	2	2	2	3	2	3	2	3	2
Seismic zone	7	7	7	7	6	7	7	6	7	6	7
Number of buildings	1	1	2	7	3	5	16	1	1	1	1

Figure 3. Risk level for 42 buildings in the Sucre State for different return periods.

Seismic Inspection of Schools Buildings

The goal is to perform seismic inspections of school buildings to establish priorities for detailed structural evaluations. The instrument developed for the inspections is a data collection form specially designed to gather structural and non-structural information for school buildings. To elaborate it several previous experiences were considered: The data collection form proposed in (FEMA 2002) to perform rapid visual screening of buildings for potential seismic hazards in USA, and the data collection form used by (Meneses and Aguilar 2004) to perform rapid inspections of school buildings for vulnerability evaluation purposes in Peru. The data collection form developed herein was prepared considering the experience of the 1997 Cariaco Earthquake

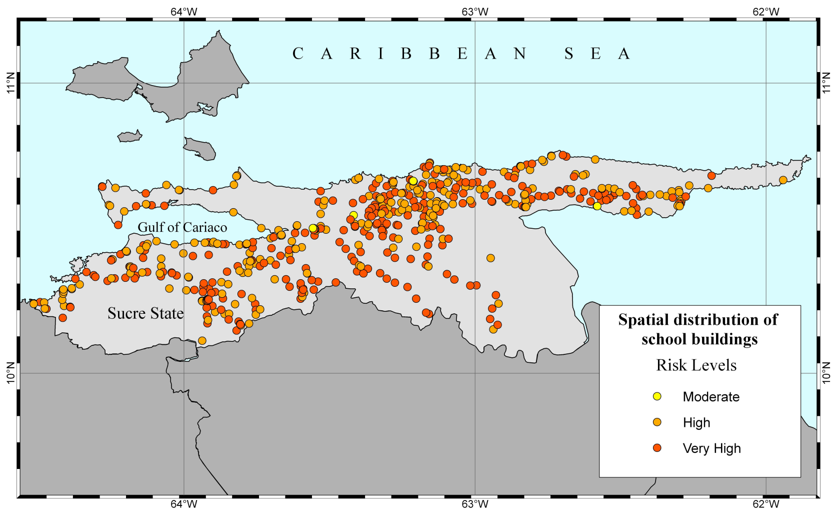


Figure 4. Risk level for 547 schools buildings in Sucre State for T= 475 years.

that led to the collapse of school buildings, and the prescriptions contained in Venezuelan seismic and structural codes (COVENIN 2001). The information gathered during the inspections can be grouped as: location (GPS), year of construction, location plan, schematic horizontal and vertical structural plans, structural configuration, structural and non-structural details, geotechnical hazard, state of maintenance, and a photographic report. To facilitate the use of the data collection form as well as to guaranty the adequate acquisition and report of the information, a manual was elaborated to be used as a guide by inspectors during training and inspections. Additionally, several workshops were performed to instruct the inspectors, including training sessions in actual school buildings, and discussion of results obtained during the practices. A total of 284 school buildings were inspected (CENAMB 2008), selected according to the following criteria: Buildings with structural configuration similar to those collapsed during Cariaco Earthquake, older buildings, and buildings located in higher seismic zones. 84% of the inspected buildings are in zones with PGA values between 0.30-0.40g (T=475 years).

The information gathered for each building was used to calculate a risk index, which is a number between 0 and 1, obtained as a multiplication of a hazard index, an occupation index, and a vulnerability index. The hazard index depends on the seismic hazard map for Venezuela, the vulnerability index depends on structural and non-structural details, and the occupation index depends of school population. Special attention in the vulnerability index is focused in the amount of short columns and the absence of well defined structural lines of resistance in two orthogonal directions. The risk index is not intended to measure the actual seismic risk of a school building, but to support technical and administrative decisions, such as establish priorities to perform detailed structural evaluations and seismic rehabilitation of school buildings. A detailed description of the indexes values is given in a companion paper (Marinilli et al. 2010). The school buildings that collapsed during the 1997 Cariaco Earthquake were used to calibrate the proposed indexes: The V. Valiente (VV) School shows seismic hazard index, occupation index, vulnerability index, and risk index values of 1.00, 0.50, 0.64, and 0.32, respectively, while M. Centeno High School (MC) shows indexes values of 1.00, 1.00, 0.45, and 0.45, respectively. Both schools were located in the town of Cariaco in Sucre State, the higher seismic hazard zone of the country. As an example of the results obtained during the inspections, Figure 5 shows the vulnerability index and risk index values obtained for 19 school buildings inspected in Sucre State. All buildings show risk index values greater than the value obtained for MC High School (0.45), and more than 60% of the buildings show risk index values greater than the value obtained for VV School (0.32). Additional information is given in the companion paper (Marinilli et al. 2010). This information will be used to establish priorities to perform detailed studies and rehabilitation of school buildings. Additionally, 10 buildings were selected in a first stage as pilot projects for retrofitting and preparedness plans carried out into the “Seismic-Classroom” Project (FUNVISIS 2010).

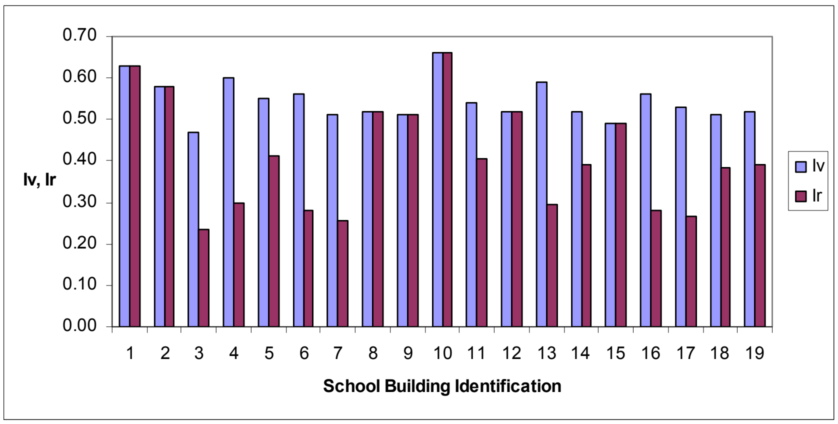


Figure 5. Vulnerability Index (Iv) and Risk Index (Ir) for schools in Sucre State.

Dynamic Properties

From ambient vibration tests the natural periods, mode shapes and damping ratios of the first vibration modes were determined for the school buildings selected as pilot projects, in order to evaluate those properties in current building conditions before structural retrofitting is performed. Each building was instrumented with six 1 Hz seismometers placed at the highest floor, as shown for the *Corazón de Jesús* Box-Type school in Figure 6. Non-parametric methods of signal processing were used for the determination of the dynamic properties. The data for each sensor goes to an A/D converter with a sampling rate set to 200 Hz; frequencies of interest rarely overpass 100 Hz. For each record, the power spectra were calculated with 60% overlap and 214 data points. A Hanning window was used to calculate the mean square Fourier spectrum. The vibration modes were calculated from the cross correlation analysis of two simultaneous records, as illustrated in Figure 6. 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. Table 4 presents results for five selected schools; high frequency values are observed due to the small vibration amplitudes with a strong influence of the non structural components, particularly the masonry infill walls. Damping ratios vary from 2 to 10 %. Dynamic properties will be measured again after structural retrofitting is completed.

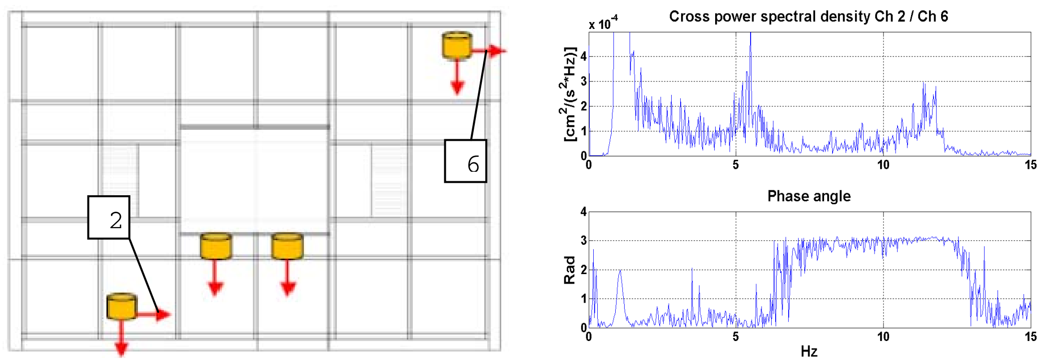


Figure 6. Layout of accelerometers, sample of cross spectral density and phase angle.

Table 4. Natural frequencies and damping ratio for selected schools

School	Playa Grande		Corazón de Jesús		Antonio R. Abreu			María R. López			Experimental Venezuela		
Mode	1	2	1	2	1	2	3	1	2	3	1	2	3
Frequency (Hz)	7.9	12	5.5	11.5	7.0	10.5	13.0	6.4	8.2	15.8	5.4	9.4	9.5
Damping (%)	3.1	10.4	10.0	-	7.1	2.7	4.7	6.2	4.9	4.7	2.7	2.1	4.2

Retrofitting of a Flat-Slab Building

The L shaped plan building (Figure 7) built in 1986 is located in Caracas (Zone 5). The 4-story reinforced concrete structure has a 30 cm deep joist floor slab with ribs along two directions, supported by 8 columns with a cross-section of 40 cm x 40 cm. All bay lengths are 6.9 m; cantilever lengths are 3.4 m. Total height is 12.8 m and weight is 963 t. Foundations consist of reinforced concrete deep piles. Infill walls of 15 cm-hollow clay blocks are present in most of the upper story bays. Concrete strength was 250 k/cm^2; steel yield stress was 4200 k/cm^2. Columns hoops of 3/8-inch diameter were installed 12.5 cm on center near the joints and 25 cm further away from the joints, with 90-degree hooks and no transverse reinforcement at the joints. The period considering effective stiffness values is 1.31 s without infill walls and 0.66 s with them. The roof drift demand was determined by means of the coefficient method (FEMA 2005); ground motions 1, 2 and 3 were defined by PGA values of 0.14, 0.30 and 0.39g, for return periods of 50, 475 and 1000 years, respectively. The roof drift demand neglecting the infill walls are plotted on the pushover curve (Figure 7); seismic motions 2 and 3 exceed the capacity of the existing structure. The retrofitting adds an auxiliary structure consisting of 6 reinforced concrete structural walls and 2 connecting beam at each floor (Figure 7). The auxiliary structure is connected to the building by the floor slabs acting as diaphragms, which are strengthened at the wall-slab joints. Structural walls are supported by reinforced concrete micro-piles. The period of the retrofitted building is 0.38 s without masonry walls and 0.29 s with them. The increase of stiffness and strength of the retrofitted structure is shown in Figure 7; the drift demand is kept below 0.5% in order to protect the existing non-ductile structure that supports the gravity loads. The cost of the structural retrofitting is estimated to be 22 % of the replacement cost.

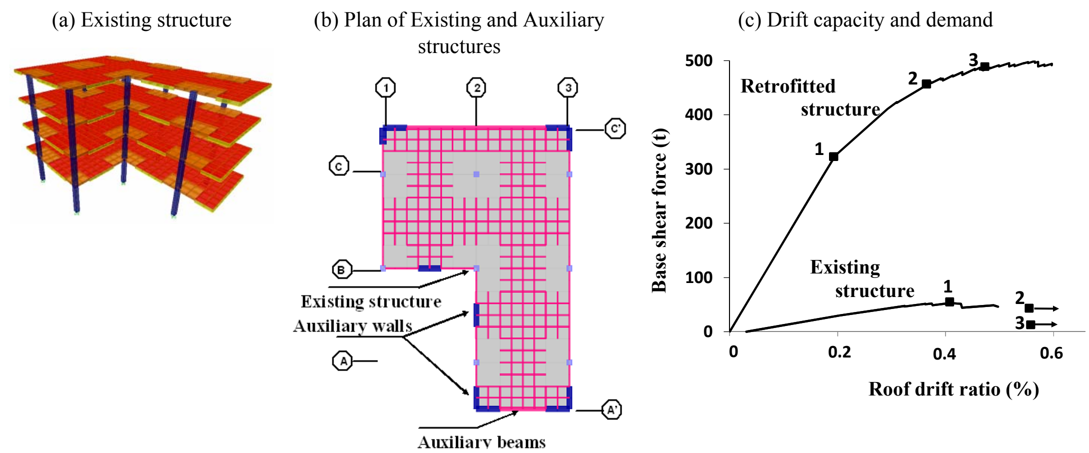


Figure 7. Retrofitting of a Flat-Slab school building

Retrofitting of a Box-Type Building

This section summary the retrofitting project of a Box-Type building located in Caracas (Zone 5) and built in 1970. It has a rectangular plan with an opening at the middle (Figure 8). The 4-story building has a reinforced concrete space frame; cross-sections are 40 cm x 40 cm for columns and 40 cm x 60 cm for beams in the longitudinal direction. The transverse beams are shallow beams having 40 cm x 30 cm dimensions. The concrete joist floor system is 30 cm deep with ribs along the transversal direction. There are 7 transverse frames spaced at 7.2 m and 6 longitudinal frames spaced a 7.20 and 3.60 m. The total height is 12.30 m. Infill walls of 12 cm-thick hollow clay blocks are located in most bays. From the 42 columns of the building, 10 are short columns of 0.35 m in length and 14 of 1.37 m, created by the infill in the longitudinal direction, at each story. Total weight is 3800 t. Columns hoops of ϕ3/8-inch were installed 12 cm on center near the joints and 20 cm further away from the joints, with 90-degree hooks and no transverse reinforcement at joints. The periods are 1.05 s and 0.90 s, for motion along the longitudinal and the transversal directions, respectively, considering the infill walls and effective stiffness values. The roof drift demand was calculated for ground motions 1, 2 and 3 and plotted in Figure 8 for the longitudinal direction. The roof drift demand exceeds the drift capacity for ground motions 2 (T=475 years) and 3 (T=1000 years). The retrofitting scheme adds an auxiliary reinforced concrete structure along the perimeter of the building, supported on micro-pile foundations. Figure 8 shows the pushover curve for the retrofitted structure; roof drift demands are kept below the values that could threaten the capacity of the existing structure to support the gravity loads. The cost of the structural retrofitting is about 15 % of the replacement cost.

Retrofitting of a Rural School

The Rural school shown in Figure 9a is a flexible structure with a lightweight roof supported on steel beams and columns. It weighs approximately 5.60 t and has periods of 2.38 s and 0.34 s in the longitudinal and transversal direction, when the masonry infill walls are not considered. Some infill walls overturned during the 1997 Cariaco earthquake. For Seismic Zone 5, roof drift demand in the longitudinal direction for ground motions 2 and 3 exceeds the

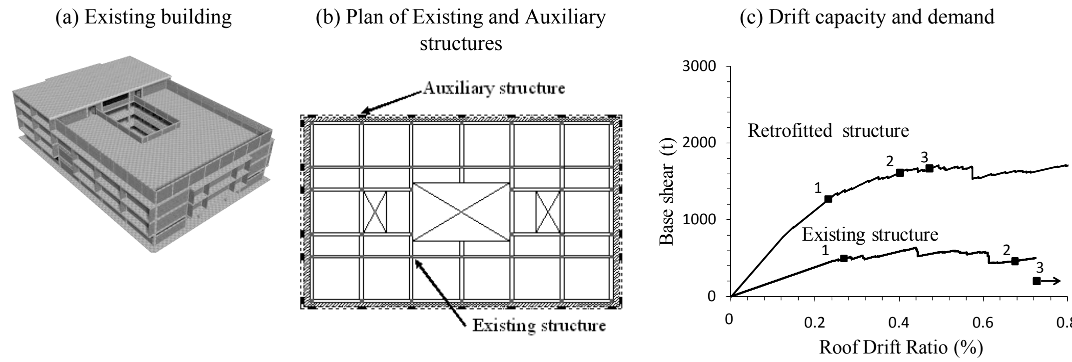


Figure 8. Retrofitting of a Box-Type school building.

limit of 3% assigned for this structure (Figure 9c). A retrofitting solution adds diagonal braces in the longitudinal direction and haunched beams in the transversal direction (Figure 9b). The lightweight roof is also replaced by a heavier roof increasing the weight to 31.6 t. The periods are reduced to 0.30 s and 0.32 s in the longitudinal and the transverse directions. Roof drift demand for the retrofitted structure shown in Figure 9c are kept below 1.5 %.

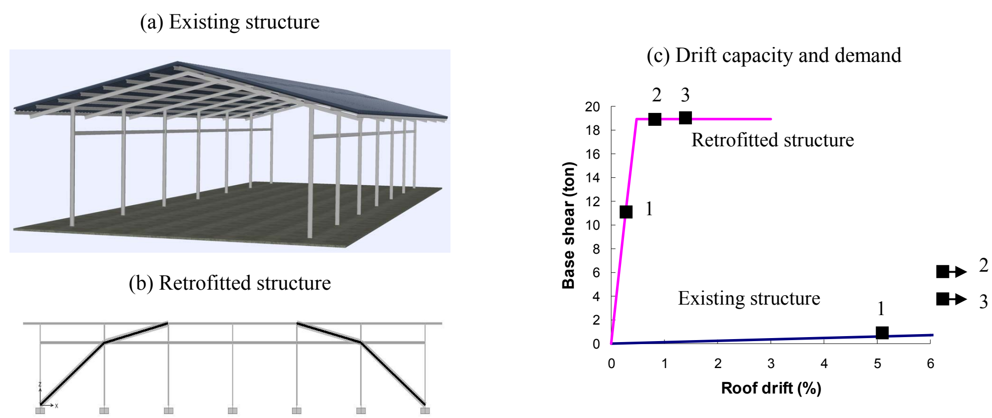


Figure 9. Retrofitting of a Rural School building

Conclusions

About 70 % of the 28,878 schools in Venezuela are located in zones with high seismic hazard. About 46 % of the buildings were built before 1982, using earthquake resistant requirements considerably less demanding than the requirements contained in the modern codes. A total of 436 buildings that are similar to the ones that collapsed during the 1997 Cariaco earthquake were identified. For the highest hazard zone, 53 % of 547 buildings examined have a risk that is characterized as Very High. A data collection form was designed to gather structural and non-structural information about school building. Special attention in the vulnerability index is focused in the amount of short columns and the absence of well defined structural lines of resistance in two orthogonal directions. A risk index is defined as function of a hazard index, an occupation index, and a vulnerability index. A total of 284 school buildings were inspected.

Ten school buildings were selected as pilot projects for implementing preparedness plans and structural retrofitting. The dynamic properties were determined from ambient vibration tests. Most of the retrofitting solution adds an auxiliary structure consisting of reinforced concrete structural walls that are connected to the existing building by the floor slabs acting as diaphragms. Structural walls are supported by micro-piles. Drift demands are kept below the values that could threaten the capacity of the existing structure to support gravity. Retrofitting costs are between 15% and 22% of the replacement cost.

Acknowledgments

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