Reducing Seismic Risk of School Buildings in Venezuela

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School buildings have frequently collapsed during earthquakes. The 1997 Cariaco earthquake led to the ruin of four reinforced concrete school buildings that were built several years ago. Failures were the result of structural deficiencies: short columns and low lateral strength, stiffness and energy dissipation capacity. Seventy percent of Venezuelan schools are in high-hazard regions; about 1,000 are similar to the collapsed schools. With the purpose of developing a national risk-reduction program, the expected seismic performance of two typical schools was evaluated: one representing schools built 50 years ago (Old-type) and one representing schools built 20–30 years ago (Box-type). These were analyzed utilizing nonlinear pushover techniques and compared with the inventory of schools in Venezuela. Old-type schools were found to need retrofitting in moderate- and above-seismic zones, and Box-type schools in higher zones. Practical retrofitting is achieved with the addition of auxiliary structures to support the seismic loads, leaving the existing structures to support only the gravity loads. This effort has led to a national program. The initial phase, surveying approximately 28,000 existing schools, has begun. [DOI: 10.1193/1.2791000]

INTRODUCTION

BEHAVIOR OF SCHOOL BUILDINGS DURING RECENT EARTHQUAKES

Recent earthquakes have confirmed the high vulnerability of school buildings. About 19,000 children died during the 2005 Kashmir earthquake ($M_w=7.6$) in Pakistan, most of them in widespread collapses of school buildings that were affected to a much higher proportion than other buildings (EERI 2006). A medium-sized earthquake ($M_w=6.4$) in 2003 caused the collapse of three new schools and a dormitory building in Bingöl, Turkey; about 60% of the 168 people killed died in those buildings (Milutinovic and Massué 2004). During the 2003 Boumerdès (Algeria) earthquake ($M_w=6.8$), 564 out of 1,800 schools were seriously damaged (Bendimerad 2004). The 2002 Molise, Italy earthquake ($M_w=5.6$) killed 27 children and one teacher due to the collapse of a school building (Dolce 2004), representing 93% of the total number of deaths. During the 2001 Bhuj earthquake ($M_w=7.7$) in India, 971 students and 31 teachers died (Jain 2004). A total of 43 schools were damaged beyond repair in the 1999 Kocaeli earthquake ($M_w=7.4$) in Turkey (Yüzügüllü et al. 2004). In Venezuela, 31 students and one teacher died

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when four school buildings collapsed during the 1997 Cariaco earthquake (M_w=6.9; Rangel 1999), a disaster that led to the definition of this research program.

Most of the school collapses have taken place in developing countries. Thousands of children have been killed because existing knowledge and technology have not been applied to keep them safe from earthquakes. A considerable effort is needed to implement plans to retrofit existing schools and to guarantee the safety of new ones. International actions are required to transfer existing knowledge and technologies to protect school children from earthquakes.

SOME ACTIONS IN THE RIGHT DIRECTION

To the authors' knowledge, the first significant proposal for school construction with seismic safety standards was the State of California Field Act that was enacted in 1933, one month after the Long Beach Earthquake in which many schools were destroyed (Steinbrugge 1970, SSC 2004a). For non-disruptive retrofitting actions, FEMA 395, the Incremental Seismic Rehabilitation of School Buildings K-12, provides an innovative approach (FEMA 2002). For nonstructural components, a Guide and Checklist are available in California Schools (SSC 2004b). Japan, Canada, Mexico, Peru, Colombia, Algeria, Ecuador, and Turkey have taken actions to reduce seismic risk in schools (Fernández et al. 1996, Tena-Colunga 1996, LTDA 2002, Bendimerad 2004, Meneses and Zenón 2004, Nakano 2004, Spence 2004, Yüzügüllü et al. 2004, Blondet et al. 2005, Taylor et al. 2006).

The protection of school buildings from earthquakes was the purpose of an international meeting organized by OECD and GeoHazards International (Tucker 2006); in July 2005 OECD countries agreed on steps to reduce earthquake risks for school children (OECD 2005). The biennial campaign for 2006–2007 of the United Nations Secretariat for the International Strategy for Disaster Reduction focuses on the theme "Disaster Risk Reduction Begins at School" (UN/ISDR 2006). The School Earthquake Safety Initiative "Reducing Vulnerability of School Children to Earthquakes" is a program promoted by the United Nations Center for Regional Development (UNCRD 2006).

Although four out of seven reinforced concrete buildings that collapsed during the 1997 Venezuela earthquake were school buildings and 35 other schools were severely damaged, only a few isolated actions have been taken in Venezuela to evaluate and reduce the seismic risk in existing schools. This paper presents the results of a research effort that has led to a national program, which points the country in the right direction for the development of seismic risk–mitigation strategies.

PURPOSE OF THIS WORK

The collapsed schools are representative of two types built several decades ago; more than a thousand identical or similar schools are found all over the country. This work aims to identify the causes of the collapses in Cariaco, to evaluate the seismic risk in these standard schools, to present retrofitting options, and to propose a national program and public policies to reduce the risk.

With that purpose, the expected seismic performance of these schools was calculated by means of linear and nonlinear analysis; the nonlinear static procedure of FEMA 356 (FEMA 2000) with the improvement described in FEMA 440 (FEMA 2005) was used to estimate seismic demands. Calculations were made with the computer program SAP2000.

PERFORMANCE OF SCHOOLS DURING THE 1997 CARIACO EARTHQUAKE

The Cariaco earthquake ($M_w = 6.9$, depth $= 9$ km) occurred at 3:24 P.M. local time on 9 July 1997, 378 km east of Caracas, causing the collapse of seven reinforced concrete buildings. In the city of Cariaco the seismic event caused the collapse of four school buildings, a two-story office building, and a three-story hotel under construction, all of them of reinforced concrete, as well as several single-family dwellings with masonry or "bahareque" walls (sticks interwoven with canes and mud). In addition, out of a total of 592 schools inspected after the earthquake, 35 (6%) suffered damage beyond repair and ought to be replaced, 66 (11%) suffered moderate structural and nonstructural damage, 398 (67%) underwent light structural and nonstructural damage, and 93 (16%) were not damaged (FEDE 1998).

Cariaco is located 10 km from the epicenter of the earthquake, but the collapsed buildings were 600 to 900 m from the rupture surface. A mean right lateral displacement in the east-west direction of about 25 cm was observed along a 30-km length of the inshore segment, corresponding to the known trace of the El Pilar fault in the boundary of the South American and the Caribbean tectonic plates (Audemard 2006). One accelerograph recorded a peak horizontal acceleration of 0.17 g in Cumaná, about 73 km from the epicenter, but 20 km from the rupture surface. For the purpose of evaluating the structural response of the collapsed buildings to similar ground motions, the probable value of the peak acceleration in Cariaco was estimated using four known attenuation relationships for near-fault motions (López et al. 2004). For $M_w = 6.9$, a distance to rupture less than 1 km, and soil condition (González et al. 2004), the median of the peak acceleration was found to be between 0.49 g and 0.54 g, with an average value of 0.52 g. The particular directivity effects are ignored, because it is not the purpose of this work to perform an accurate evaluation of the response to the Cariaco earthquake, but to estimate the probable response for a set of similar conditions. However, the spectrum estimation is determined for the fault-parallel seismic component, considering the collapse direction of the school buildings. According to the calculations, there is a 50% probability that the peak acceleration was in the 0.39 g to 0.71 g range. A representative pseudo-acceleration spectrum for the motion along the east-west direction was estimated from the median spectrum of 33 fault-parallel components of near-fault motions recorded on soil (Chopra and Chintanapakdee 2003), scaled to a median peak ground acceleration of 0.52 g (Figure 1a).

COLLAPSE OF THE VALENTÍN VALIENTE SCHOOL BUILDINGS

Description of the Buildings and Observed Performance

The Valentín Valiente (VV) School consisted of two similar, independent two-story buildings. They were typical school buildings built about 50 years ago and defined as

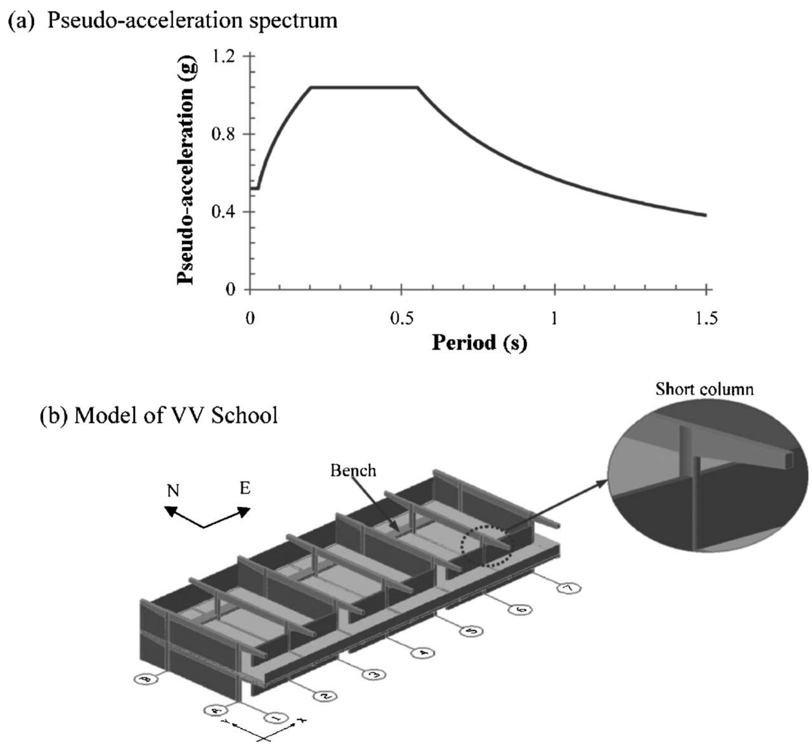

Figure 1. (a) Pseudo-acceleration spectrum for the ground motion estimated in Cariaco; (b) idealized model of VV School, Building I, with the roof removed, showing masonry walls, short columns, and concrete bench.

Old-type schools. The height of each story was 3 m. Each building had reinforced concrete frames. Most columns had a 20-cm × 30-cm cross-section, with the smaller dimension along the longitudinal direction of the building. Frames with beams (20 cm wide by 65 cm deep) were located along the transverse direction of the building, with no beams along the longitudinal direction (Figure 1b). The concrete joist floor system was 25 cm thick and had a 5-cm slab with ribs along the longitudinal direction spaced 50 cm apart. A mean concrete strength of 14 MPa was obtained from testing. Yield stresses were 235 and 276 MPa for the longitudinal and transverse reinforcement bars, respectively. Transverse reinforcement consisted of plain bars of 1/4-inch diameter set 25 cm on center in beams and 15 cm in columns; no transverse reinforcement was placed at the joints. Masonry infill, made of 15 cm-thick hollow concrete blocks, completely filled the transverse frames along lines 1, 3, 5, and 7. Short columns with 55 cm clear length were generated by the 1.70-m masonry infill that partially filled the longitudinal frame along line A. A stiff concrete bench located along line B also generated short columns (Figure 1b; IMME 1998).

Both buildings showed large permanent displacements along the longitudinal (east-

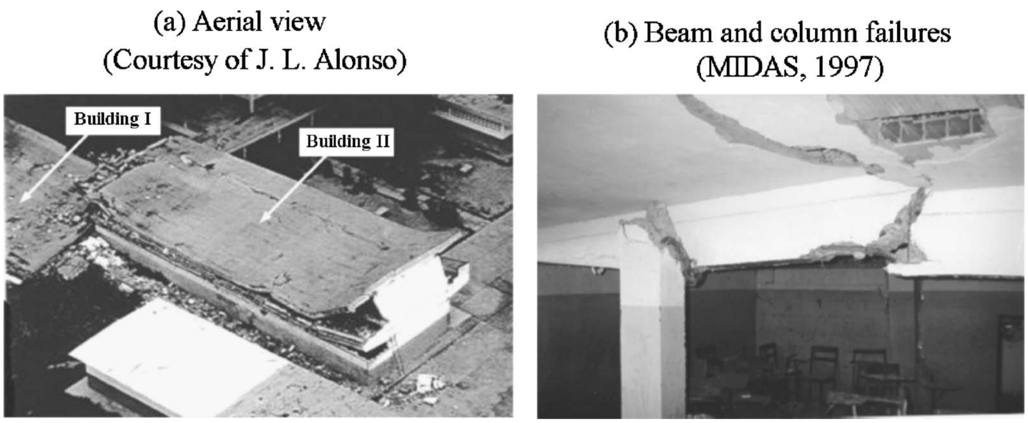

Figure 2. Structural failure of the VV school buildings during the 1997 Cariaco earthquake.

west) direction (Figure 2a), which is also the direction of the fault trace. Building I suffered a total collapse with the slabs resting on the ground, but Building II had a partial collapse with the slabs left resting on the masonry walls. Brittle shear failures in the short columns, ductile bending failures in the other columns, and combined beam-column failures were observed (Figure 2b).

Identifying Structural Deficiencies

The mathematical model of Building I includes the contribution of the infill walls, the bench, and the joist floor system to the stiffness and strength of the structure. Beam and columns were modeled considering non-conforming transverse reinforcement. The building weighs 315 tons and has an initial elastic period of 0.70 s. A three-dimensional pushover analysis was performed to determine the lateral load capacity of Building I in the longitudinal direction (i.e., the direction of the observed collapse). A lateral load distribution similar to the first mode loading was applied from left to right, which was the orientation of the collapse. Loading in the opposite direction would result in a stronger but more brittle response. Figure 3 shows the results of the analysis. A first shear failure at short columns A2, A4, and A6 of the first story (Figure 3a) was observed for a roof displacement $\Delta \cong 0.8$ cm (roof drift ratio $\cong 0.13\%$) and a base shear force $V \cong 24$ tons (Figure 3b). This was followed by shear failures of the same three columns at the second story when $\Delta \cong 2.8$ cm (roof drift ratio $\cong 0.47\%$) and $V \cong 32$ tons, and subsequent bending failures of joists and columns up to $\Delta \cong 6.6$ cm (roof drift ratio $\cong 1.1\%$; Del Re 2006).

The expected base shear force of the equivalent linear system was estimated by an elastic analysis using the fault-parallel pseudo-acceleration spectrum of Figure 1a. Results indicate a base shear elastic demand of about 224 tons, which is 8.6 times greater than the yield base shear force ($\cong 26$ t) obtained from the bilinear idealization shown in Figure 3b. From the nonlinear static procedure (FEMA 2000), the expected maximum

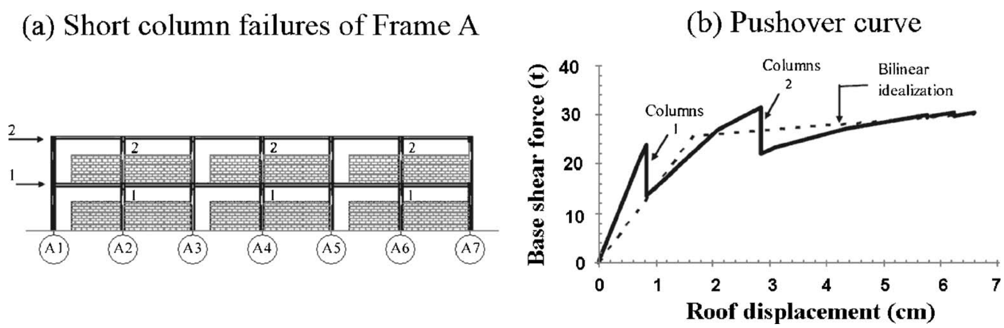

Figure 3. Pushover curve of VV School, Building I, showing the brittle shear failures in short columns of Frame A.

roof displacement imposed by the ground motion was estimated to be 17 cm (roof drift ratio of 2.8%), which is about 10 times the equivalent yield displacement and about 2.6 times the ultimate displacement (Figure 3b).

The collapse of the VV school buildings was the result of a large seismic demand that could not be withstood because of: i) very low resistance and rigidity of the structure in the longitudinal direction, due to the small size of columns and the absence of beams; ii) the presence of short columns; and iii) the limited energy-dissipation capacity of the structural elements. The presence of the short columns precipitated a brittle shear failure in a structure that would have failed in any event, even developing all its low ductility. The failure was not the result of faulty construction; it was the result of well-known structural deficiencies in the seismic design of the buildings, certainly not foreseen in the standards in use 50 years ago.

COLLAPSE OF THE RAIMUNDO MARTÍNEZ CENTENO SCHOOL BUILDINGS

Description of the Buildings and Observed Performance

The Raimundo Martínez Centeno (RMC) school buildings (Figures 4–6) were designed in 1978 and built in 1985. They were typical school buildings defined as Box-type schools. Although the structures had been designed for Zone 2 of the 1967 Seismic Code, they were built in Cariaco (Zone 3), where lateral design loads were twice those of Zone 2. The school consisted of two similar, independent buildings, each with a C-shaped floor plan. The three-story Building I analyzed herein had reinforced concrete frames along both horizontal directions and masonry infill of 15 cm-thick hollow clay blocks. The concrete joist floor system was 30 cm deep with ribs along the north-south direction. Column cross-sections were 35 cm $\times$ 35 cm and beam cross-sections were 30 cm $\times$ 40 cm and 30 cm $\times$ 70 cm wide and deep, respectively. The height of each story was 3.10 m. Frames along lines 1 and 5 were totally filled with masonry. Short columns of 70 cm in length were created by the masonry infill in all columns, in all stories of the longitudinal frames B and E, and in three out of four columns in the upper stories of frames C and D; frames C and D has no infill walls at story one (Figure 6a).

(a) Before the earthquake (b) After the earthquake

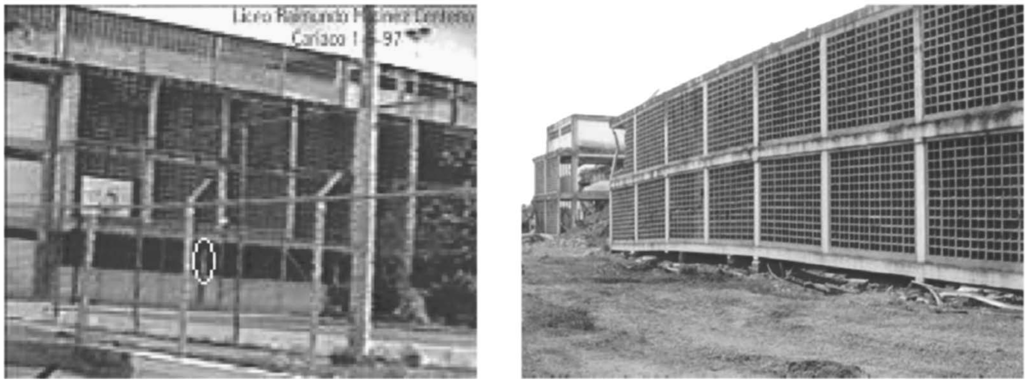

Figure 4. Building I of RMC School, before the earthquake (courtesy of E. Castilla) and after the earthquake, showing crushing of the first story (MIDAS 1997).

Column hoops of 3/8-inch diameter were installed 10 cm on center near the joints and 20 cm further away from the joints, with no transverse reinforcement at the joints. Stirrups and hoops observed at the site had 90-degree hooks. Mean values obtained from tests for the concrete strength, 25 MPa, and steel yield stress, 414 MPa, complied with the values specified in construction plans (IMME 1998).

Both buildings exhibited similar behavior during the earthquake, consisting of failure of the columns at story one, leaving story two resting on the ground, with the larger

(a) (b)

Figure 5. (a) Compression column failure and (b) shear column failure at the RMC School (MIDAS 1997).

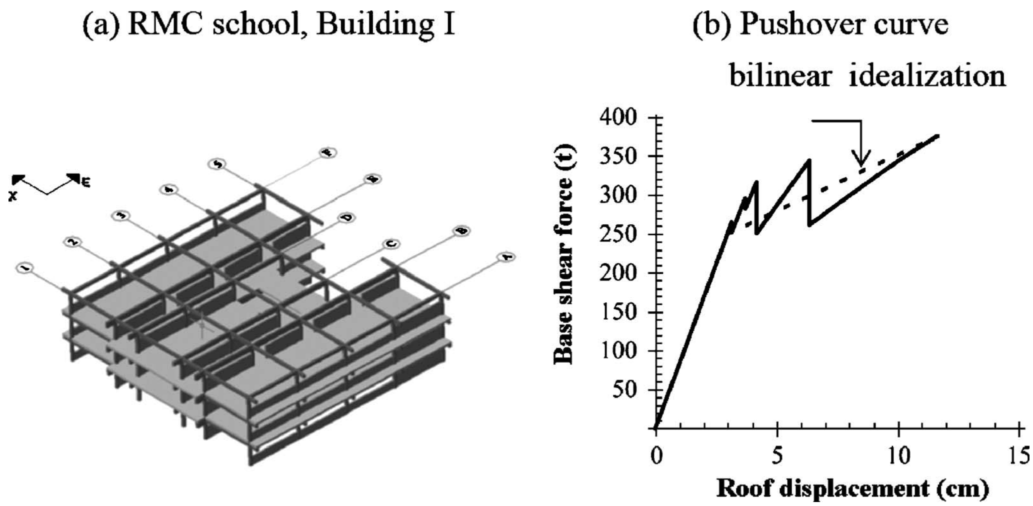

Figure 6. (a) Idealized model of the RMC school, Building I, showing masonry infill walls and short columns. The roof and masonry walls in the north-south direction are not shown. (b) Pushover curve in the east-west direction for Building I.

displacement along the east-west direction (Figure 4). Shear failures of short columns and compression failures and buckling of the longitudinal steel in other columns were observed on stories two and three (Figure 5).

Identifying Structural Deficiencies

Mathematical modeling of Building I considers the contribution of the infill walls and effective moments of inertia for beams and columns (Figure 6a). The weight of the building is 1,900 tons and the initial elastic period is 0.69 s, corresponding to motion with a predominant component along the east-west direction. Modeling parameters for beams and columns are for non-conforming elements. The lateral load capacity (base shear force-roof displacement) of the building in the east-west (longitudinal) direction, the direction of the observed collapse, is shown in Figure 6b. The nonlinear response is initiated by the shear failure of nine short columns at the first story, followed by a similar failure at the short columns of the second and third stories (Puig 2006). The base shear force demand, obtained from an elastic dynamic analysis using the estimated fault-parallel pseudo-acceleration spectrum (Figure 1a), is about 1,500 tons, which exceeds 5.9 times the yield base shear force estimated from the bilinear idealized pushover curve (Figure 6b).

The nonlinear response history of frame B (or identical frame E) was investigated; these frames are the critical frames of the building due to the large number of short columns (70 cm long; Figure 7a). The analysis was performed for several ground acceleration records: the motions recorded at Stations 5028 (Array 7) and 942 (Array 6) during the Imperial Valley earthquake (10/15/1979), which were selected given the similarities

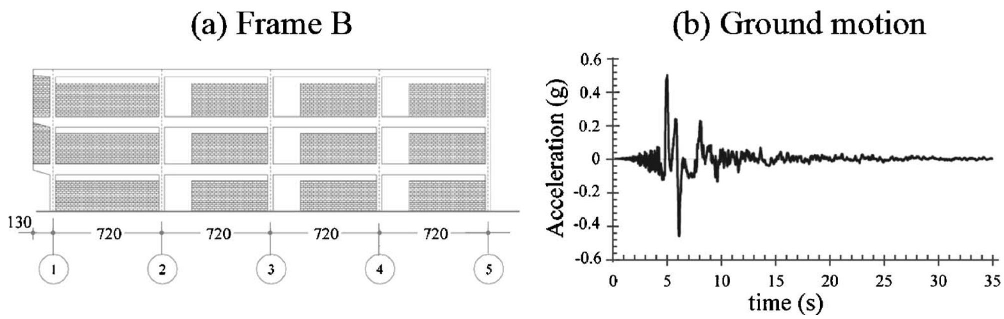

Figure 7. (a) Frame B of RMC School, Building I; (b) scaled Imperial Valley accelerogram (15 October 1979), Station 5028 (Array 7), longitudinal component.

in magnitude, distance to rupture, and soil condition; and the accelerogram recorded at 20 km from the rupture surface during the Cariaco earthquake. All the accelerograms were scaled to 0.52 g peak acceleration. Selected results are presented in Figure 8 for the longitudinal component at Array 7 (Figure 7b). Figure 8a shows the drift ratio response history at each story. The shear-drift response at each story is presented in Figure 8b. The collapse of the structure is reached toward the west at a drift ratio of 1.2% in story one at about 5.1 seconds, due to the brittle shear failure of the four short columns at story one and the flexural failure of the last column at the same story. At this moment the response of story three is essentially elastic (drift ratio less than 0.4%), and story two shows the brittle shear failure of two short columns. The failure mode that emerges from these analytical results is similar to the observed behavior, consisting of a large displacement toward the west that led to the collapse and crushing of the first story (Figure 4b) and the shear failure of some columns at the second story (Figure 5b). Response histories to the other acceleration records show similar patterns (López and Espinosa 2007).

The collapse of the two RMC school buildings was influenced by the combination of two factors: structural deficiencies typical of past design practices, and construction in a seismic zone with double the intensity stipulated in the design. The structural deficiencies were the presence of short columns that precipitated brittle failures, low strength, and the limited energy-dissipation capacity of the structure.

REDUCTION OF SEISMIC RISK IN STANDARD SCHOOLS

SEISMIC HAZARD

The zoning map of the Venezuelan standard for seismic regulations (COVENIN 2001) divides the country into seven zones; the hazard in these zones can be described as very high, high, intermediate, and low (Table 1). Design peak ground acceleration varies from 0.40 g in zone 7 to 0.10 g in zone 1 at rock sites, associated to a probability of exceedance of 10% in 50 years. The design procedure in the Venezuelan standard increases by 30% the spectral acceleration values for schools, which implies higher peak acceleration values that have a probability of exceedance of about 5% in 50 years. There

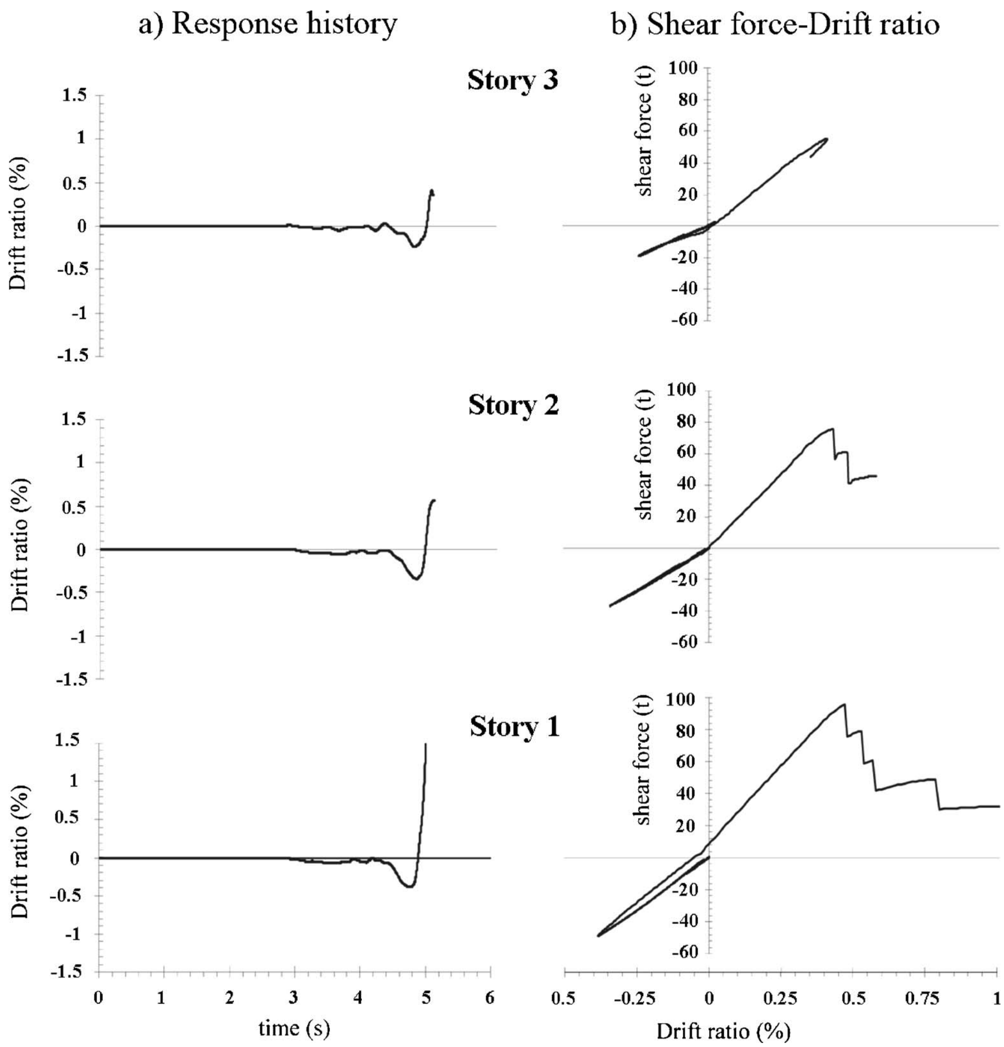

Figure 8. Response at each story of frame B to the scaled Imperial Valley accelerogram. (a) Drift ratio response history; (b) shear force-drift ratio response.

are about 28,000 schools in the country. Approximately 70% are exposed to a hazard ranging from high to very high (Table 1). Only 3% are in the low hazard zones and 27% are in the intermediate hazard zones.

Historically, the construction of many schools around the country has been based on a handful of architectural and structural designs. It is estimated that there are several hundred Old-type and Box-type buildings similar or identical to the VV and the RMC schools, respectively, that collapsed in Cariaco. The exact number and location of these

Table 1. Distribution of schools in the seismic zones of Venezuela

Seismic Hazard	Zone	Design Peak Acceleration (g) (475 Years Mean Return Period)		Number of Schools	School percentage
Very high	6 and 7	0.35 and 0.40		1,671	5.9%
High	4 and 5	0.25 and 0.30		17,844	63.5%
Intermediate	2 and 3	0.15 and 0.20		7,698	27.4%
Low	0 and 1	0 and 0.10		906	3.2%
		Total	=	28,119	100%

buildings is unknown, particularly in the case of the Old-type schools (Figure 9) that were built about 50 years ago. The Box-type schools are between 20 and 30 years old.

A MODERATE EARTHQUAKE CAUSES DAMAGE

The ground acceleration from the 17 November 1991 moderate Curarigua earthquake (m_b=5.3, 16 km depth) was recorded at 47 km and 37 km from the epicenter, indicating horizontal peak accelerations of 0.037 g and 0.044 g, respectively (FUNVISIS 1991). That motion caused a brittle shear failure in three short columns of the first floor in an Old-type school (Figure 10) located at Arenales, 22 km from the epicenter, which was practically identical to the VV School that collapsed in Cariaco (Figure 9).

The moment magnitude and the rupture length were estimated as M_w=5.5 and 5 km, respectively. The distance from the fault plane to the school was estimated to be 18 km. From several attenuation relationships that were adjusted to fit the peak values of the recorded motions, the median value of the peak acceleration at the school site was found to be in the 0.062 g–0.101 g range, depending on the relationship taken into consideration, with an average value of 0.080 g. The average of the median plus one standard

(a) (b)

Figure 9. Old-type school buildings: (a) VV school that collapsed in Cariaco; (b) identical buildings can be found in several locations in the country.

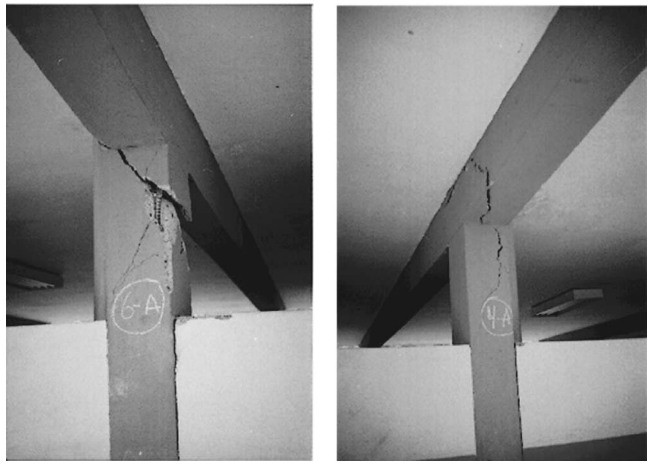

Figure 10. Shear failures in columns at an Old-type school building during a moderate seismic motion (courtesy of A. Morón).

deviation is 0.14 g. The expected maximum roof displacement was estimated using the nonlinear static procedure, assuming that the nonlinear behavior is described by the pushover curve of Figure 3b. For the 0.08 g peak ground acceleration, the roof displacement is 3.2 cm (roof drift ratio=0.54%), which is larger than the values associated to the shear column failures and somewhat lower than the maximum displacement that the building can take (Figure 3b). This moderate-intensity seismic motion caused serious damage to the building, but the structure could later be retrofitted. It is concluded that the Old-type school buildings are exposed to considerable risk even in moderate seismic hazard zones.

DRIFT DEMANDS FOR THE STANDARD SCHOOLS AT EACH SEISMIC ZONE

The Old-type and Box-type schools were selected for evaluation because they are identical to the collapsed schools in Cariaco and are found all over the country. Roof drift demands were estimated at each seismic zone using the nonlinear static procedure (FEMA 2000) for the ground motions specified in the national code (Table 1). Figure 11 shows the pseudo-acceleration spectrum for each zone; stiff soil condition is assumed to be representative for most cases and is adopted for estimation purposes. The yield strength and the ultimate drift values are taken from the results of the pushover analysis (Figures 3 and 6), assuming that those values represent the behavior of the standard schools in each seismic zone. An improved estimation will require on-site investigations at each specific building, which is part of the national program described below. Results of this approximate assessment for the Old-type schools presented in Figure 12a indicate that the ultimate roof drift ratio is exceeded in most of the seismic zones and points out the need for retrofitting even in the moderate-hazard zones. Results for the Box-type school (Figure 12b) show that the ultimate drift ratio is exceeded only in the high and very high hazard zones (zones 5 to 7, Table 1).

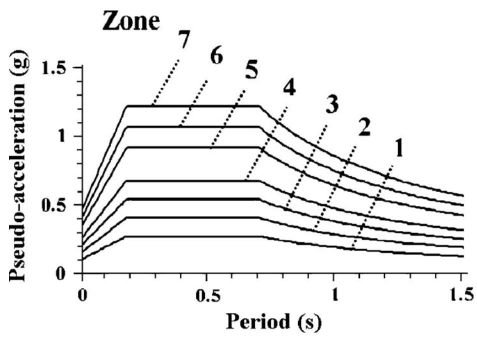

Figure 11. Pseudo-acceleration spectra for each seismic zone, for stiff soil.

RETROFITTING OF STANDARD SCHOOLS

Several options of structural retrofitting for the Old-type and Box-type school buildings were evaluated using technical as well as cost-effective criteria, to increase seismic reliability to the level required in the Venezuelan Code for new schools (COVENIN 2001). The code defines peak acceleration with a mean return period of 475 years for each seismic zone (Table 1). The elastic 5% damped spectrum depends on the soil profile, and is divided by a period-dependent reduction factor that takes into account structural type, detailing, and irregularities. The displacements obtained from an elastic dynamic analysis with the reduced spectrum are amplified to obtain the total displacement. The structures are required to satisfy drift ratio limits that vary between 1.2% and 2.4%. The design codes for reinforced concrete and steel structures are similar to ACI and AISC codes.

All retrofitting options include the separation of the masonry walls from the columns

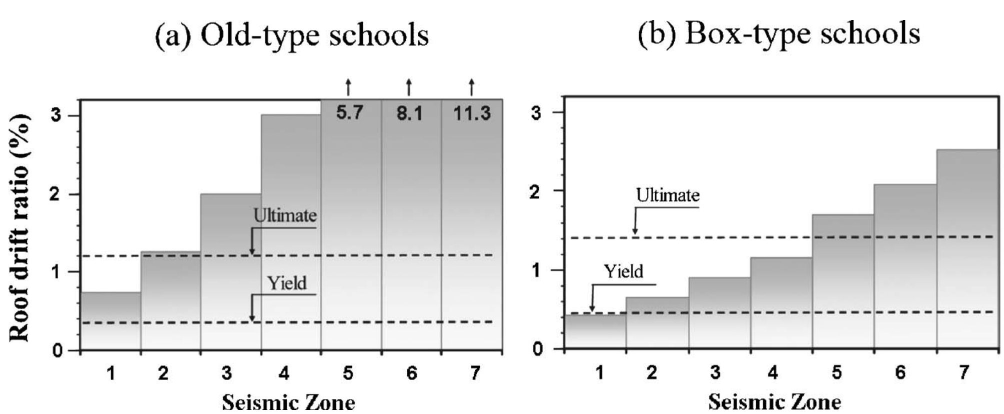

Figure 12. Roofs drift ratio demand, yield, and ultimate drift at each seismic zone for Old-type and Box-type schools.

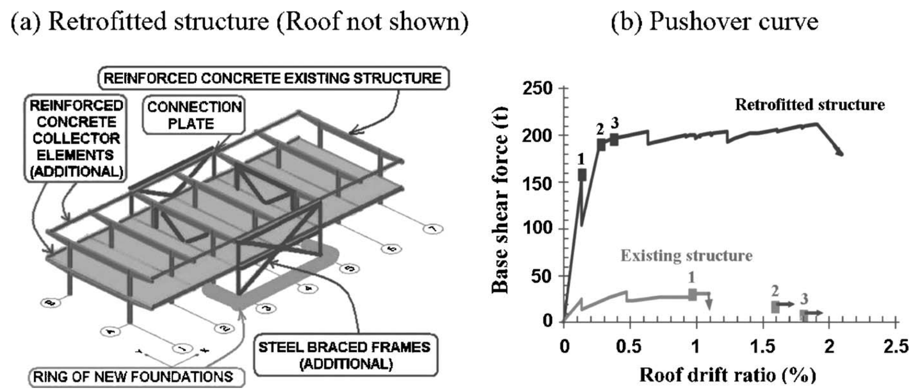

Figure 13. (a) The retrofitted structure for Old-type school buildings is composed of the existing structure, four additional steel braced frames, RC collector elements in the longitudinal direction, and a quadrilateral ring of new foundations (Hernández 2004); (b) pushover curve along the longitudinal direction shows the increase of earthquake-resistant capacity of the retrofitted structure.

in those cases where a short column can be developed; the walls are appropriately anchored to avoid out-of-plane failure. In Option (1) the columns are strengthened and beams added where needed. In Option (2) diagonal steel struts were added in the frame plane, together with an increase in the capacity of joints and columns where the struts are connected. Both options require substantial alterations to the existing structure (demolition of masonry walls, perforation of slabs, etc.) and an increase in the size and reinforcement of the existing foundations. Option (3), selected as the recommended solution, adds an auxiliary system with reinforced concrete walls or steel braced frames to resist the earthquake loads independently of the existing structure. The auxiliary structure is connected to the building by the floor slabs acting as diaphragms, which are strengthened with shear collectors to improve load transmission. The slabs transfer the seismic loads to the auxiliary structure, which in turn transfers it to the new foundations. Because of its great stiffness the auxiliary structure absorbs practically all the lateral loads, leaving the existing weak and brittle structure to accomplish its main function, which is to support the gravity loads. This solution also minimizes alterations to the existing building, hence reducing disruptions of school operations. For moderate-hazard seismic zones an additional retrofitting option of utilizing reinforced infill walls to provide enhanced strength can be considered.

Figure 13a shows the proposed retrofitted structure (Option 3) for two twin Old-type school buildings located in seismic zone 5, using concentric steel braced frames as the auxiliary structure (Hernández 2004). In the longitudinal direction the braced frames are connected to new reinforced concrete collector elements in order to guarantee the 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 of each building to improve the bearing and uplift capacity. A drift limit of 0.7% was imposed in

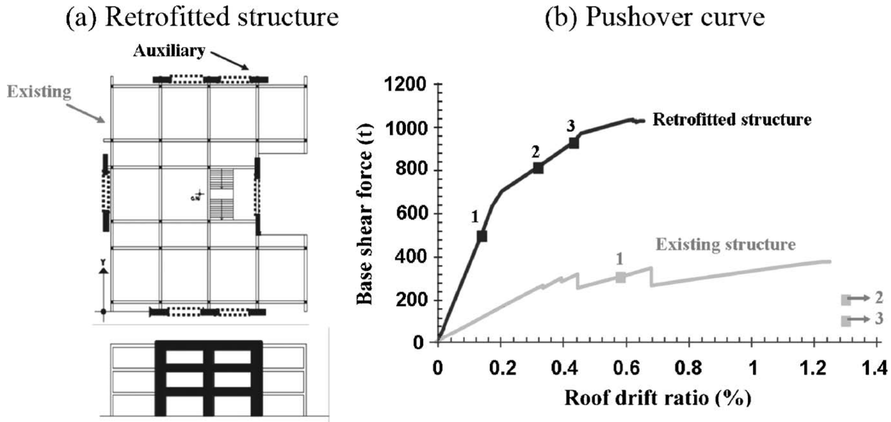

Figure 14. (a) The retrofitted structure for Box-type schools adds auxiliary reinforced concrete walls with openings to the existing structure; (b) pushover curve along the X direction.

the design to protect the existing structures. The increase in stiffness, base shear strength, and ductility of the retrofitted structure is pointed out in the pushover curves shown in Figure 13b. Although a diagonal element buckles at a roof drift ratio of 0.12%, the structure has enough deformation capacity. The design has included rigorous detailing of the connections, for member's overstrength, which also reduces greatly the probability of failures coming from the small system redundancy. The roof drift ratio demand imposed by three ground motion levels in the city of Caracas was determined using the nonlinear static procedure (FEMA 2000). Ground motions 1, 2, and 3 were defined by peak accelerations of 0.18 g, 0.39 g, and 0.49 g, corresponding to mean return periods of about 100, 1,000, and 2,000 years, respectively. The roof drift ratio demand for each ground motion is shown with a number (1, 2, or 3) on the pushover curve for the retrofitted as well as the existing structure (Figure 13b). The retrofitted structure does not display structural damage for ground motion 1. Some structural damage may be expected for ground motions 2 and 3, but the structure is far from collapse and the drift demand of the retrofitted structure is kept below the values that could threaten the capacity of the existing structure to support the gravity loads. On the contrary, the existing structure would have collapsed under ground motions 2 and 3 and would even be near collapse for ground motion 1. The conceptual solution shown in Figure 13a has been proposed as a basis for retrofitting similar school buildings in the country, as a part of the national program described below.

Reinforced concrete coupled shear walls were selected to be used as the auxiliary structure for retrofitting the Box-type schools as shown in Figure 14a. The pushover curves plotted in Figure 14b point out the benefits of the proposed solution. It can be noted that the existing structure would have collapsed for ground motions 2 and 3. The retrofitted structure does not have structural damage under ground motion 1. Ground motions 2 and 3 induce some structural damage but the structure still maintains enough strength, stiffness, and deformation capacity. Drift ratios are kept below levels that can weaken the capacity of the existing structure to bear gravity loads.

NATIONAL PROGRAM TO REDUCE SEISMIC RISKS IN SCHOOLS

A seismic risk–mitigation program is proposed to evaluate and reduce the vulnerability of existing schools and to enhance the construction of new, safe schools. For existing schools the program includes the following activities: (1) Development of a nationwide catalog of the approx. 28,000 existing schools buildings, including information concerning type of construction, location, date of construction, number of stories, school population, and current physical conditions. (2) Design and implementation of a Geographical Information System based on the structural and architectural data collected in the national survey. Structural building data will be correlated with age of construction, school population, and seismic hazard to build risk maps and estimate possible loss from future catastrophic events, among other applications. (3) Visual inspection of 500 selected schools located in high to very high hazard zones, with emphasis on the older ones. The information gathered will include digital photographs, GPS coordinates, floor and elevation plans, dimensions of structural elements, reinforcement details, quality of materials, and current building condition. (4) Specific studies of 10 standard school types selected as pilot projects, including in-situ tests of dynamic properties (periods, mode shapes, and damping), material quality testing, soil and foundation surveys, and the development of cost-effective and nondisruptive retrofitting projects. Accelerographs will be installed in four schools to record future events. (5) Development of a guide for reducing nonstructural seismic hazards. (6) Production of videos and brochures addressed to students, teachers, and parents to enhance the level of community awareness and preparation for seismic events. Workshops will take place at the ten pilot schools. (7) Construction of the retrofitting solution for the pilot projects. (8) Planning for retrofitting the higher-risk school buildings in the country at short and long terms.

This program was initiated in 2006 with the participation of IMME (Central University of Venezuela), FEDE (Ministry of Education), and FUNVISIS (Ministry of Science and Technology). The survey for gathering structural information of the about 28,000 schools is being carried out by 4,000 properly instructed high school students. Workshops and instruction guides on DVD are used for training high school students. The data in the survey includes school population, construction age, number of stories, and construction type; the last is identified with the help of drawings and photographs that describe the typical construction types built in the country in the last century.

For construction of new school buildings, a detailed revision of both architectural and structural designs has been recommended to make sure that they fulfill all requirements and specifications of current seismic and construction codes. An in-depth supervision at construction stage, carried out by independent inspectors, and the determination of unambiguous responsibilities for each member involved in each particular school project, are also included. The development of an earthquake-resistant culture is underway.

CONCLUSIONS

Recent earthquakes have confirmed the high level of vulnerability of school buildings, especially in developing countries. An enormous effort is needed to retrofit existing schools; a worldwide commitment of developed nations is required to transfer knowledge and technology to less developed ones.

Nonlinear analysis of the school buildings that collapsed in the 1997 Cariaco earthquake indicates failure modes that are consistent with the observed behavior. The failures were primarily the result of structural deficiencies in the reinforced concrete frame systems, typical of the design practice of several decades ago: low lateral strength and stiffness, low energy-dissipation capacity, insufficient shear resistance, and the presence of short columns that precipitated brittle failures.

Approximately 70% of the approx. 28,000 schools in Venezuela are located in zones of high to very high seismic hazard. A number of them, which could total a thousand, are similar or identical to the schools that collapsed in Cariaco, which were built several decades ago with significantly lower seismic-resistant design requirements than those included in the modern standards. Assuming nonlinear properties similar to those of the collapsed buildings, the analysis points out that the Old-type schools are exposed to high risks and must be retrofitted, even in moderate-hazard zones. The Box-type schools should be retrofitted only in the higher-hazard zones.

The retrofitting solutions for the standard schools add auxiliary structures to withstand the earthquake loads independently of the existing structures, supported in properly reinforced foundations. The auxiliary structures are connected to the buildings by slabs and are mainly built along the perimeter of the buildings so as to minimize the alteration of the existing structures and optimize the construction. The benefits of the solutions have been verified for ground motions corresponding to mean return periods of 100, 1,000, and 2,000 years. Drifts are kept below levels that can weaken the capacity of the existing structure to bear gravity loads.

A seismic risk-reduction program has been initiated in Venezuelan schools with a national survey that is intended to identify the structural characteristics of the approx. 28,000 schools in the country. Ten pilot projects have been planned to develop cost-effective and nondisruptive retrofitting solutions and to enhance the level of community awareness and preparation for seismic events.

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