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EARTHQUAKE-RESISTANT PERFORMANCE OF PERUVIAN SCHOOL BUILDINGS

Alejandro MUÑOZ[1], Marcial BLONDET[2], Ursula QUINTANA[3], Henry LEON[3]

SUMMARY

All recent Peruvian earthquakes have caused considerable damage in the educational infrastructure built before 1997. School buildings designed and constructed according to the 1997 Peruvian Seismic Code, however, were essentially undamaged during the Atico M_w 8.4 earthquake of 2001.

This paper presents the seismic performance of Peruvian school buildings subjected to three levels of earthquake hazard. Analysis is performed via spectral procedures and performance is evaluated according to the location of demand points in the corresponding capacity curves.

Results show that traditional buildings (pre-1997) would have large inelastic demands in frequent events and could collapse in larger events. It is expected, however, that modern buildings would have adequate performance even in extreme events. The radical improvement in the expected and observed performance of modern school buildings is due to the increase in the stiffness demands of the 1997 code.

INTRODUCTION

The Peruvian seismic design code of 1997, (SENCICO [1]) maintains the strength requirements of the previous 1977 code [2] but significantly increases the stiffness demands. This implies that school buildings, which traditionally had been flexible in one direction, had to be more robust after 1997. Whereas modern school buildings had excellent performance during the June 2001 earthquake, traditional school buildings suffered extensive damage. This motivated a comparative assessment of the seismic performance of new and traditional school buildings, together with a brief analysis of the influence of the new Code requirements on the good performance of the modern school buildings.

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[1] Professor, Catholic University of Peru, Department of Engineering. Email: amunoz@pucp.edu.pe
[2] Professor, Catholic University of Peru, Department of Engineering. Email: mblondet@pucp.edu.pe
[3] Student of Civil Engineering, Catholic University of Peru.

PERUVIAN SCHOOL BUILDINGS BEFORE 1997

Peruvian school buildings have one to four stories. Their structural system is a combination of reinforced concrete frames and confined masonry walls. Floor systems are slabs with joists parallel to the facade. Figure 1 shows a typical school building of the coast of Peru. In the longitudinal direction the earthquake resistant system is composed exclusively of reinforced concrete frames parallel to the facade. In the transverse direction, seismic forces are resisted by masonry walls confined within R/C frames.

Figure 1. Typical Peruvian school building

In all important earthquakes in Peru, traditional school buildings have suffered extensive damage because of the poor performance of the longitudinal frame system (Stratta *et al.* [3], Zegarra, Repetto [4], Muñoz *et al.* [5, 6]). The lack of stiffness of these frames is responsible for the well known problem of captive short column, which in some cases leads to important but repairable damage (Figure 2), and in other cases to damage so extensive and severe that repair is impossible.

Figure 2.
Short column failure, Nasca 1996 earthquake

Figure 3.
Generalized short column failure. Atico 2001 earthquake

Confined masonry walls in the transverse direction have generally shown a good seismic performance.

AN IMPORTANT CHANGE IN THE PERUVIAN SEISMIC CODE

In 1997 the Peruvian seismic code underwent an important revision. Even though seismic strength demands were very similar to those of the previous code of 1977, stiffness demands were significantly increased (Muñoz [7]). This stiffness increase was due to drastic modifications of the procedures to estimate response displacements and to a slight reduction of the maximum admissible drift, from 1% to 0.7%.

Figure 4 shows the ratio between expected lateral displacements for a given structure analyzed following the specifications of the 1997 and 1977 codes. For a specific short-period structure, the displacements obtained with the 1997 code are approximately 3.3 larger than those obtained with the 1977 code. Considering the reduction in permissible drift limits from 1% to 0.7%, the stiffness demands for short period buildings are 4.8 times larger.

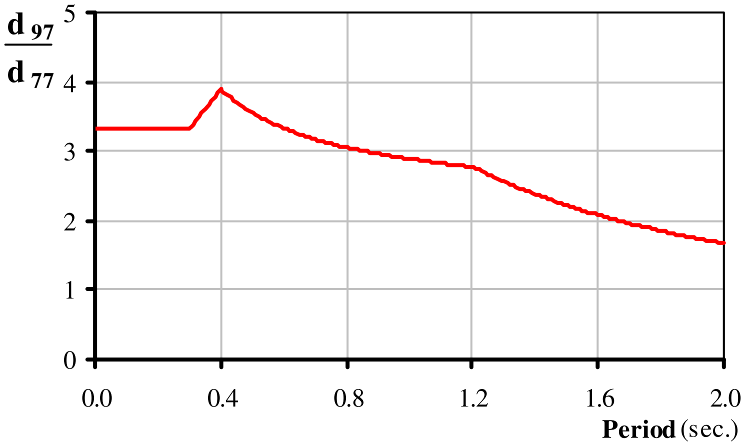


Figure 4. Ratio of expected displacements according to 1997 and 1977 Peruvian seismic codes

Furthermore, the importance factor for school buildings was increased from 1.3 to 1.5. Since in the Peruvian code this factor is used directly in the calculation of lateral drift, the new stiffness requirements for school buildings are 5.5 times larger than those of the previous code.

The most recent Peruvian seismic code, published in 2003, SENCICO [8], practically maintains the stiffness requirements of the 1997 code.

PERUVIAN SCHOOL BUILDINGS AFTER 1997

The important change in stiffness requirements introduced in the 1997 seismic design code implied that, after 1997, school building structures had to be significantly more rigid in the longitudinal direction. Facade beams, which were traditionally 0.25m wide and 0.30 to 0.45 m high, were replaced by beams measuring 0.25 x 0.55 m. Rectangular section columns 0.3 m wide were replaced by T-section columns with flanges measuring 0.90 to 1.20 m. The structural system in the transverse direction, with confined masonry walls, remained the same, since it satisfied the stiffness requirements of the new code.

Figures 5 and 6 show, respectively, a traditional (pre-1997) and a modern school building after the 2001 Atico earthquake. The modern building was undamaged.

Figure 5. Pre-1997 school building with flexible facade beams and columns, damaged in the Atico 2001 earthquake

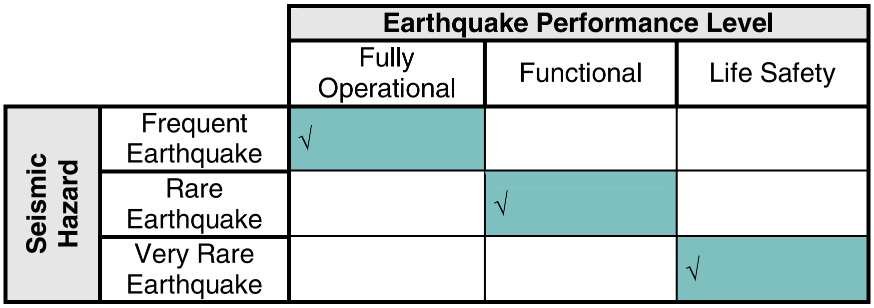
Figure 6. Modern school building, undamaged. Notice the larger beams and columns

SEISMIC PERFORMANCE EVALUATION

Methodology

Peruvian schools are built employing typical architectural and structural systems, which do not change significantly in many years. Four school buildings, representative of typical traditional and modern construction were selected for this study. Two buildings were 2-story high; the remaining two were 3-story high. All buildings are located on the coast of Peru, the region of highest seismic activity, and built over soil profiles of intermediate quality.

Seismic performance of the selected buildings was assessed using an adaptation of the framework suggested by SEAOC [9]. Three levels of seismic hazard were considered, associated with 50, 500 and 1000 year events, respectively. Performance levels were defined globally, as sectors of the capacity curves. Structural response was estimated using demand and capacity spectra. Minimum acceptance criteria were defined by the diagonal of the performance matrix shown in Figure 7, below.



		Earthquake Performance Level		
		Fully Operational	Functional	Life Safety
Seismic Hazard	Frequent Earthquake	√		
	Rare Earthquake		√	
	Very Rare Earthquake			√

Figure 7. Seismic performance objectives

Representation of seismic demand

Table 1 shows peak accelerations in rock, associated with the 3 levels of seismic hazard for the coast of Peru (Castillo, Alva [10]).

Table 1. Levels of seismic hazard and peak rock acceleration

		Recurrence interval (years)	**Peak rock acceleration** (g)
Seismic Hazard	**Frequent** earthquake	50	0.20
	Rare earthquake	500	0.40
	Very Rare earthquake	1000	0.50

Acceleration response spectra for intermediate soil conditions corresponding to the 3 levels of seismic hazard were calculated using a soil factor of 1.2. They are shown in Figure 8 below.

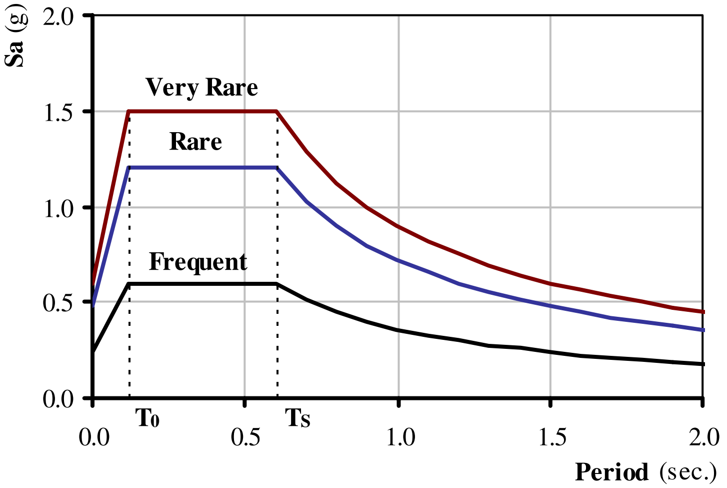


Figure 8. Response spectra for three levels of seismic hazard

Analytical models

The selected school buildings were modeled as 3D frames with rigid diaphragms. The frame elements were capable of axial, flexural, and shear deformations and were assumed to be completely separated from all non-structural components. Nonlinear response was considered through point hinges at the ends and at the center of the elements. Incremental displacement analyses (pushover) were performed in the longitudinal direction, assuming a distribution of lateral displacements proportional to the fundamental mode of vibration (ATC40 [11], FEMA357 [12]).

Selected school buildings

Figure 9 shows the structural system of the modern school buildings selected for this study. In the transverse direction the earthquake resisting system is composed of confined masonry walls, also used to separate the classrooms. In the longitudinal direction, two reinforced concrete frames are provided, with robust beams and columns.

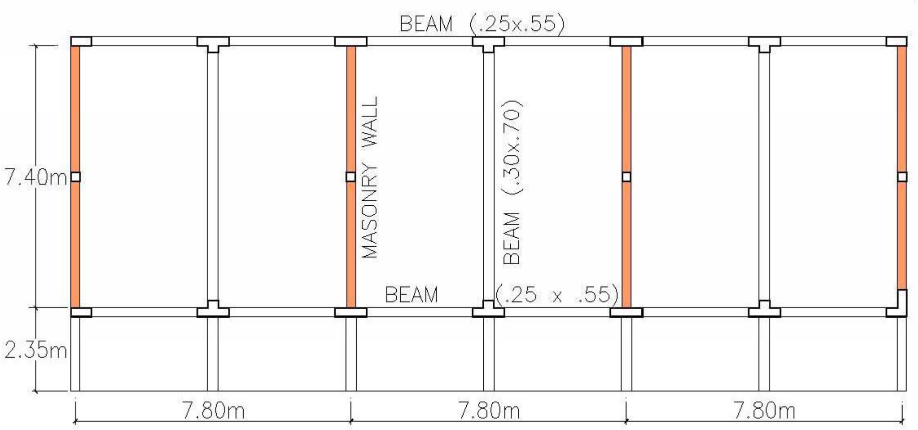


Figure 9. Structural floor plan

Figures 10 and 11 show sections and reinforcement of beam and columns of the two-story modern school building selected.

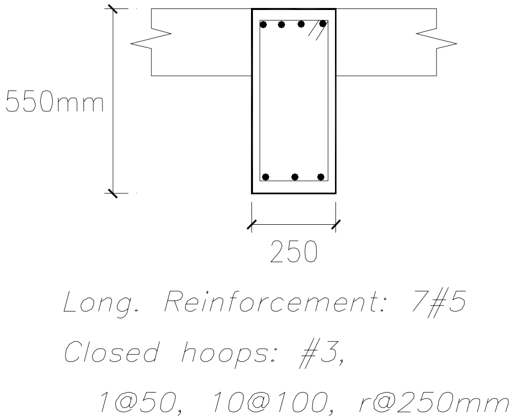


Figure 10. Longitudinal beam section of a typical two-story school building

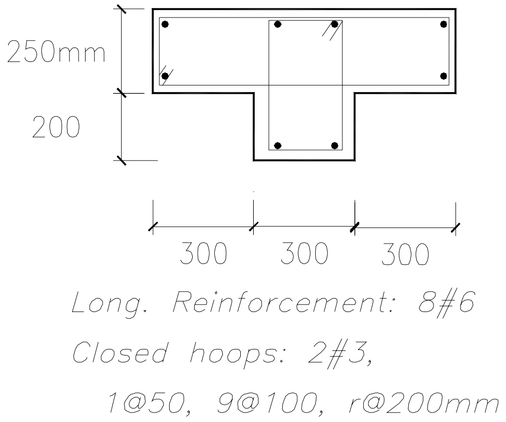


Figure 11. Column section of a typical two-story school building

The traditional school buildings have the same structural system as the modern buildings, but with less competent elements. Beam sections are 0.25 x 0.30 m, provided with 4 #5 steel reinforcement bars. Column sections are 0.30 x 0.45 m (short dimension along the facade of the building), with 8 #6 bars. These buildings are very flexible. Although they satisfied the stiffness requirements of the Peruvian seismic code of 1977, they do not comply with the 1997 and 2003 codes.

Strength and ductility

Figure 12 shows the capacity curves for the selected two-story school buildings. A solid line is used for the modern building, a dashed line for the traditional building. Horizontal lines indicate the base shear strengths required by the 1997 and 1977 codes (V_{97} and V_{77}, respectively).

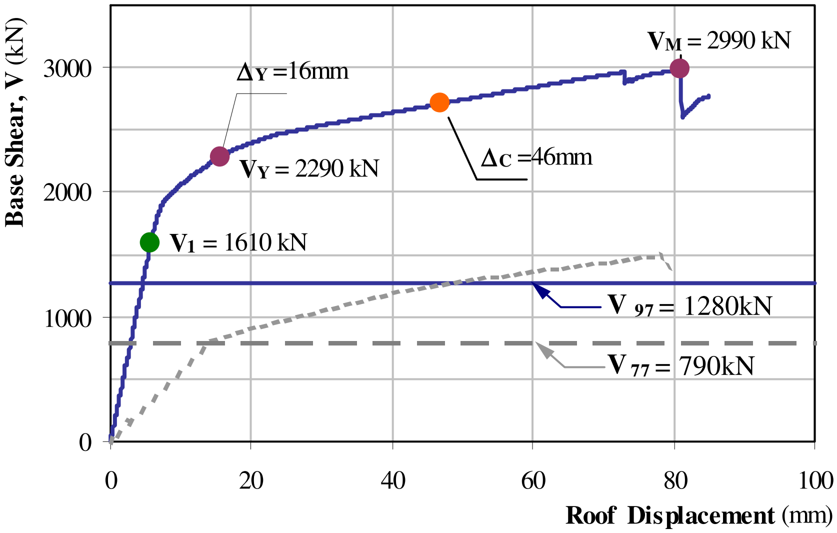


Figure 12. Force displacement curves for modern and traditional 2-strory Peruvian school buildings

The maximum shear strength of the modern building, V_M, equal to 2990 kN, is 1.85 times larger than the lateral force corresponding to the formation of the first plastic hinge, V_1, and 1.3 times larger than the effective yield strength, V_Y. Notice that V_1 and V_Y are, respectively, 1.26 and 1.80 times larger than the 1997 design base shear V_{97} of 1280 kN.

The modern building is able to develop a global displacement ductility approximately equal to 5, corresponding to a yield displacement of 16mm and an ultimate displacement of 81 mm. The maximum drift permissible by the 1997 code (0.7%) is reached, however, with a displacement of 46 mm, which roughly corresponds to the midpoint of the available inelastic range. The traditional building showed similar values for the maximum lateral displacement and global ductility.

The lateral strength of the traditional building is considerably smaller than that of the modern building (less than 50% for the effective yield force). This difference is due to several factors, such as the increase of importance factor in the new code (from 1.3 to 1.5), the increase in the design spectrum platform width (from 0.3 to 0.4 s), the larger overstrength of rigid structures, and basically because rigid modern structures reach significantly higher spectral ordinates, and thus reach a higher strength than traditional flexible structures.

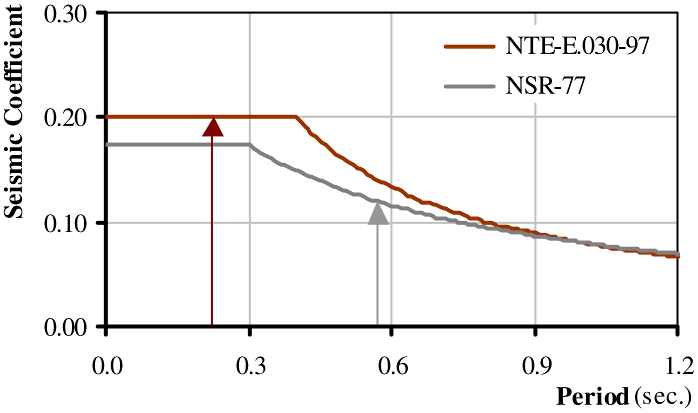


Figure 13. Seismic coefficient for two-story school buildings according to 1997 and 1977 codes. Arrows correspond to the selected buildings

Expected seismic performance

The capacity curves of both buildings were subdivided according to suggestions of SEAOC [9]. The demand points corresponding to the three levels of seismic hazard, estimated according to the procedure suggested in ATC40 [11], were located in the corresponding curves, as shown in Figure 14.

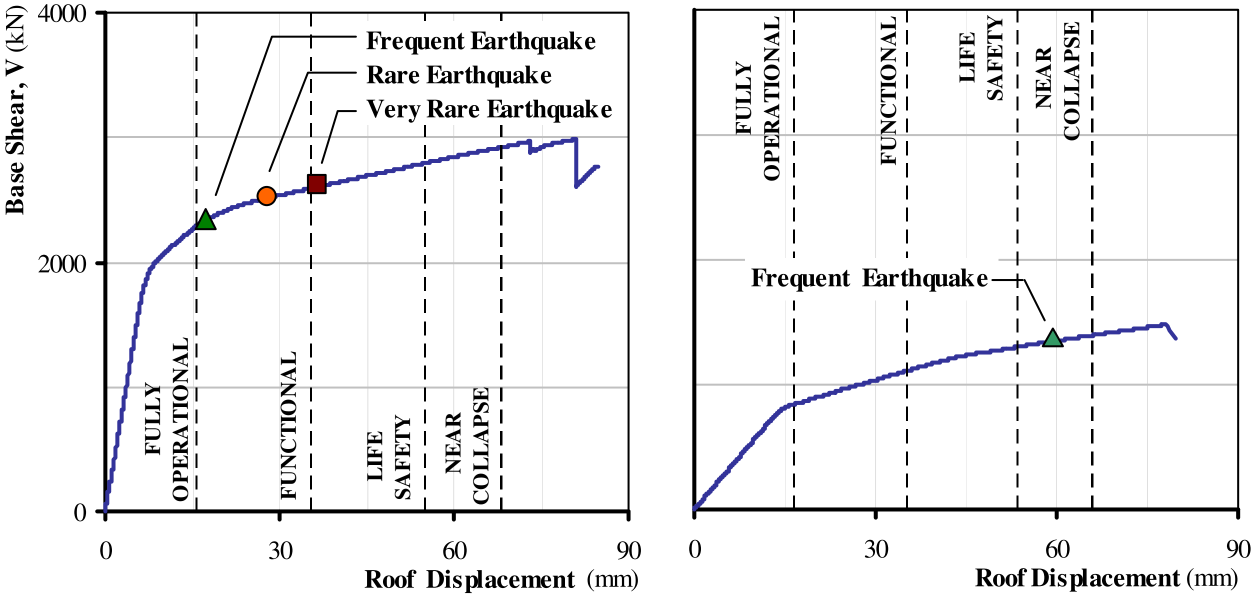


Figure 14. Demand points for modern (left) and traditional (right) two-story school buildings

Similar results were obtained for the 3-story school buildings. Therefore, the analytical study indicates that in a frequent earthquake, the modern buildings would be slightly over the desired full operational level. In stronger earthquakes, the buildings would attain the desired performance: they would be functional after a 500 year event and would provide life safety after a very rare 1000 year event. The traditional buildings, on the other hand, would have unacceptable performance: they would be subjected to high inelastic displacement demands and be near collapse even during frequent earthquakes, and would possibly collapse in stronger events.

These results are conservative, but in general agreement with the observed performance of traditional and modern school buildings during the Atico earthquake, where the soil conditions and peak acceleration in many cities were consistent with the assumptions made for this study of frequent earthquake and intermediate soil conditions (ASCE [13]). Analysis results predicted slight damage in modern buildings after a frequent earthquake, but no damage was reported in the modern schools located in the area. Extensive damage, close to collapse, was predicted for traditional buildings. Although many traditional school buildings suffered damage due to the short column effect, even with a 25 mm separation between the frame and the non-structural walls, only a few were near collapse. The conservatism of the analysis results might be due to material overstrength and limitations of the modeling technique.

CONCLUSIONS

Modern Peruvian school buildings, designed and constructed according to the newer code requirements, showed excellent behavior during the Atico M_w 8.4 earthquake of 2001, and it is expected that they will have an acceptable performance during stronger earthquakes. This dramatic improvement of the seismic safety of the modern Peruvian educational infrastructure was obtained through a significant increase of the stiffness requirements imposed in the seismic design code after 1997.

Peruvian school buildings designed before 1997, however, have a poor earthquake-resistant performance, and many of these buildings may collapse during a strong earthquake. It seems important, therefore, to start a national program of reduction of the seismic hazard of these important buildings.

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