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PERFORMANCE OF TEMPLATE SCHOOL BUILDINGS IN TURKEY AND PERU DURING EARTHQUAKES

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ABSTRACT

Most of the public school buildings in Turkey and Peru are built according to a small number of template plans. Over the years, these template plans are kept the same while the structural designs are varied with the seismic design codes in force. The Turkish and the Peruvian seismic design codes have been using similar concepts in earthquake-resistant design of RC buildings for a long time. The codes agree on the minimum base shear strength levels but differ on drift limits and implied overall lateral stiffness levels. However, the Peruvian code has more stringent drift limits and higher implied stiffness for the design of lateral load resisting systems. During recent strong earthquakes in Turkey and Peru, the design concepts and construction styles for these template school buildings have been put to test. The observed performances of these school buildings during recent earthquakes demonstrate the implications of the Turkish and the Peruvian approaches to design and construction of RC school buildings.

Introduction

Most of the public school buildings in Turkey and Peru are built according to a small number of template plans. Typically, these buildings have reinforced concrete (RC) moment-frames or moment-frames and shear walls (dual system) to resist the seismic forces. Within each template, the buildings have very similar mass distributions while the structural characteristics vary with the seismic code in effect at the time of construction. This unique nature of the template school buildings allows comparison of their performance under different earthquakes and over different seismic codes. During recent strong earthquakes in Turkey and Peru, the design concepts and construction styles for these template school buildings were put to test.

Design of School Buildings in Turkey and Peru

The Turkish and Peruvian seismic design codes evolved through different paths (Irfanoglu 2009). However, since mid-1970s, the U.S.-based developments in earthquake-resistant design approaches influenced design provisions in these countries. The current Turkish code (2007) and the current Peruvian code (2003) are similar to the codes they succeeded, namely, the 1997 Turkish and the 1997 Peruvian codes. Below, the 1997 Turkish and 1997 Peruvian codes and their older counterparts, the 1975 Turkish and 1977 Peruvian seismic codes, are discussed in greater detail because the sampled school buildings that experienced strong earthquakes recently were built following these codes. However, given the similarity of the codes, observations from the newer structures are expected to apply to the buildings designed and built following the current codes.

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Code Requirements for School Building Design in Turkey and Peru

A detailed comparison of the 1997 Turkish and the 1997 Peruvian codes is given in Irfanoglu (2009). Both codes have similar and extensive provisions for use of design spectra to calculate equivalent lateral seismic loads. The design base shear force coefficients for typical two to four-story RC moment-frame school buildings built on stiff soil sites in the highest seismic zone in Turkey and Peru are approximately the same at 18%[2]. However the codes have different allowable lateral drift limits. For RC structures, the 1997 Turkish code permits the allowable interstory drift ratio to be 2% and the 1997 Peruvian code limits it to 0.7%. In the case of RC shear wall buildings, both codes reduce the seismic load reduction factor to ¾ that of the RC frame buildings. Accordingly, the design base shear force coefficients become 0.23 (Turkey) and 0.24 (Peru). For moment-frame and shear wall dual system RC school buildings, the design base shear coefficients are computed as the average of the values for frame-only and shear wall-only cases resulting in values of 0.20 (Turkey) and 0.21 (Peru). The same allowable interstory drift ratio limits apply, i.e. 2% (Turkey) and 0.7% (Peru) regardless the type of the lateral load system in RC school buildings.

The code requirements in place before 1997 in Turkey and Peru. The 1975 Turkish seismic code (MRR 1975) required the RC frame school buildings situated on stiff soil sites and in the highest seismic zone to be designed using a design base shear coefficient of 0.12~0.15 and with a maximum allowable interstory drift ratio of 2.5%. Accordingly, compared with the 1977 code, the 1997 Turkish code required these school buildings to be designed for 15%~45% higher lateral loads and, effectively, be 45%~80% stiffer. In the 1977 Peruvian code, school buildings had an importance factor of 1.3. For school buildings as defined above, the 1977 Peruvian code required a base shear coefficient of ~0.15. The allowable drift ratio in the 1977 Peruvian code was 1%. Major modifications were introduced in the 1997 Peruvian code to several factors used in calculating the design base shear strength and estimating the actual displacements (Muñoz et al. 2004). Within the context of the RC school buildings, the unscaled elastic load level was increased by a factor of 2.5 and the reduction coefficients that depended on the structural system type were increased by a factor of 2 to 2.5. These changes in the 1997 Peruvian code yielded a design base shear strength close to the one prescribed by the 1977 code. However the main impact was on the required stiffness: changes in the reduction coefficients, omission of a reduction factor that had been used to relate the design displacements to the ones calculated from linear elastic model based analysis, together with the reduction of the allowable drift ratio to 0.7% and the increase in the importance factor to 1.5, required that the 1997-code based RC school buildings be 550% stiffer than those built per the 1977 code (Piqué and Martel 2004).

Template School Buildings and their Performance during Recent Earthquakes

Turkey

The template plans used in construction of most of the RC school buildings in Turkey are

[2] For RC school buildings, the 2007 Turkish code is similar to the 1997 code but asks for more detailed analysis. The 2003 Peruvian seismic code differs very little from the 1997 version except for a change in the seismic amplification factor formula and decreased reduction factors for certain structural systems. These changes amount to approximately 20% increase in the design base shear coefficient for RC school buildings.

given in Fig. 1 (Gur et al. 2009). The plan is 34x17.5 m. The same plan is used for two to four-story buildings. Columns are 0.3x0.5m and the typical dimensions for beams are 0.3x0.7m. Shearwalls are 0.2 m thick. The thickness of plastered hollow clay-tile infill walls are 25 cm for interior walls and approximately 40 cm for exterior walls. All infill walls are built flush to the structural elements (i.e. columns on the sides and beams on top). Along the perimeter of the building, and often adjacent to the columns, window and door openings are made in the infill walls.

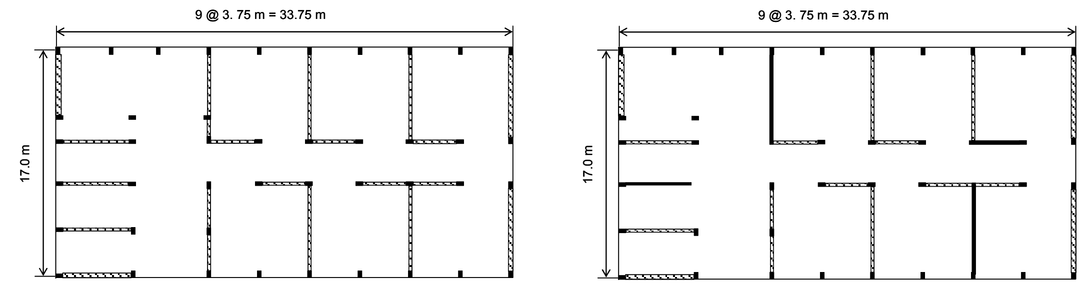

Figure 1. Floor plans for template RC moment-resisting frame (left) and dual system (shear wall and moment-resisting frame) (right) schools in Turkey. Solid small rectangles: columns; solid long rectangles: RC shear walls; hatched long rectangles: full-bay masonry infill walls; solid lines: perimeter masonry infill walls with openings.

Figure 2. Typical RC school buildings with template floor plans. (a), (b), (c): structures with moment- frame system; (d) with dual system (i.e., moment-frames and shear walls).

In structures with moment-resisting frames only, the total column area at ground level is ~1% of the floor area, regardless of the number of stories. In dual system school buildings, the floor plan is kept same except that two bays of interior masonry infill walls in each principal direction of the building are replaced with 20 cm thick RC shear walls. The total concrete wall area is estimated to be 0.4% of the floor area in the long direction and 0.5% in the short direction of the building. Typically, 8-mm diameter bars with yield strength of 220 MPa are used for transverse reinforcement in the columns. The tie spacing in the columns is 20~25 cm (typical). In the column end regions, the tie spacing was observed to be 10~12 cm in some schools. The as-built transverse reinforcing spacing did not always meet the code requirements. Depending on the location in a column, the column transverse reinforcement ratio ranged from 0.1% to 0.2%. Fig. 2 show photos of typical school buildings in Turkey built according to the template school plan.

Performance of template school buildings during the 1999 Kocaeli (Mw7.6), 1999 Düzce (Mw7.2), and 2003 Bingöl (Mw6.4) earthquakes

Seismic performance of template RC school buildings in Turkey can be judged by their responses to three recent earthquakes. The city of Düzce in northwestern Turkey was affected by two powerful earthquakes: the first on 17 August 1999 (with moment magnitude, Mw=7.6) and the second on 12 November 1999 (Mw=7.2). Fig. 3 shows the acceleration and displacement response spectra, for 5% of the critical damping, for the ground motions recorded in Düzce during these two earthquakes. The intensity of the ground shaking represented by these spectra is deemed to be representative of that experienced by the schools in the Düzce region. The third event that is part of this study is the 1 May 2003 Bingöl earthquake (Mw=6.4). Fig. 4 shows the response spectra, for 5% of the critical damping, for the ground motion recorded in Bingöl during the Bingöl earthquake (Ozcebe et al. 2004). Based on field observations including similar proximity of the sites to the ruptured fault, similarity in local soil conditions and the damage distribution in the surrounding structures, the intensity of the ground shaking at visited school sites in Bingöl is considered to be similar to that experienced at the Bingöl station (Ozcebe et al. 2004). 21 template school buildings affected by these earthquakes were surveyed: five RC dual system school buildings in the Düzce region inspected after the 1999 Düzce earthquake and 16 RC moment-frame school buildings in Bingöl after the 2003 Bingöl earthquake (Gur et al. 2009).

Fig. 5 shows a two-story RC dual system template school building built per the 1975 Turkish code. Despite its proximity to the fault, this dual system building sustained no damage during the two earthquakes in 1999. In Fig. 6, another dual system school building is shown. This four-story building, located in Düzce, sustained no damage in its shear walls. However, the structure suffered heavy damage at its perimeter columns at the basement level. Infill masonry walls restrained these to deform over a very short length that resulted in formation of a captive column condition. As such, the captive columns failed in shear-critical, non-ductile manner (so-called “shear failure”) before they could develop their flexural capacity fully.

Performance of template school buildings in which RC moment-resisting frames form the lateral load resisting system were documented after the 2003 Bingöl earthquake (Gur et al. 2009). Fig. 7 shows a three-story school building in Bingöl after it was built in 1999 and after the 2003 Bingöl earthquake. During the earthquake, the first-story columns failed. It is difficult to reconstruct what might have initiated the collapse. However, a nearby school with identical floor plan and structural system provided clues. Figs. 8 and 9 show the state of that nearby school after the earthquake. It sustained significant damage in many columns, both interior and exterior, and infill walls, at the first story. Cracks in captive columns near a corner of the structure indicated the onset of brittle failure. Fig. 9 illustrates that failure in full-bay full-story high infill walls could cause concentration of deformations in the mid-height region of columns and make columns that originally appear to be integrated into infill walls to fail in a non-ductile manner.

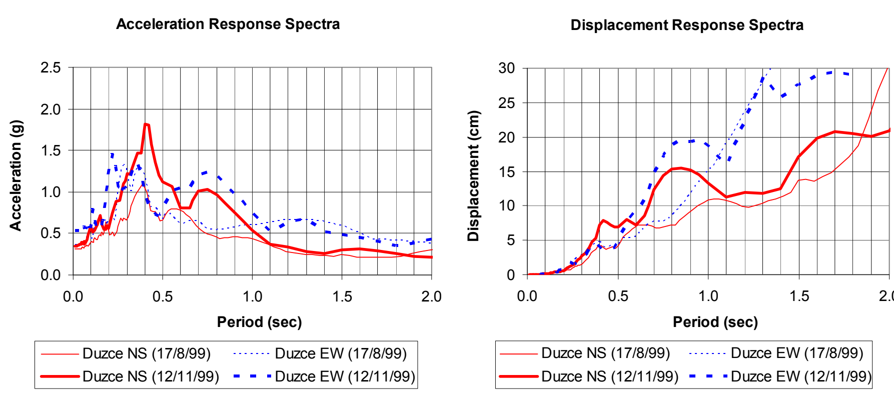

Figure 3. Response spectra, for 5% of critical damping ratio, for the ground motions recorded in Düzce during the 8/17/1999 and 11/12/1999 earthquakes.

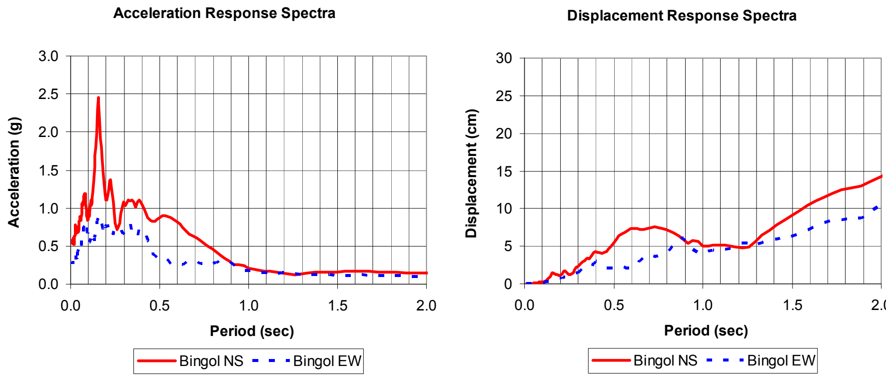

Figure 4. Acceleration and displacement response spectra, for 5% of critical damping, for the ground motion recorded in Bingöl during the 1 May 2003 Bingöl, Turkey earthquake.

The most common failure patterns in interior and exterior columns that were initially restrained by full-bay masonry infill walls are shown in Fig. 10. These failure patterns indicate that captive column conditions can develop dynamically in columns restrained by full-bay infill walls. It should be noted that infill walls in contact with a column could cause formation of captive column conditions in directions orthogonal to their longitudinal axes.

Figure 5. A two-story template RC dual system school building in Kaynasli near Düzce. No structural or non-structural damage during 8/17/1999 and 11/12/1999 earthquakes.

Figure 6. View of a dual system RC template school building in Düzce after the 12 November 1999 Düzce earthquake. The captive exterior columns in the basement failed.

Figure 7. A three-story RC moment-frame template school building with captive columns in Bingöl before and after the 5/1/2003 Bingöl earthquake.

Figure 8. A three-story RC moment-frame template school in Bingöl after 5/1/2003 earthquake.


Figure 9. A view of the interior of the building shown in Fig. 8.

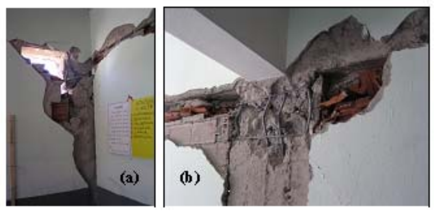

Figure 10. Typical captive column failures observed in (a) exterior and (b) interior columns restrained by full-bay masonry infill walls.

Peru

The template plans for school buildings built following the 1977 and the 1997 codes in Peru are given in Fig. 11. The footprint of these structures was approximately 23.4x7.4 m with 2.1 m balcony overhangs. Typically these school buildings have one to four stories. The lateral load resisting system consists of RC moment resisting frames along the longer (longitudinal) axis of the structure and confined solid masonry walls along the shorter (transverse) axis of the structure. In the 1997 design, the RC columns are either rectangular shaped with 0.9x0.25 m cross-section or have a T-shaped cross-section with a 0.9~1.2x0.25 m flange and a 0.2x0.3 m stem. A typical school building built according the 1997 code using the template plan is shown in Fig. 12. Typically, the transverse reinforcement in the 1997 design columns is, for the rectangular columns a single hoop of 9.5-mm diameter (size #3) bar, and for T-shaped columns two hoops of 9.5-mm diameter bars at every 25 cm. The bars have nominal yield strength of 220 MPa, typically. The tie spacing in the columns is 25 cm in general but 10 cm in the column end regions. Depending on the location in a column, the column transverse reinforcement ratio ranges from approximately 0.2 to 0.35%. The thickness of the confined masonry walls is 30cm. These walls, which are typically 7m in length, span between rectangular columns acting in the longitudinal direction of the building. The solid confined masonry walls have 30x30cm column at mid-length. The façade perimeter beams are, typically, 25x55cm in cross-section. The nonstructural perimeter masonry walls below the window openings are 13-cm thick. A RC perimeter frame, made out of a 13x10cm beam and two 13x25cm columns, confine the nonstructural masonry walls. A gap of 2.5 cm is left between these infill wall frames and the structural columns of the building. This gap is filled with an elastomeric material to protect the building from outside climate (see Fig. 12).

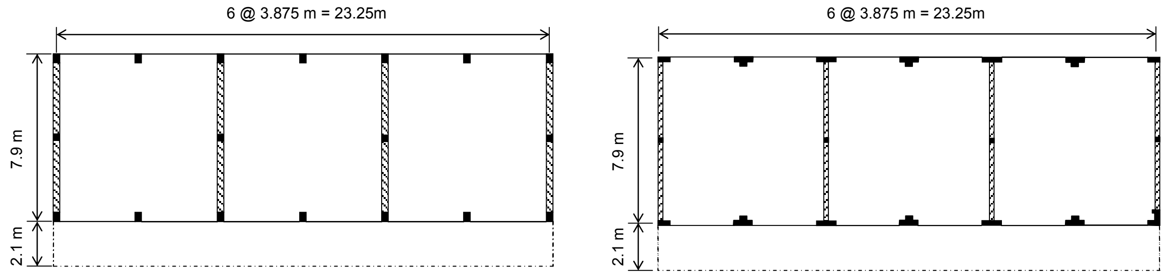

Figure 11. Plan for template school buildings in Peru built per 1977 (left) and 1997 (right) codes. Solid rectangles/squares/T-shapes: columns; hatched: confined masonry walls; solid lines: perimeter masonry infill walls. The 2.1m balcony overhang is also shown.

Figure 12. A school building in Peru built according to the template plan per the 1997 seismic code. Separation between the structural column and non-structural perimeter wall. (Photo credit: Eduardo A. Fierro - BFP Engineers, Inc.-Bertero-Fierro-Perry.)

Before the 1997 seismic design code, the Peruvian school buildings were designed following the 1977 code and built following a template plan that has the same footprint. In that template plan (Fig. 11), the lateral load resisting system in the transverse direction is identical to that in the newer, 1997 code-based template. However, in the older template, the columns in the structural system in the longitudinal direction were all rectangular and with 30x45cm typical cross-section with their strong axis oriented in the transverse (short) direction of the school building. The change in column cross-sections came about because of the 1997 code requirements. In the 1997 Peruvian seismic code, even though the seismic design load levels were kept similar to those in the 1977 code, the actual displacement estimates were approximately three times as high. Furthermore, the 1997 code reduced the allowable displacements from 1% to 0.7%. Effectively, the 1997 code requires the structures to be built approximately five times stiffer than demanded by the 1977 code. To provide the required stiffness, half of the rectangular columns in the template school building were replaced by T-shaped columns while the remaining columns were replaced with 25x90cm columns oriented along the longitudinal direction of the structure. The confined solid masonry walls designed per the 1977 seismic code had enough stiffness to meet the requirements of the 1997 code and as such were not modified. It should be noted that like in the 1997 code-based template, in the 1977 code-based template the infill wall frames were to be separated from the structural columns by 2.5 cm. But in many 1977 code-based template school buildings the infill wall frames were built either flush to the columns or the styrofoam-filled gaps were plastered over with up to 4-cm thick stucco on both sides, rendering the gaps ineffective. In the 1997 code-based template school buildings, greater care was given to leave the 2.5 cm gaps functional: no stucco was allowed over the gaps now filled with elastomeric material. In both templates, the potential for formation of captive columns was acknowledged by requiring use of closely spaced transverse reinforcing bars in the "short column" zone. However, the suggest remedy, i.e, installing closely spaced transverse reinforcing bars, are ill-fated. Columns in 1977 code-based template schools performed very poorly when the captive column conditions developed under strong shaking. However in 1997 code-based schools, separations between the infill walls and the columns were sufficiently wide and no captive conditions were formed.

Performance of template school buildings during the 2001 Atico (Mw8.4) earthquake

A major earthquake, Mw 8.4, struck the coastline of Peru on 23 June 2001 (EERI 2003). The event had an epicenter near Atico. Unfortunately, strong motion accelerometers in the high intensity shaking region malfunctioned. The only strong-motion acceleration record from the earthquake was obtained in the town of Moquegua, approximately 400 km away from the epicenter and approximately 100 km from the ruptured fault. Fig. 13 shows the acceleration and displacement response spectra, for 5% of the critical damping, for the ground motion recorded in Moquegua during the 2001 Atico earthquake. The ground shaking intensity in Moquegua is estimated to be VII on the Modified Mercalli Intensity Scale (EERI 2003). The earthquake affected a very large region in southwestern Peru and many RC template school buildings, particularly along the Pacific coastline of Arequipa region, experienced strong shaking: even though no instrumental record of the ground motion from that region exists, the ground shaking there is estimated to be stronger than that observed in Moquegua and based on field observations, is estimated to be VIII-IX on the Modified Mercalli Intensity scale along the coastal Arequipa region (EERI 2003).

Fig. 14 depicts a two-story RC template school building in the coastal area of Arequipa region. This building was designed per the 1977 Peruvian seismic code. The infill walls were not separated from the columns sufficiently. The architectural infill wall assemblies restrained the columns inappropriately and caused them to fail due to the resulting captive column condition. In contrast, the1997 code based RC template school buildings in the region shaken strongly during the 2001 Atico earthquake sustained no structural or nonstructural damage. Fig. 15 shows one those schools buildings, in the Arequipa region. A view of the elastomeric material filled 2.5 cm gap region from this school building has already been given in Fig. 12. It sustained no structural or nonstructural damage during the earthquake. In fact, none of the template school buildings designed and constructed per the 1997-code sustained any structural or nonstructural damage during the 2001 Atico earthquake[3].

[3] In a reconnaissance report (EERI 2007) of the August 15, 2007 Pisco, Peru earthquake (Mw8.0), it is reported that even in the region with the strongest shaking no cracking was observed in the newer schools.

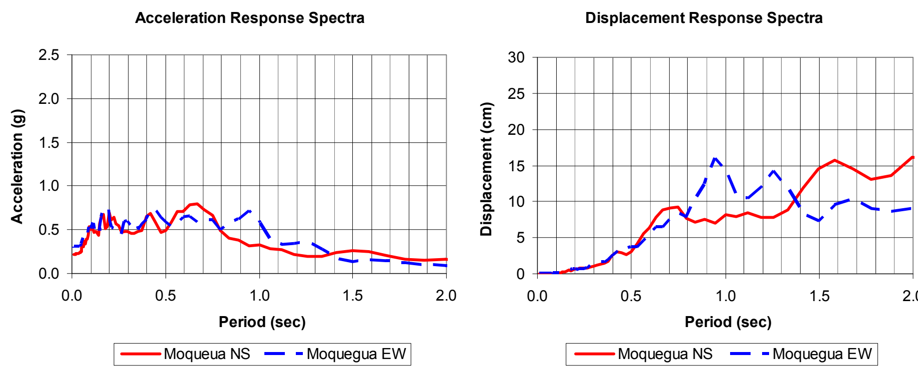

Figure 13. Response spectra, for 5% of critical damping, for the ground motion recorded in Moquegua, Peru during the 6/23/ 2001 Atico, Peru earthquake.

Figure 14. A template school building in Arequipa designed per the 1977 code after the 2001 Atico earthquake. center: a ground story column; right: a second story column. (Photo credit: Eduardo A. Fierro -BFP Engineers, Inc.-Bertero-Fierro-Perry.)

Figure 15. Views of a RC template school in Arequipa built per the 1997 Peruvian seismic code, seen after the 6/23/2001 Atico earthquake. No structural or nonstructural damage. (Photo credit: Eduardo A. Fierro - BFP Engineers, Inc.-Bertero-Fierro-Perry.)

Conclusions

Modern Turkish and Peruvian approaches to seismic design of RC structures are similar with regard to procedure and the minimum requirements for strength of lateral load resisting systems. However, recent Peruvian seismic design codes require these structures to be designed much stiffer than the earlier Peruvian codes did. The Turkish seismic design codes allow the structures to be more flexible.

In each country, many school buildings are built according to a small number of template plans. Based on the observed performance of these template RC school buildings during recent earthquakes in Peru and Turkey, it could be concluded that captive columns are the leading cause of heavy damage and, at times, collapse in these school buildings.

In Turkey, it was observed that presence of shear walls while improving performance of the structures significantly relative to those seen in moment frame-only structures meant no guarantee of damage-free performance. In Peru, it was observed that with the 1997 Peruvian seismic design code, the new Peruvian approach eliminated captive column conditions altogether by requiring the structural systems designed to be significantly stiffer and constructed with adequate separation between structural and nonstructural elements. Earthquake engineers should take heed of this new Peruvian approach as it has been producing school buildings that perform outstandingly well even during strong earthquakes.

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