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Seismic Retrofit of Low-Rise School Building Using Post-Tensioned Bracing Systems

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ABSTRACT

An analytical study regarding the seismic upgrading of existing three-story and four-story school buildings in Mexico City using post-tensioned bracing systems is presented. The schools, located in Mexico City's lake-bed region, were moderately damaged during the 1985 Michoacán Earthquake. The damage was primarily observed in their longitudinal direction where RC columns have their weak axis. In addition, these columns are confined by masonry walls that do not run all the story height. These walls are supposed to be non-structural components, however, they experienced shear cracking during the quake due to the distress of the confined columns.

The school buildings were retrofit after the Michoacán Earthquake adding post-tensioned bracing systems composed of prestressed high-slenderness steel strands (tension-only bracing systems). The effectiveness of the retrofit scheme is discussed through the comparison of the seismic behavior of original and retrofit structures using a comprehensive set of analyses. Three-dimensional elastic analyses were used to define dominant frequencies and modes of response. Limit analyses were performed to assess lateral-load capacities. Nonlinear dynamic analyses were needed to determine deformation and strength demands of the structures for postulated ground motions for a $M_S = 8.1$ earthquake.

The present study addresses the importance of including the masonry walls (commonly assumed as non-structural) in the modeling of the original structures and shows that the retrofit method used improves substantially the dynamic behavior of the original school buildings. This study confirms the importance of using moderate prestressing forces to insure the elastic behavior of the braces and to inhibit that the braces would become slack during the dynamic loading. If braces become slack, they may prematurely fracture if a high tension force is abruptly applied.

INTRODUCTION

Typical low-rise school buildings were severely affected at Mexico City during the 1985 Michoacán Earthquake. The most common structural system used for school buildings before the 1985 earthquake consisted of RC ordinary moment resisting frames. These buildings usually have one bay in the transverse direction and several bays in the longitudinal direction (Fig. 1), having slender columns with their weak axis oriented in the longitudinal direction, which makes these schools very flexible in this

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direction. Infill unreinforced masonry (URM) walls are provided in both directions, but are assumed to be non-structural in the longitudinal direction. The severe shear damage that the URM walls of many of these schools suffered during the 1985 Michoacán Earthquake showed the contrary, and suggested that all walls participated in the structural response.

Because of the damage presented in school buildings in Mexico City during the 1985 earthquake, several techniques have been studied to retrofit these structures. Among them, the use of post-tensioned bracing systems composed of prestressing cables was a popular solution. This system was initially introduced for this purpose in Mexico by a design firm. Comprehensive studies have been carried out to assess the effectiveness of this system in the seismic upgrading of existing school buildings in Mexico City (Miranda, 1990) and in the Mexican Pacific Coast (Miranda and Bertero, 1990). Both studies concluded that this upgrading technique significantly increases the strength and stiffness of these structures, and, if adequately implemented, the system will improve the performance of school buildings during future earthquakes. In addition, Miranda and Bertero warned that, when using this retrofit technique, special attention has to be paid to the following aspects: a) changes in dynamic characteristics of the building and the frequency contents of expected ground motions, and b) verify that the increment in axial loads on the original columns does not endanger them under the expected levels of deformation. These studies have been very valuable, however, they ignored the participation of the original URM walls, assumed to be non-structural, in the seismic response of the structure. Damage presented in these URM walls during the 1985 earthquake suggests that the walls contributed in resisting lateral forces. It should be clear that the URM walls not only modify the strength but the stiffness and dynamic characteristics of both the original and retrofit school structures. This study addresses the importance of including these masonry walls in the modeling and shows that this retrofit method improves substantially the dynamic behavior of the original school buildings. The study confirms the importance of using moderate prestressing forces to insure the elastic behavior of the braces and to inhibit that braces would become slack during the dynamic loading.

DESCRIPTION OF THE SCHOOL BUILDINGS

Plan views and elevations of the school buildings under study are depicted in Figs. 1 and 2. Both buildings are found at the lake-bed region of Mexico City within five blocks one from each other. School EP1 is composed of two three-story buildings 9m tall (story height of 3m) with typical bay width of 3m in the longitudinal direction (E-W) and 9m in the transverse direction (N-S). Transverse infill walls are provided every three bays and are made of unreinforced hollow concrete masonry units (UHCMU). Longitudinal "non-structural" clay URM walls do not run all the story height as they have window and door openings, shortening the columns (Fig. 1). The main structural system consists of 30x50 cm rectangular RC columns oriented in the transverse direction, 25x65 cm (axis A), 15x65 cm (axis B) and 30x65 cm (axes 1 to 24) rectangular RC beams, and 10 cm thick RC slabs. Longitudinal reinforcement is the same in all columns and the supplied steel ratio is $\rho=0.034$. Longitudinal reinforcement provided at the top and bottom of the beams is symmetric and varies from $\rho=0.0088$ for the top story beams to $\rho=0.0175$ for the fist story beams. School EP2 is a four-story building 12.4m tall (story height of 3.1m) with typical bay width of 3.5m in the longitudinal direction (E-W) and 8.7m in the transverse direction (N-S). Transverse infill UHCMU walls are placed every two bays. Transverse outer walls are reinforced concrete walls. Longitudinal clay URM walls do not run all the story height also, and they shorten the columns (Fig. 2). The main structural system consists of 25x50 cm rectangular RC columns oriented in the N-S direction, 25x50 cm rectangular

RC beams, and 10 cm thick RC slabs. Longitudinal reinforcement is the same in all columns ($\rho=0.046$). The longitudinal reinforcement supplied at the top and bottom of the beams is symmetric and varies from $\rho=0.0114$ for the top story beams to $\rho=0.0190$ for the first story beams. For both buildings, the specified strength of the concrete (f'_c) was 200 kg/cm^2 and the yielding strength of the reinforcement steel (f_y) was 4200 kg/cm^2. The assumed compressive strength of the masonry (f^*_m) was 15 kg/cm^2 for the clay units and 20 kg/cm^2 for the UHCMU, according to the masonry provisions of the 1987 Mexico's Federal District Code (NTCM-87, 1987). No specific soil-mechanics studies are available, however, the natural period of the site is about 1.3 seconds according to the isoperiod chart contained in the seismic provisions of the 1987 Mexico's Federal District Code (NTCS-87, 1987).

Both buildings were retrofit adding post-tensioned bracing systems as depicted in the elevations of Figs. 1 and 2. The post-tensioned cables used in school EP1 are composed of six 1/2" ϕ prestressed high-slenderness steel strands protected from weathering with a grouted steel tube. In school EP2, braces are made with eight 1/2" ϕ prestressed high-slenderness steel strands protected with a grouted PVC tube. Yielding strength of the steel strands (f_y) is 13200 kg/cm^2. The prestress applied to each cable was equivalent to 20% of the yielding strength of the strands for school EP1 and to 21.3% for school EP2. This prestressing is lower than that range (33-35%) reported by Miranda (1990) and Miranda and Bertero (1990).

GROUND MOTION RECORDS

Artificial acceleration records were generated for the site for the 1985 Michoacán Earthquake. These artificial accelerograms were obtained according to a procedure proposed by Ordaz et al (1992) to generate acceleration records at any site in Mexico City based upon the strong motion data recorded in more than 100 stations in the last five years and the accelerograms of a reference station (usually CU station, rock site) for the earthquake of interest. The artificial accelerograms for the 1985 earthquake and their corresponding response spectra for 2% equivalent viscous damping are presented in Fig. 3. Peak ground accelerations were 0.12g for the N-S direction and 0.19g for the E-W direction, with a representative duration of 70 seconds.

ELASTIC ANALYSES

Three-dimensional elastic analyses using ETABS (Habibullah, 1992) were done to define dominant frequencies and modes of response for different idealizations of the original and upgraded structures, that is, including or not the longitudinal URM walls as structural members. Results are summarized in Table 1. Original schools EP1 and EP2 have short natural periods for the N-S direction because of the contribution of the infill walls in the transverse direction, regarding of the modeling. On the other hand, it can be observed that the natural periods of original schools EP1 and EP2 for the E-W direction are reduced dramatically when the longitudinal walls are included in the modeling, leading the structures away of peak responses (Fig. 3). If longitudinal walls are considered "non-structural", the structures are very flexible in the E-W direction, having high E-W natural periods because of the reduced moment of inertia of the columns in this direction. If longitudinal walls acted indeed as non-structural, then, school EP2 could have had a resonant response as the natural period for the site is around 1.3 seconds (Fig. 3). Translational mode shapes are very clean for both directions for either idealization, although coupling increases when the longitudinal walls are included in the modeling because walls of axes A and B are not identical (Figs. 1 and 2). The exception is the coupling observed for the N-S mode shapes of building A of school EP1 because the distribution of the transverse walls and the location of the stairs lead to additional stiffness and mass eccentricities (Fig. 1). It can be concluded that the contribution of the longitudinal walls helped the structures to move away from resonant response. However, the negative effect is that these walls do shorten the columns and a short-column brittle failure could develop under these conditions. Fortunately, this undesirable mechanism did not develop on these specific structures, but it was observed in other similar building structures during the 1985 Michoacán Earthquake.

Table 1. Dynamic characteristics of school buildings EP1 and EP2

Model	Direction	Period (sec)	Modal Mass (%) N-S	E-W	Rotation
Original EP1, building A, no longitudinal walls	N-S	0.18	74.83	0.00	12.40
	E-W	0.70	0.00	90.76	0.00
Original EP1, building A, longitudinal walls	N-S	0.17	76.06	0.01	11.20
	E-W	0.32	0.00	83.76	0.00
Retrofit EP1, building A, no longitudinal walls	N-S	0.17	78.16	0.02	9.52
	E-W	0.27	0.00	91.10	0.07
Retrofit EP1, building A, longitudinal walls	N-S	0.17	78.06	0.12	9.67
	E-W	0.23	0.10	90.47	0.00
Original EP1, building B, no longitudinal walls	N-S	0.17	87.64	0.00	0.00
	E-W	0.68	0.00	90.60	0.00
Original EP1, building B, longitudinal walls	N-S	0.17	87.50	0.11	0.10
	E-W	0.38	0.03	90.14	0.17
Retrofit EP1, building B, no longitudinal walls	N-S	0.17	87.92	0.00	0.00
	E-W	0.26	0.00	90.86	0.00
Retrofit EP1, building B, longitudinal walls	N-S	0.17	87.93	0.16	0.04
	E-W	0.22	0.13	90.27	0.01
Original EP2, no longitudinal walls	N-S	0.12	85.60	0.00	0.00
	E-W	1.23	0.00	88.56	0.00
Original EP2, longitudinal walls	N-S	0.12	85.54	0.00	0.00
	E-W	0.63	0.00	88.35	0.00
Retrofit EP2, no longitudinal walls	N-S	0.12	77.40	0.00	0.00
	E-W	0.32	0.00	88.53	0.00
Retrofit EP2, longitudinal walls	N-S	0.12	77.40	0.03	0.01
	E-W	0.28	0.00	88.95	0.00

Natural periods for the N-S direction of schools EP1 and EP2 are practically unaffected by the retrofit with the post-tensioned cables (Table 1). On the other hand, it can be observed that the natural periods of schools EP1 and EP2 for the E-W direction are reduced dramatically with the retrofit, particularly for the idealizations where the longitudinal walls are not included (Table 1). The retrofit scheme leads the structures away of peak responses (Fig. 3). The stiffening effect of the post-tensioned cables is reduced when the longitudinal walls are considered "structural" (Table 1). Coupling is reduced in the E-W translational mode shapes with the retrofit when the longitudinal walls are included in the modeling (Table 1). Therefore, it can be concluded, from the modal response viewpoint, that the use of post-tensioned cables is an effective solution when stiffening is recommended to take a flexible low-rise structure away of resonant responses and/or peak dynamic responses.

LIMIT ANALYSES

Limit analyses were done to assess lateral load capacities for the different idealizations of the original and retrofit structures. Several failure mechanisms were studied for each idealization in either direction. Critical failure mechanisms are summarized in Table 2. It can be observed that the critical failure mechanism for all models in the E-W direction is brittle in nature, described by the collapse of the base columns at their top and bottom. However, the base shear capacity associated with this mechanism is high, even when the contribution of the longitudinal walls is neglected, except the original EP2 building where its ultimate strength without including the transverse walls is moderate. Longitudinal walls considerable increase the ultimate lateral-load capacity of the schools, however, it is uncertain that these walls would develop all their effective shear capacity when the columns bear on them, as it was assumed in the analyses. In any case, the ultimate base shear capacities of the original school buildings under study satisfy the requirements of the building codes of their time of construction. Original school EP1 would also satisfy current seismic provisions of Mexico's Federal District Code of 1993 (NTCS-87, 1987), where the minimum base shear capacity for this structure should be 0.27W, taking into account its type, location, natural period and a response modification factor of two allowed for this structure. Original school EP2 would only satisfy NTCS-87 if the longitudinal walls would be completely effective, as a minimum base shear of 0.30W is required for this structure. The use of post-tensioned cables considerable increases the strength of the school buildings in the E-W direction, as it was reported before (Miranda, 1990, Miranda and Bertero, 1990), although their inclusion does no inhibit the brittle story column failure mechanism. However, due to the considerable increase in strength, it is likely that the structure would remain in the elastic range when subjected to strong ground shaking.

Table 2. Failure mechanisms for the different idealization of the school buildings

Model	Failure Mechanism	Dir	V/W
Original EP1(A), no long. walls	Base columns	E-W	0.28
Original EP1(A), long. walls	Base columns	E-W	0.54
Retrofit EP1(A), no long. walls	Base columns, yielding of cables	E-W	0.94
EP1 (A), original and retrofit	Transverse walls overturning	N-S	0.29
Original EP1(B), no long. walls	Base columns	E-W	0.29
Original EP1(B), long. walls	Base columns	E-W	0.38
Retrofit EP1(B), no long. walls	Base columns, yielding of cables	E-W	1.14
EP1(B), original and retrofit	Transverse walls overturning	N-S	0.29
Original EP2, no long. walls	Base columns	E-W	0.17
Original EP2, longitudinal walls	Base columns	E-W	0.31
Retrofit EP2, no long. walls	Base columns, yielding of cables	E-W	0.76
EP2, original	Transverse walls overturning	N-S	0.42
EP2, retrofit	Transverse walls overturning	N-S	0.59

For the N-S direction, the critical failure mechanism is dictated by the overturning of the transverse walls. The strength on this direction is also high and satisfies the strong provisions of NTCS-87 for both original school buildings in this direction (0.26W). Additional strength on the retrofit school EP2 is because two interior transverse URM walls were replaced by RC walls.

NONLINEAR DYNAMIC ANALYSES

Two-dimensional nonlinear dynamic analyses were performed to determine deformation and strength demands of the original and retrofit structures for postulated ground motions for a $M_S = 8.1$ earthquake. The E-W ground motion record of Fig 3 obtained as outlined before was used for this purpose. DRAIN-2DX (Prakash et al, 1992) was used to do these analyses. Frames A of the school buildings (Figs. 1 and 2) were modeled for the idealizations discussed in this study. Gravitational loads due to dead loads and reduced live loads were included in the modeling. Results from the dynamic analyses are summarized in Figs. 4 to 6. The variation of the axial force in the post-tensioned cables with respect to time is depicted in Fig. 4 for the schools under study, whether or not the transverse walls are included in the modeling. For all models, the initial prestressing force is clearly affected by the gravity loads, but this prestressing is not lost at any stage, therefore, the lateral stiffness in the retrofit schools remains unchanged through the duration of the seismic excitation. Overall, the variation of the axial load in the cables is smaller when the walls are included in the modeling (buildings EP1-A, EP1-B). However, there can be instances where the variation of the axial loads could be slightly higher when the walls are included, for example, the case of school EP2. This phenomenon is probably caused by the frequency content of the ground motion that might lead the EP2 model with the walls to respond to higher forces and deformations.

Peak dynamic story drifts and story shear columns index for the different models of the original and retrofit buildings EP1-A and EP2 are depicted in Fig. 5. In this figure, OM stands for the original structures including the walls in the modeling, O for the original structures neglecting the contribution of the walls in the modeling, RM for the retrofit structures with the cables including the walls, and R for the retrofit structures neglecting the walls. For the drift curves, (a) stands for the allowable RCDF-87 code drift limit for structures that may have non-structural elements separated from the structural elements ($\delta = 0.006$), and (b) for the allowable RCDF-87 code drift limit where non-structural elements should be separated from the structural elements ($\delta = 0.012$).

It can be concluded from the drift curves depicted in Fig. 5 that the retrofit with the post-tensioned cables is very effective as the maximum dynamic drifts are well below the more strict allowable limit prescribed by RCDF-87. Thus, the structures remained elastic as it was confirmed with further analysis of the data, where no hinging was observed in any structural element at any time-step. On the other hand, it can be observed that the distortions for the original structures (O) are extremely high if the walls are not included in the modeling. For these cases, the peak dynamic drifts surpass considerably the code limits and lead one to believe that the structure should have collapsed. This fact was confirmed with the mapping of the dynamic hinging where a first-story mechanism was formed at the time of maximum dynamic drift and shear responses for all models under this idealization. Also, it can be observed from Fig. 5 that drifts are considerably reduced when walls are included in the modeling for the original structures. For school EP1-A, the story drifts under this modeling (OM) are within the more strict allowable drift limits of RCDF-87 code, and the size of these deformations lead one to believe that the masonry walls should have not cracked. However, it can also be observed that the presence of the walls demand higher deformations along the length where the columns are not confined by the walls, evidencing the dangerous side of the short-column effect (Figs. 1 and 5). For school EP2, story drifts are within the maximum allowable limit of RCDF-87 code ($\delta=0.012$), but surpass the limit when non-structural elements are not properly separated from the structural ones ($\delta=0.006$). It is expected that the masonry walls should have considerably cracked under these levels of deformation. In addition, damage should be expected on non-structural elements, and at the structural elements as well. Columns and beams hinging were recognized for this model in several time-steps.

It can be concluded from the maximum dynamic story shear index curves of the columns depicted in Fig. 5 that: (1) Original columns are subjected to smaller shear forces for the retrofit models, and (2) For the models where walls are included (OM and RM), shear forces are generally reduced along the height of the walls. However, the shear forces attracted by the columns along the height where they are free to deform are considerably high, evidencing the dangerous side of the short column effect. Some dynamic hinging was observed for the OM idealization on this zones. Also, for the original structures (O), it can be deducted from Fig. 5 that base shear capacities for the modeled frames correlate well with those computed with the limit analyses. These frames (A) should carry about half of the base shear reported in the E-W direction (Table 2).

Some conclusions can be addressed from the peak dynamic story drifts and maximum story shear columns index curves depicted in Fig. 5: (1) the retrofit with post-tensioned cables is very effective, leading the structures to remain elastic; and, (2) the contribution of "non-structural" walls may have saved the schools from the structural collapse during the 1985 Michoacán Earthquake, because they lead the structures away from high responses as a consequence of considerably reducing their natural period (see Table 1 and Fig. 3). However, the short-column effect may trigger the collapse of similar structures no properly detailed to resist the increased shear forces and deformations, especially when stiffening of the structure is not helpful because of the frequency content of the ground motions of a site.

Global hysteretic curves for the original and retrofit idealizations of school EP2 when the walls are ignored in the modeling are depicted in Fig. 6. It can be confirmed that: (1) the original structure could have responded to high deformation and strength demands that should have lead the structure to collapse, and (2) the retrofit with the cables leads the structure to a reduced elastic response, hence, illustrating the effectiveness of the retrofit for these structures when subjected to ground motions typical of soft soil conditions, where stiffening of the structure is advised to lead structures away of resonant responses.

SUMMARY AND CONCLUSIONS

An analytical study of the seismic upgrading of existing three-story and four-story school buildings at Mexico City using post-tensioned bracing systems was presented. The effectiveness of the retrofit scheme and the influence of "non-structural" URM walls was discussed through the comparison of the seismic behavior of original and retrofit structures using a comprehensive set of analyses. The results of these analyses permit one to conclude the following: (1) The retrofit with the post-tensioned cables is very effective, leading the structures to reduced dynamic responses and to remain elastic; (2) The initial prestressing force is affected by the gravity loads, but the prestressing is not lost at any stage. Therefore, the use of moderate prestressing forces seems adequate for these structures, taking into consideration that higher prestressing forces may affect the capacity of original columns (positively or negatively) and the foundation, (3) If URM walls do not participate in the response, the original structures should have responded to high deformations and strength demands that should have lead them to the structural collapse, regardless that these structures satisfy the strength requirements of current building codes such as RCDF-87; and, (4) The contribution of "non-structural" walls may have saved the original school buildings from the structural collapse during the 1985 Michoacán Earthquake, because they lead the structures away from high responses as a consequence of considerably reducing their natural period. However, the short-column effect may trigger the collapse of similar structures no properly detailed to resist the increased shear forces and deformations, especially when stiffening of the structure is not helpful because of the frequency content of the ground motions of a site.

The findings of this work have good agreement with those reported by Miranda (1990) and Miranda and Bertero(1990). Therefore, many of their suggestions related to the factors to account for the retrofit of typical old low-rise school buildings in Mexico using post-tensioned cables (summarized in a previous section) apply. Besides these suggestions, some improvements could be made in the retrofit plan of these structures, as for example: (1) separate properly the transverse URM walls from the columns, so they will no participate in the response of the retrofit structure, and (2) RC jacketing of the original columns to improve both the stiffness and strength of these columns with respect to their weak axis. Finally, instrumenting some of these schools to monitor the effectiveness of the retrofit using post-tensioned cables during moderate and strong earthquakes would be very helpful.

ACKNOWLEDGMENTS

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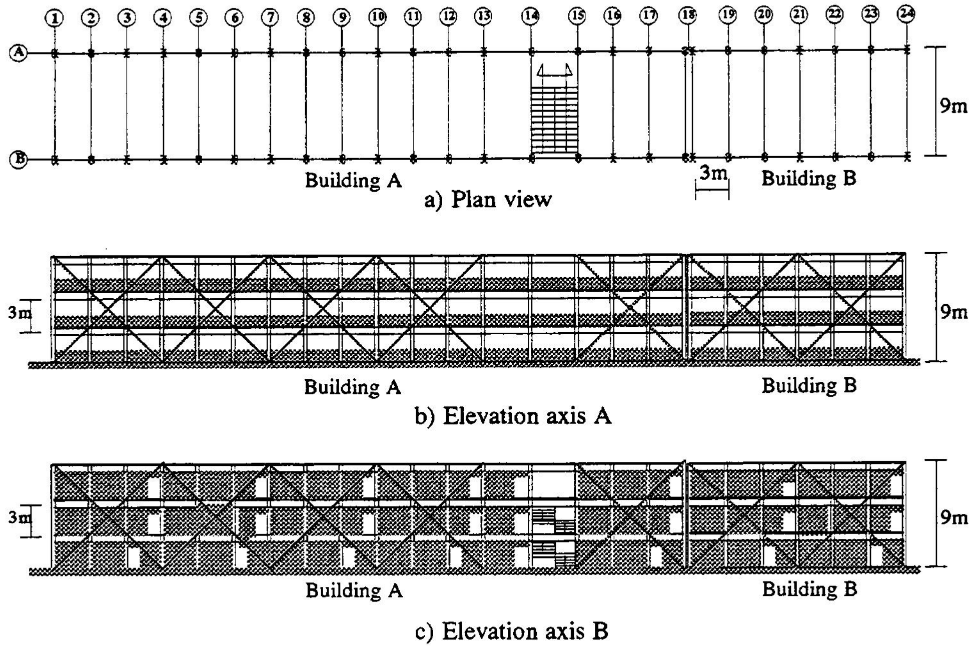

Figure 1. Plan view and elevations of school EP1

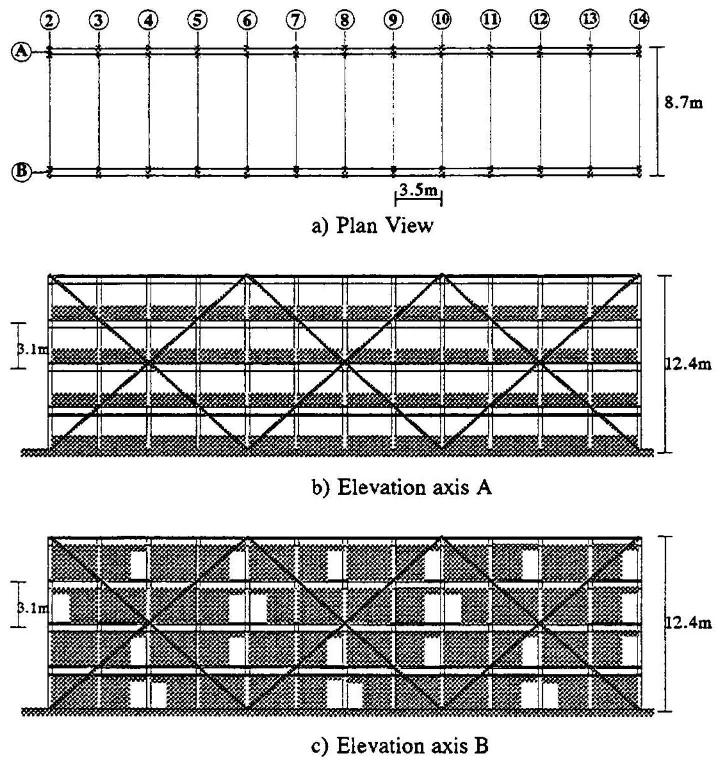

Figure 2. Plan view and elevations of school EP2

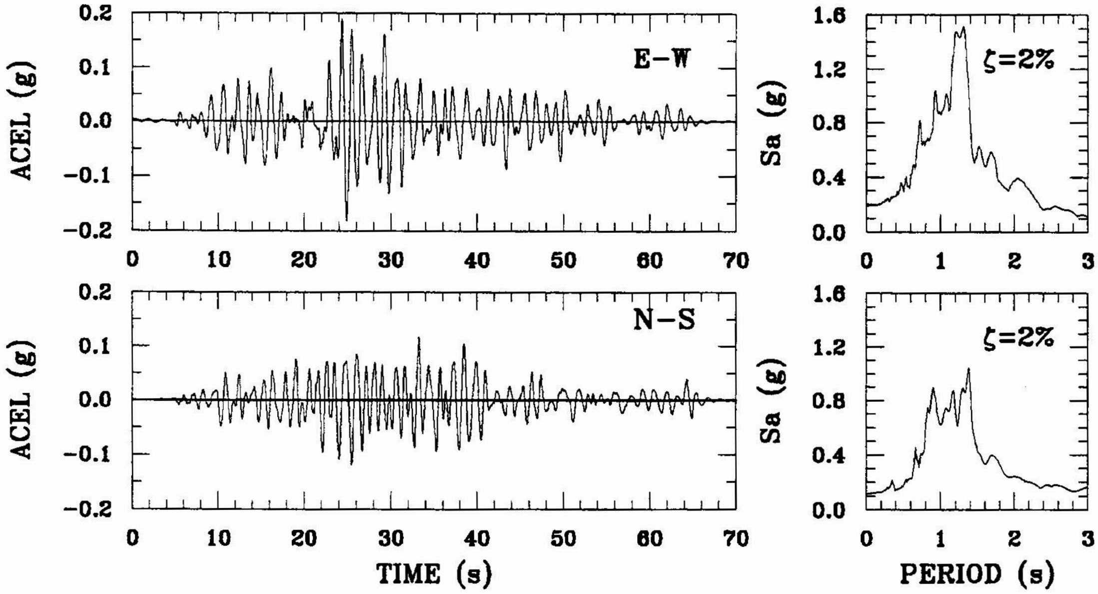

Figure 3. Ground accelerations and response spectra for the site

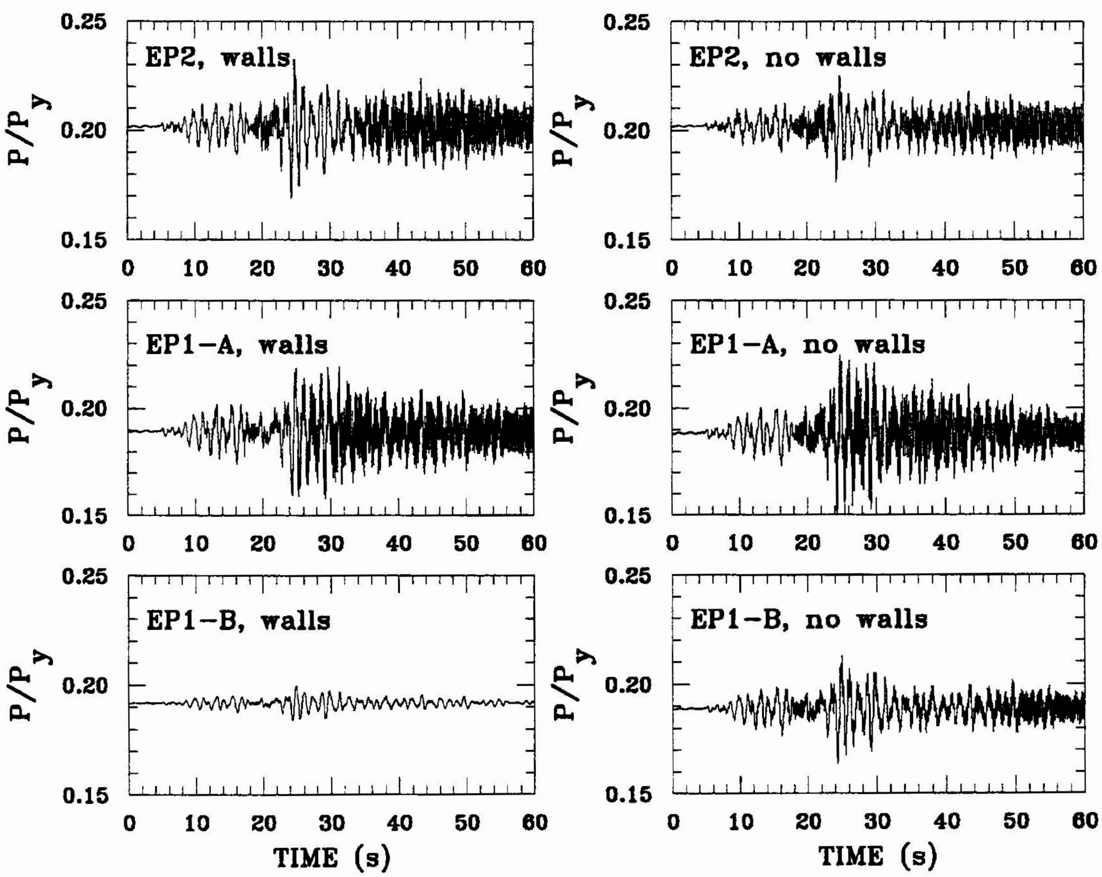

Figure 4. Variation of the axial load on typical cables

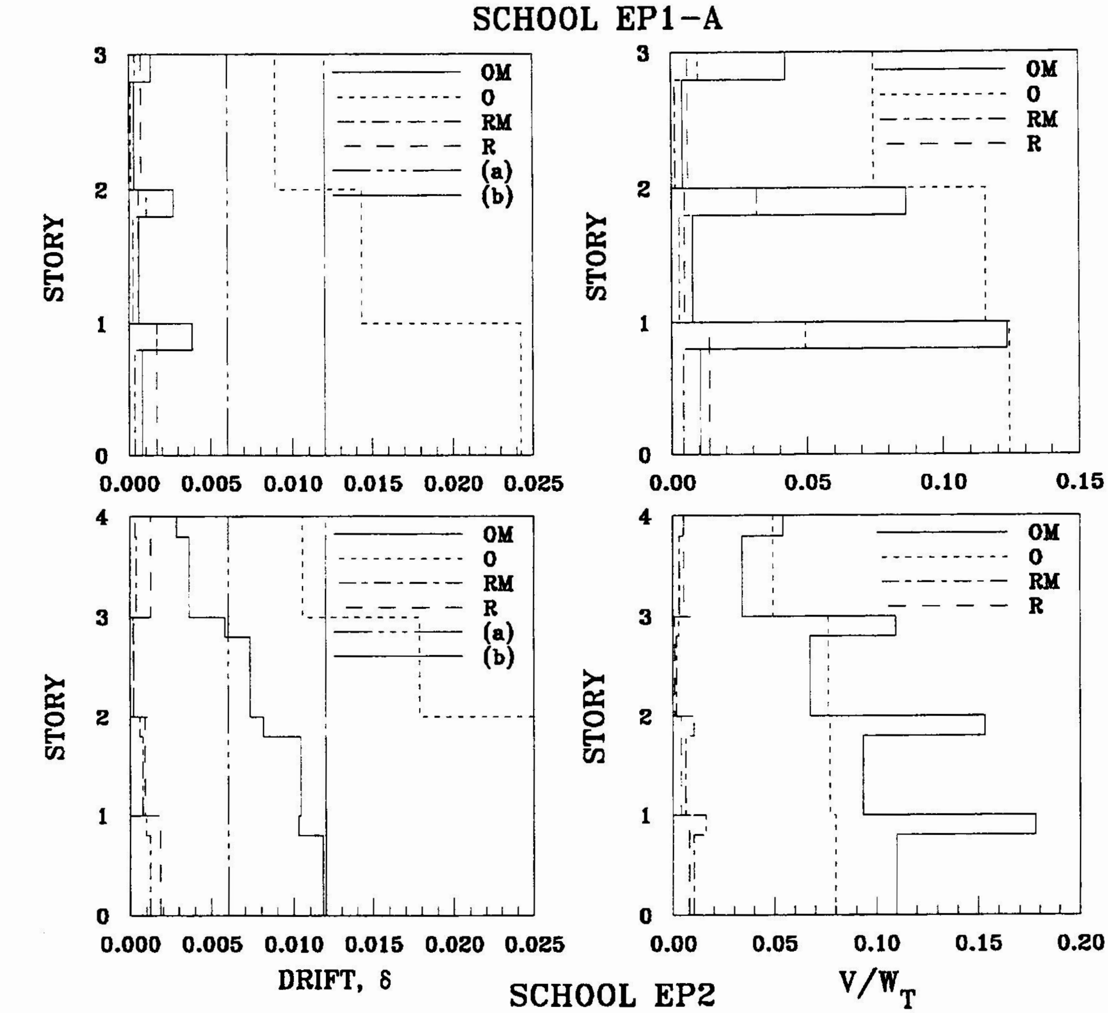

Figure 5. Peak dynamic drifts and columns shear index

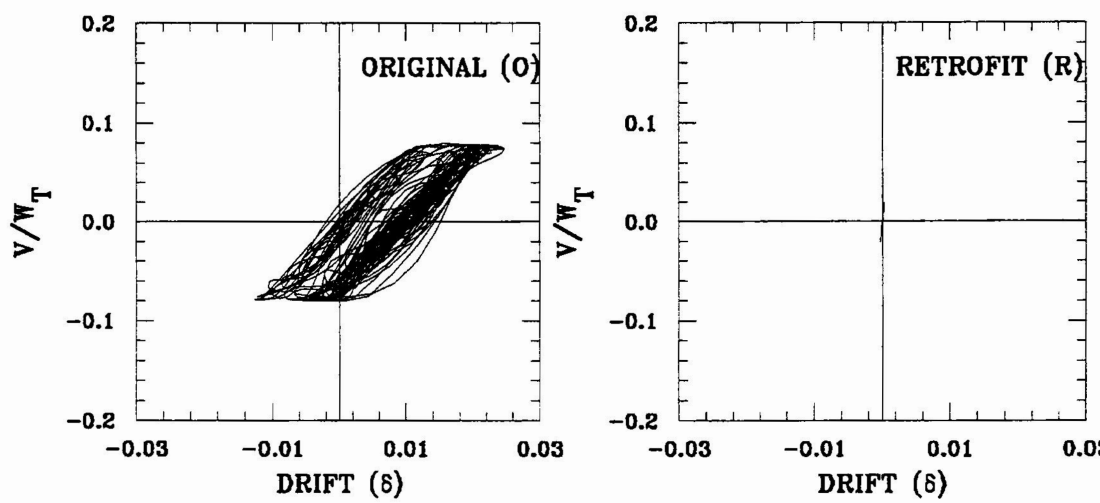

Figure 6. Global hysteretic curves for models of school EP2