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SEISMIC RETROFIT OF A MID-RISE BUILDING USING STEEL BRACING OR ADAS ENERGY DISSIPATION DEVICES: A COMPARATIVE STUDY

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ABSTRACT

Paper presents a comparative study of an existing retrofit for a mid-rise steel building using additional stiff steel braced-frames against an alternate retrofit using ADAS (Added Damping and Stiffness) passive energy dissipation devices. The subject building, located in downtown Mexico City, is a ten-story office building that was damaged during the 1985 Michoacán Earthquake because of resonant response with the site. The building was later retrofitted using additional braced frames. The retrofit scheme was planned to take the structure away from resonant responses and to inhibit structural damage. A proposed upgrade using ADAS energy dissipation devices was studied to compare energy dissipation against traditional stiffening using steel braces as retrofit options for mid-rise buildings in Mexico City's lake-bed zone. Different sets of analyses were carried out to compare both alternatives fairly: a) Three-dimensional elastic analyses; b) Limit analyses; c) Nonlinear dynamic analyses for postulated site ground motions for a M_S=8.1 earthquake; and d) Initial cost of retrofit analysis. The comparative studies suggest that a retrofit using ADAS devices would have a superior dynamic performance than the one using steel braces. However, the steel bracing retrofit provides more strength and its initial cost of retrofit is much cheaper. The ADAS are expensive to use in Mexico because of loyalties and trade taxes. Therefore, if the initial cost of the ADAS could be reduced, then, it would be an attractive option both technically and economically to retrofit mid-rise buildings in Mexico City.

KEYWORDS

Seismic retrofit, energy dissipation, ADAS devices, steel bracing, nonlinear dynamic analysis, initial costs

INTRODUCTION

Crowded cities have been severely struck by damaging earthquakes during the last decade. Mexico City was severely shaken during the September 19, 1985, M_S=8.1 Michoacán Earthquake. More than 4,500 people died and about 16,000 were injured. A total of 12,700 structures were affected, where 1,778 were severely damaged or collapsed and 4,826 experienced moderate damage. Medium-rise, moment-resisting frame buildings were among the most severely affected because the local soil conditions of the lake-bed region of Mexico City, and the structural dynamics of these buildings lead these structures to resonant responses with the ground in many cases. Given the large amount of medium-rise buildings affected by the quake and the need to use these facilities as soon as possible, several retrofit techniques were used in Mexico City for their seismic upgrading. A popular solution used in Mexico City after the 1985 Michoacán earthquake was the stiffening and strengthening of buildings with concentric diagonal steel bracing to take them away of resonant responses. This solution has been successful in the past for the seismic retrofit of RC buildings in Mexico City that survived the 1985 Michoacán Earthquake with practically no structural damage (ie, Foutch et al., 1988). Recently, some structures have been upgraded in Mexico City using energy dissipation devices. Energy dissipation devices are attractive to use because they improve the overall behavior of the structure by increasing its internal damping through the energy dissipated by the inelastic deformation of these special devices. Consequently, the dynamic structural response is considerably reduced, specially in the original members of the structure. Because many of these systems have to be mounted on steel braces to be attached to the original structure, the lateral stiffness of the structure is also increased, making these systems particularly attractive for buildings that are suspicious of having resonant response with the ground in Mexico City lake-bed region. The Added Damping and Stiffness (ADAS) energy dissipation device, which has been extensively tested and studied at the Universities of California at Berkeley (Whittaker et al., 1989) and Michigan, has caught the attention of Mexican structural engineers and researchers. Up to now, there are three RC buildings upgraded with ADAS devices in Mexico City. For these buildings, the structural engineer used the load-deformation curves obtained experimentally by the company that owns the patent of the ADAS device. However, numerical modeling of the ADAS have recently been proposed (ie, Whittaker et al., 1989; Tena-Colunga, 1995), so these numerical formulations can be used for preliminary design purposes and perhaps trigger their use in structural design.

There is a natural interest among Mexican practicing and research engineers in knowing when energy dissipation might be more advantageous than traditional stiffening for both original design and retrofit of buildings in Mexico City. There might not be a straight answer. Nevertheless, some research efforts are being conducted in this direction in idealized structural systems, looking to general response quantities. The present study deals with a case study where a proposed upgrade using ADAS energy dissipation devices was compared against traditional stiffening using steel braces as retrofit options for an existing mid-rise steel building in Mexico City's lake-bed zone. Detailed analytical studies were conducted to compare both alternatives fairly. The type of analyses and their results are discussed in following sections.

ORIGINAL BUILDING

The subject building, located nearby Alameda Park in downtown Mexico City, is a ten-story office building that was built in the 1950's according to the provisions of the 1942 Mexico's Federal District Code. For this code, the structure was classified to be type III and was designed for a seismic base shear of 0.025W, where W is the total weight of the structure. A plan view of the original structure is depicted in Fig. 1. Typical bay widths were 5.55 m in the longitudinal direction and 5.85 m or 6.50 m in the transverse direction. The total height of the structure from the ground level is 33.5 m, with typical story heights of 3.5 m but the first floor, with a height of 5.5m.

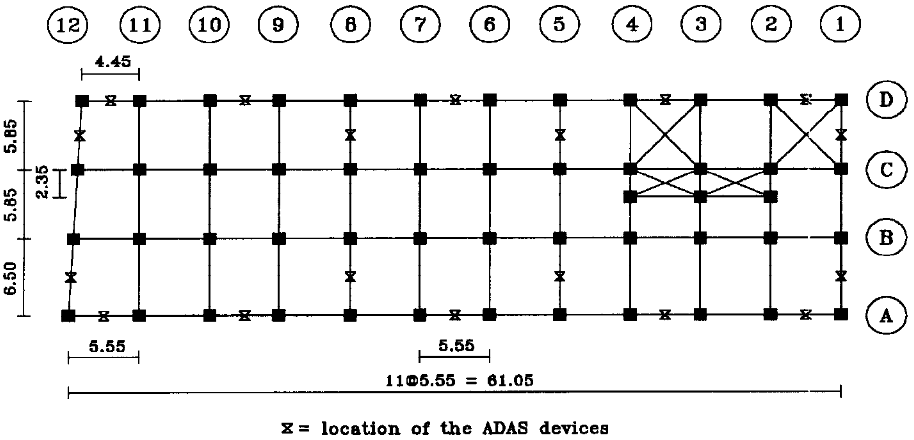


Fig. 1 Plan view for the original and ADAS retrofit building (dimensions in meters)

The original steel structure consisted of ordinary moment resisting frames (OMRF) in both orthogonal directions. Typical columns are of box cross section made either with two channels riveted to two 0.95 cm (3/8") steel plates or with four 15.24x15.24x0.95 cm (6"x6"x3/8") angles riveted to four 1.27 cm (1/2") steel plates. The dimensions of these columns vary considerably within a story and go from 65 x 50 cm at the first story to 35 x 32.5 cm to the upper three stories. Beams are approximately S15x50 for the first three stories, S12x35 from the fourth to seventh stories and S12x31.8 for the eight to ten stories. All original connections are riveted. The original foundation system is mixed and consists of a 4.8 m deep box foundation over friction piles. The original structure was later modified adding a three-story appendix with elements similar to the original sections for stories eighth to tenth. At the time of the 1985 Michoacán earthquake, the structure consisted of thirteen stories and a total height of 44 m. The structure under these conditions experienced moderate structural damage during the quake due to its flexibility and torsional response.

RETROFITTED BUILDING WITH ADDITIONAL BRACED FRAMES

Because of the poor performance during the 1985 Michoacán earthquake, the building was retrofitted by removing the three-story appendix and by adding stiff, "macro" braced frames (MBF) as depicted in plan in Fig. 2 and in elevation in Fig. 3. Each MBF has a story height equivalent to four stories of the original frames. Two exterior MBF were used in the longitudinal direction and four MBF were used in the transverse direction (Figs. 2 and 3). The design of the MBF was done considering that these frames should carry 100% of the seismic forces according to the requirements for seismic design stipulated by the 1987 Mexico's Federal District Code (RCDF-87, 1987). A seismic response modification factor for global ductility of two (Q=2) was assumed for the design of the MBF, according to the provisions of RCDF-87.

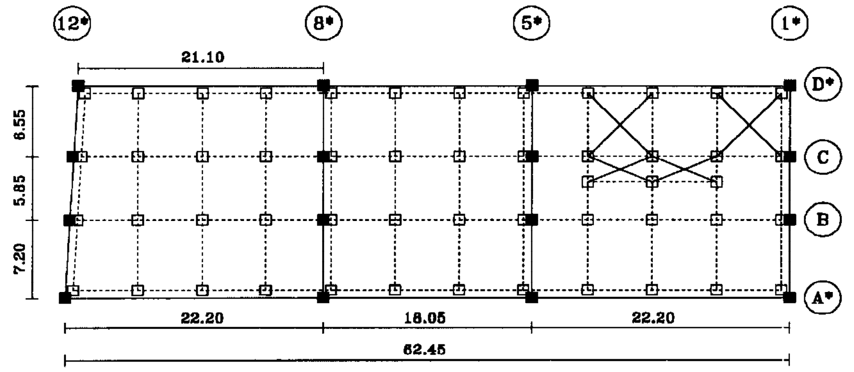
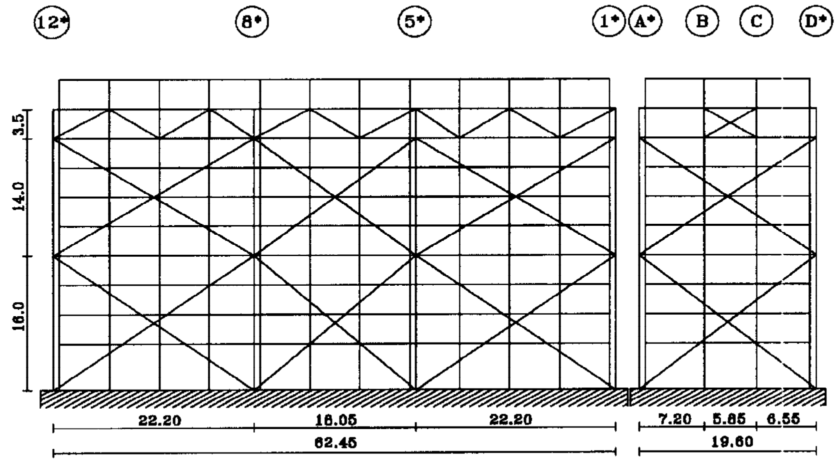


Fig. 2. Plan view for the existing MBF retrofit (dimensions in meters)



Frames A* and D*

Frames 1*,5*,8* and 12*

Fig. 3. Elevations for the existing MBF retrofit (dimensions in meters)

Columns of the MBF are of box cross section made by welding four A-36 steel plates. The MBF exterior columns A*1*, A*5*, A*8*, A*12*, D*1*, D*5*, D*8* and D*12* (Figs. 2 and 3) measure 35x35 cm with plate thicknesses of 1.91 cm for the first story and 0.95 cm for the remaining stories. Exterior columns B1*, B12*, C1* and C12* measure 30x30 cm with plate thicknesses of 0.95 cm for all the height of the building. Interior columns B5*, B8*, C5* and C8* were made by connecting two IPR sections measuring h=30 cm, b_f=15 cm, t_f=1.27 cm and t_w=0.95 cm with latticed plates 0.95 cm thick to make an open box-section. Beams for the new MBF are IPR sections measuring h=40 cm, b_f=25 cm, t_f=1.59 cm and t_w=0.95 cm for the transverse frames (1*, 5*, 8* and 12*) and h=25 cm, b_f=14.6 cm, t_f=1.27 cm and t_w=0.95 cm for the longitudinal frames (A* and D*). Diagonal braces were made with four welded plates to form a 35 x 35 cm box section, with thicknesses of 0.95 cm for frames A* and D* and 1.59 cm for frames 1*, 5*, 8* and 12*.

ALTERNATE RETROFIT WITH ADAS ENERGY DISSIPATION DEVICES

A retrofit scheme using energy dissipation devices could have been a sound technical solution for this building too, because the poor performance of the original building during the 1985 Michoacán earthquake was likely triggered by resonant response. Thus, a retrofit scheme using ADAS devices was planned for this building to compare against the existing MBF retrofit scheme described in previous sections. To make a fair comparison, the retrofit with ADAS devices was designed to strengthen the structure in the same areas covered by the

MBF option, as it can be seen by comparing Figs. 1 and 4 (ADAS retrofit) with Figs. 2 and 3 (MBF retrofit). The three-story appendix was also removed for this solution. The ADAS devices were assumed to be mounted on chevron steel braces (Fig. 4). Because there are no recommendations for the design or retrofit of buildings with energy dissipators available in RCDF-93 yet, the design of this retrofit was done attending to what can be assumed from research experiences while still observing the general seismic provisions for the RCDF-93 code. It has been shown in experimental research studies (Whittaker et al, 1989) that ADAS energy dissipation devices increase the global ductility and energy dissipation characteristics of traditional structural systems. Thus, it is reasonable to assume the highest response modification factor allowed by RCDF-93 code (Q=4) for the design of the ADAS devices.

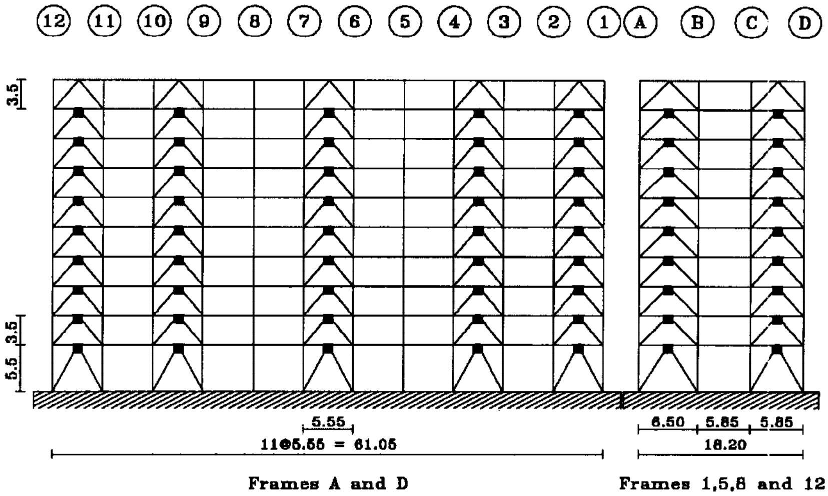


Fig. 5. Elevations for the alternate ADAS retrofit (dimensions in meters)

A 3-D ETABS model of the projected retrofit building was used for design purposes. The design of the retrofit was done by an iterative procedure using RCDF-93 design spectra for zone III, Q=4 and the SRSS combination. For ease in the iterative design procedure, the ADAS-chevron bracing system in ETABS was idealized by two equivalent diagonals. The axial stiffness of each equivalent diagonal, K_{eq}, was estimated as:

$$\frac{1}{K_{eq}} = \frac{1}{K_{diag}} + \frac{2}{K_{ADAS}} \tag{1}$$

where K_{diag} is the axial stiffness of each bracing and K_{ADAS} is the shear stiffness of the ADAS device. The mathematical stiffness and strength modeling of the ADAS devices was done according to a procedure recently proposed in the literature (Tena-Colunga, 1995). The design procedure starts by proposing diagonal braces capable of carrying the axial forces in the system in absence of ADAS devices. Then, the initial ADAS devices were designed to carry the shear forces transmitted by the chevron braces at the top joint, this is, where the ADAS elements are to be located. Once there is an initial design for the braces and the ADAS, the axial stiffness of the equivalent diagonals is modeled according to Eq. 1, and the building is analyzed again. The ADAS are redesigned to hold the shear forces at the top joint and the braces are redesigned to carry the axial forces of the equivalent diagonal using a safety factor of 1.7 to insure preventing brace buckling. The design of the ADAS and the chevron bracing is therefore reduced to an iterative process where elements are proposed until a convergence criterion is met. A total of 162 ADAS devices were needed for the proposed retrofit scheme (Tena-Colunga and Vergara, 1995; Vergara, 1995). The chevron bracing design consisted of square cross sections made by 2CPS 305x44.64 for stories 1 to 3, 2CPS 305x37.20 for stories 4 to 7 and 2CPS 254x22.76 for stories 8 to 10. In the tenth story there are no ADAS devices, as the design procedure suggested that the chevron bracing alone was enough to control drift deformations. For the design of retrofitted buildings is also important to check the state of the original elements, reviewing their stress conditions using suitable response modification factors according to the provisions of the design code. For the subject building, a response modification factor as high as Q=4 could have been used for all the frames according to RCDF-93, however, the old, unstrengthened steel frames were checked using Q=3. According to these analyses, the original elements did not need to be strengthened.

ACCELERATION RECORDS

Artificial acceleration records were generated for the Alameda Park site for both the 1985 Michoacán Earthquake. The artificial accelerograms were obtained according to a procedure where acceleration records are generated at any site in Mexico City based upon the transfer function of the site, the strong motion data recorded in more than 100 stations in the last seven years, and the accelerograms of a reference station for the earthquake of interest. The artificial accelerograms for the E-W and N-S components and their associated response spectrum for 2% viscous damping are presented in Fig. 5. Response spectra's curves suggest peak dynamic responses for structural systems with associated natural periods in the 1.7s to 2.3s period range.

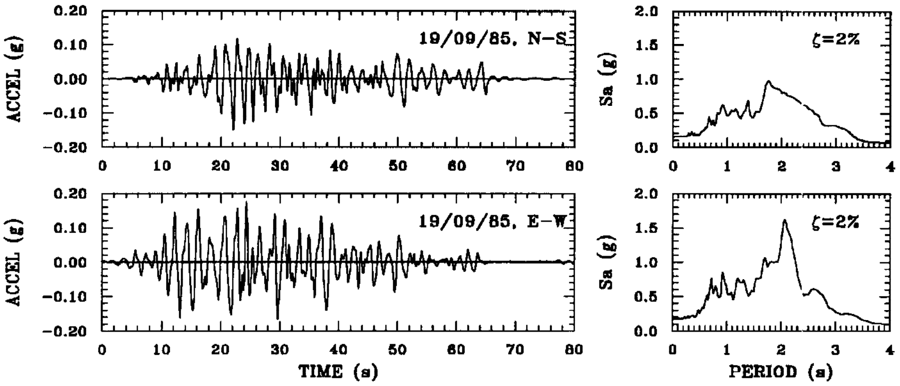


Fig. 5. Simulated acceleration records for Alameda Park site for the 1985 Michoacán Earthquake

3-D ELASTIC ANALYSES

To assess the initial, elastic dynamic characteristics of the different structural models for the subject building, 3-D frequency analyses of each model were done in ETABS. In these analyses, rigid-end zones, elevators' walls and soil-structure interaction effects were included. Results from the frequency analyses revealed that the mode shapes for the original and appendix models are highly coupled in translation, with important torsional components (Vergara, 1995). The natural periods for the original structure are in the 1.83s-1.96s range, where resonant responses can be expected for the Alameda Park site (Fig. 5). It can be assumed that if the original structure had been present during the 1985 earthquake, it may have suffered severe structural damage or collapsed because of resonant response with the site, besides the torsional response. The natural periods for the appendix model are in the 2.43s-2.64s period range, which are in the descendant branch of the response spectra for the site (Fig. 5). Thus, perhaps the construction of the additional three stories may have helped the building to survive the 1985 earthquake. Nevertheless, because of its flexibility and the torsional coupling, the structure experienced high deformations that caused the damage observed after the 1985 earthquake. Therefore, a retrofit for the structure that survived the 1985 earthquake was needed to improve its stiffness, strength and dynamic characteristics. The existing retrofit with MBF considerably increased the lateral stiffness of the structure in both directions and substantially improved its dynamic characteristics. The natural periods (0.90s for the N-S direction and 0.81s for the E-W direction) are well below the region for resonant responses with the site (Fig. 5). In addition, the translational mode shapes are almost pure as the stiffening wiped off the torsional coupling (Vergara, 1995). The alternate retrofit with ADAS devices is apparently less effective than the one with MBF from the frequency analysis viewpoint, but adequate to take the structure away of resonant responses. The natural periods, 1.19s for the N-S direction and 1.24s for the E-W direction are reasonably below the region for resonant responses with the site (Fig. 5). The modes are cleaner than for the original and appendix structures, but they are still coupled (Vergara, 1995).

LIMIT ANALYSES

Limit analyses of different idealizations for the subject building (original, appendix, MBF and ADAS) were carried out to estimate their ultimate capacity when subjected to lateral loading. Several failure mechanisms were studied for each idealization, including the weak beam - strong column (wb-sc) mechanism and fragile story failure mechanisms. For the original structure, a wb-sc mechanism ruled for the N-S direction, whereas a combined failure mechanism with hinges in the base columns and top eight-story columns and all beams from stories 1 to 7 ruled for the E-W direction. For the appendix model, the failure mechanism for both the E-W and N-S directions was the same combined mechanism described above. Similar combined failure mechanisms controlled the ultimate lateral load capacities for the ADAS retrofit. For the MBF, the dominant failure mechanisms are associated to combined mechanisms for the first MBF story, that is, the first four stories of the original structure. The described failure mechanisms are not completely ductile, thus, attending to these analyses, neither retrofit scheme help improve the nature of the collapse mechanism for the structure.

Ultimate base shear capacities associated to the failure mechanisms described above were compared against the design base shear for different versions of Mexico's Federal District Design Code (RCDF), taking into account the response modification factor "Q" allowed by the code according to the structural system for each case (Vergara, 1995; Tena-Colunga and Vergara, 1995). The original structure satisfied the strength requirements established by the ruling code at the time of construction (RCDF-42) and still satisfies the 1976 code (Q=4), but cannot satisfy entirely the 1987 code requirements (Q=4) that are the same for the current 1993 code. The appendix structure satisfies the 1976 code requirements (Q=4), but cannot satisfy the 1987 and 1993 code requirements (Q=4). The building on its actual condition (MBF) satisfies the strength requirements for the 1987 and 1993 codes by a large margin, taking Q=2 as allowed by the code. The additional MBFs hold 71% of the shear forces in the E-W direction and 70% in the N-S direction. The proposed upgrade with the ADAS devices also satisfies the 1987 and 1993 codes as a higher response modification factor would be allowed for this solution (Q=4). Although the ultimate strength is lower for the ADAS retrofit than for the MBF option, the strength distribution and the failure mechanisms are better. The retrofitted frames with ADAS devices carry 84% of the shear forces in the E-W direction, and hold 61% of the shear in the N-S direction. It can be concluded that, from a ductility and strength distribution viewpoint, the ADAS retrofit is superior to the MBF retrofit, even if the latter one has more strength. Strength alone is not a good parameter to judge the capability of a structure to resist adequately seismic forces.

NONLINEAR DYNAMIC ANALYSES

To rationalize the structural damage experienced during the 1985 Michoacán earthquake, and the dynamic response that could be expected for the MBF and ADAS models, representative frames for the models in the N-S direction were analyzed using the N-S accelerogram presented in Fig. 5 and DRAIN-2DX software. The critical frames for the 2-D analysis, according to the 3-D ETABS and the limit analyses, were frames 8 and 8* (Figs. 1 to 4). Four models were studied. Model ORIG stands for the original structure. Model APEN represents the appendix structure as it was during the 1985 earthquake. Model MACRO is the current MBF retrofitted structure. Finally, model ADAS stands for the retrofitted structure with ADAS devices. Details on the modeling and the results can be consulted elsewhere (Vergara, 1995, Tena-Colunga and Vergara, 1995). Peak dynamic story drift angles and maximum dynamic story shear indexes are depicted in Fig. 6 for the referenced models. In Fig. 6, RDF-a represents the limiting drift angle of current Mexico's Federal District Code (RCDF-93) for a structure that could have nonstructural elements no properly separated from the structural system, whereas RDF-b is the maximum drift angle allowed by the code when nonstructural elements are properly separated from the structural system. Also, W_T=8784 Ton, the estimated weight of the original building (model ORIG).

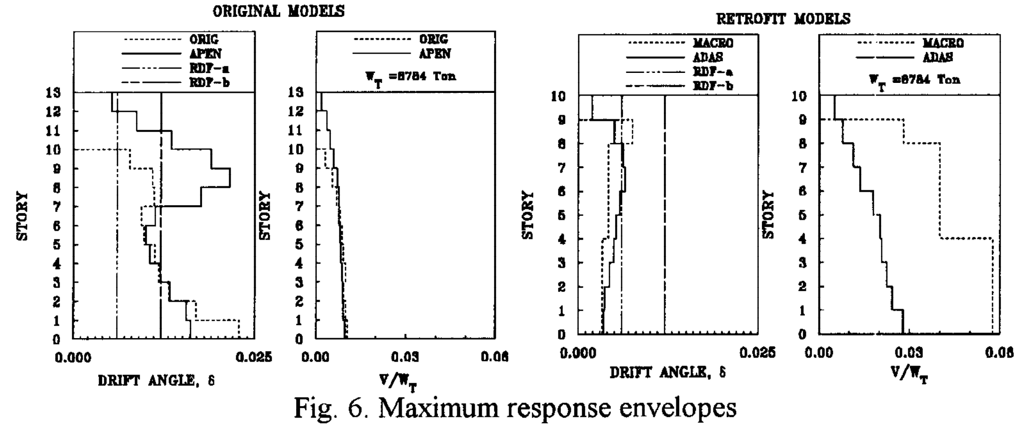


Fig. 6. Maximum response envelopes

The analyses for model ORIG suggest that the original structure could have collapsed during the 1985 earthquake as significant deformation, strength and ductility demands are detected for the frame under study (Fig. 6). The peak dynamic story drifts are higher than the code limit RDF-a from stories 4 to 10 and much higher than code limit RDF-b for the first three stories. The studied frame had clear weaknesses in the first three stories, where significant drift angles and ductility demands were detected (Fig. 6). Ductility demands of 3 to 5 are needed in these stories to achieve dynamic stability. The detailing of the original columns and beams and the existing connections could not warrant achieving these levels of deformation without substantial damage. The analyses for model APEN suggest that the structure could have experienced substantial damage due to large deformations during the 1985 earthquake, particularly in stories 1 to 3 and 8 to 10 (Fig. 6). However, the ductility, strength and deformation demands are smaller than for model ORIG in the lower five stories (Fig. 6). Drift angles were high. The peak story ductility demand was about 3.6 for the first story. Overall, the dynamic analyses suggest that adding three stories could have helped the structure to survive the 1985 Michoacán earthquake despite the observed structural damage, as the dynamic response for model APEN is better than for model ORIG.

The dynamic analyses for the retrofitted models MACRO and ADAS confirm their proficiency in improving the seismic behavior of the subject building. Peak dynamic drifts angles are within reasonable limits according to the RCDF-93 code (Fig. 6). Peak dynamic drifts are slightly higher for the ADAS model than for the MACRO model. However, the peak dynamic story shears for the ADAS retrofit are less than half of those for the MACRO model (Fig. 6). As the pseudo-acceleration response spectrum for 2% damping for the N-S record (Fig. 5) yields similar values for the elastic natural period of both models, it is clear that the ADAS retrofit yields smaller story shear forces because of the energy dissipation provided by the ADAS devices, which can be translated into a higher equivalent internal damping. Also, the axial forces transmitted to the foundation are less than half of those transmitted by the MACRO retrofit, so the ADAS retrofit is more advantageous on this regard than traditional stiffening with bracing.

The superior dynamic performance of the retrofit with ADAS devices over the existing MBF option can be confirmed with story hysteresis curves (Tena-Colunga and Vergara, 1995, Vergara, 1995) where it can be observed that the energy dissipation for model MACRO is limited and is due primarily by column yielding and dynamic brace buckling. In contrast, energy dissipation in the ADAS retrofit is high and stable. Story ductility demands range from 1.8 to 3.8, in the range assumed for design. The ductility and energy dissipation is provided by the ADAS devices, as it can be observed from the hysteresis curves of the ADAS devices depicted in Fig. 7, which are normalized with respect to the yield shear capacity of the ADAS of the first story. In Fig. 7, Δ is the ADAS' drift computed as the difference between the displacements for the top and bottom nodes of the ADAS element over the height of the ADAS device. It can be observed that the ADAS dissipate substantial energy in a stable way, with local ductility demands that range from 1.8 (N2) to 5.3 (N7). Also, for the ADAS retrofit, the ADAS-chevron system carries from 52.5% to 92.0% of the total story shear, thus, alleviating the work of the original elements. In fact, at the time of peak dynamic responses, the only elements that yield under the ADAS retrofit model are the designed ADAS elements and the central beams for stories 5 and 6. Overall, there is no doubt that the retrofit with ADAS energy dissipation devices has a superior dynamic performance than the constructed MBF retrofit, as it has been shown in the present study.

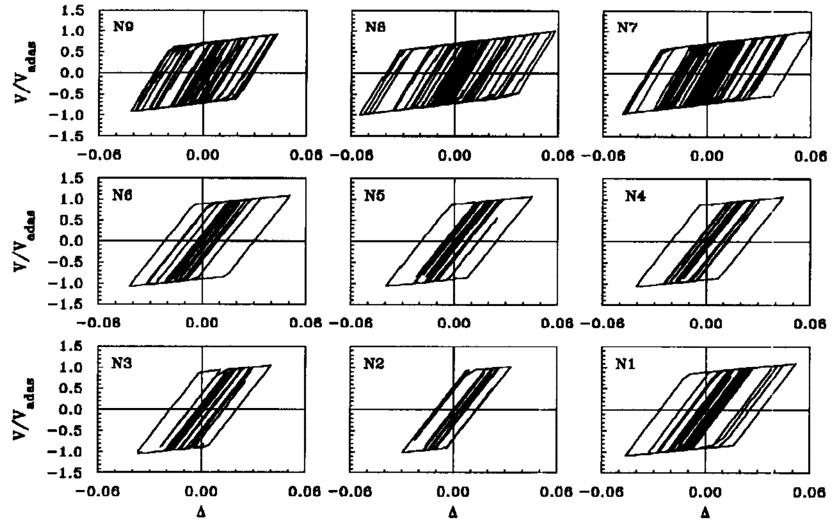


Fig. 7. Hysteresis curves for the ADAS elements for bay A-B, ADAS model.

INITIAL COST OF RETROFIT ANALYSIS

An important issue on the decision process to start a retrofit plan is the cost analysis. Unfortunately for structural engineering practice in Mexico, long-term cost analyses are seldom weighted in this process as the building owners always want to have their facility readily available as soon as possible at the cheapest initial cost. For this building, the initial cost of retrofit would include the cost for erecting the additional structural elements for each case, the demolition costs of the upper three stories including the relocation of the elevators' machinery, any cost related to a possible foundation strengthening and cost due to improvements for the facilities and aesthetics of the building. Nevertheless, the present initial cost study will only include the cost associated to the retrofit of the superstructure because no reliable information was obtained for the other issues. The superstructure cost of the existing MBF retrofit involves 285 Ton of structural steel, including a 15% waste because of the complexity of the connections. Thus, considering a cost of $1515.15 US/Ton of mounted structural steel, the initial cost of retrofit for the MBF due to the superstructure was $431,818.20 US. For the ADAS retrofit, a total of 145 Ton of structural steel is needed, including a 10% waste because of the connections. Thus, the initial cost due to structural steel was $219,697.00 US. In addition, 162 ADAS devices are needed. The company that trades the ADAS in Mexico City estimated a cost of $604,480.00 US, including installation, transportation and trade costs. Thus, the initial cost of retrofit for the ADAS option due to the superstructure is $824,177.00 US, 1.91 times the initial cost for the superstructure of the existing MBF retrofit. On this regard, there is no doubt that the MBF retrofit looks more attractive to the building owner, especially if the required foundation strengthening for both alternatives do not substantially differ.

SUMMARY AND CONCLUSIONS

A comparative study of an existing retrofit for a mid-rise steel building in downtown Mexico City using additional stiff steel braced-frames against an alternate retrofit using ADAS passive energy dissipation devices was presented. The building was damaged during the 1985 Michoacán Earthquake and was later retrofitted according to the seismic provisions of 1987 Mexico's Federal District Code. Different sets of analyses were carried out to compare both alternatives fairly: a) Three-dimensional elastic analyses; b) Limit analyses; c) Nonlinear dynamic analyses for postulated site ground motions for a M_S=8.1 earthquake; and d) Initial cost of retrofit analysis. The comparative studies suggest that a retrofit using ADAS devices would have a superior dynamic performance for postulated ground motions associated to a M_S=8.1 earthquake than the existing retrofit using steel braces (MBF retrofit). Energy dissipation is effective, leading the structure to reasonable levels of deformation and alleviating the original structural elements from stress. The nonlinear response is almost exclusively concentrated to the ADAS devices, which are subjected to deformation and strength demands that they can hold. The shear and axial forces transmitted to the foundation are considerable smaller than the ones for the existing retrofit. The ADAS retrofit also has enough reserve capacity to withstand more severe ground motions than the ones assumed in the analysis. Although the existing MBF retrofit provides more strength and stiffens the structure more, its dynamic response is clearly inferior to the ADAS retrofit, as there is potential brace buckling because they are slender. In fact, this study proves the danger of designing slender braces in earthquake regions, that unfortunately is a common practice, as many structural engineers design the braces as "tension-only members". Nevertheless, the existing MBF might be a good solution as leads the structure to reasonable levels of dynamic deformation, wipes torsional responses away and has considerable strength reserve capacity too, especially if one considers the additional strength capacity because of three-dimensional response, that could not be evaluated in this study. In addition, the initial cost of retrofit for the existing MBF option due to the superstructure is much cheaper than the ADAS retrofit. The ADAS are expensive to use in Mexico because of loyalties and trade taxes. Therefore, if the initial cost of the ADAS could be reduced, then, it would be an attractive option both technically and economically to retrofit mid-rise buildings in Mexico City's lake-bed region.

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