COMPARISON OF THE INELASTIC SEISMIC BEHAVIOR IN A NINE LEVEL BUILDING STRUCTURED WITHOUT AND WITH ENERGY DISSIPATION

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ABSTRACT :

The inelastic seismic behavior of a new nine level building structured by the following ways is compared: a) only frames (monolithic beams and slabs with columns); b) frames with the help of steel braces and energy dissipaters ADAS type. It is intended to observe how the seismic effects are distributed in the different existent structural elements in order to decide what the most convenient is to reduce damages according to the design point of view. The building of both cases, reinforced concrete, was dimensioned under the requirements of Mexico City Code, making practical considerations: B group (offices), zone III_b (soft soil), permissible interstory lateral deformation of 0.012, seismic behavior factor Q= 3. The second order and gravitational loads effects were included. The energy dissipaters distribution as well as the diagonals was made based on the idea of accomplish with architectural aspects and also to look which position and plate numbers of such dissipaters was convenient to achieve a more uniform seismic behavior in all the structure. The calculation of the inelastic responses is done with step-by-step dynamic analysis with the SCT-EW-1985 record, earthquake representative of the soft zone in Mexico City. Inelastic seismic behavior comparison is made based on the local and global ductility maximum demands. With the help of ADAS, the reinforced concrete elements are checked to verify and prove than in these members a different and favorable behavior was obtained. Some conclusions are obtained to new and to retrofit structures with this kind of energy dissipation.

KEYWORDS: Seismic, inelastic, step-by-step analysis, energy dissipate device ADAS

1. INTRODUCTION

A great number of damaged buildings in 1985 earthquakes had between 7 to 17 levels; several buildings that experimented serious damages were office type, without the help of structural walls and with no-structural divisions. The main probable argument why a lot of these types of edifications were damaged is that they were extremely flexible and also not efficient enough to develop ductility. In those buildings, between 1 and 2 seconds fundamental periods, that did not suffer important damages, the over-resistance effects probably helped to reduce them and also the foundation ones in order to dissipate part of the energy transmitted by the earthquake. Such additional resistance reserves facing the earthquake are due among other factors, to the existent masonry walls and/or because during the original design nominal resistance values were taken, probably inferior to the real ones. Results of the seismic behavior or a 9 levels building (offices), with two kinds of structural pattern: 1) only reinforced concrete frames, both directions, and 2) reinforced concrete frames with energy dissipation elements and steel braces (diagonals), are presented. For its design the structural security facing the limit state of service for the permissible interstory angular deformations of $\gamma_p \leq 0.012$ was checked, and the resistances for the seismic behavior factor Q=3 were given with the spectral modal dynamic method, including the gravitational loads effects, the P-Δ effects and the soil-structure interaction ones. Afterwards, step-by-step inelastic dynamic seismic analysis were performed in order to estimate the ductility demands developed globally as well as locally, facing the SCT-EW-85 record representing the 1985 earthquakes for soft soil and for the Mexico City's seriously damaged zone.

2. STRUCTURAL MODEL

The 9 levels building is composed of frames with reinforced concrete beams and columns, plus a basement with typical dimensions for office structures with and without braces and ADAS energy dissipation elements, located in the compressible zone of Mexico City. In the transversal direction (X), there are 3 axes, with 8 meters bays; in the longitudinal direction (Y) there are 4 axes with also 8 meters bays. The first story height has a double height with 7.0 meters, and the others of 3.50 meters. A concrete of f'_c= 250 kg/cm^2 (class 1) and reinforced steel with f_y= 4200 kg/cm^2 were considered. The first case (only frames) was checked with the permissible interstory angular deformation of 0.012 (design condition in which the non-structural elements are not linked to the main structure), according to the Mexico City Code (RDF-04) and its Norms. The transversal dimensions obtained were columns of 65x65 cm, in levels 9 and 8, 75 x 75 cm in levels 5, 6 and 7, 85 x 85 cm in levels 3 and 4, and of 100 x 100 cm in the remaining ones; beams of 60 x 30 cm in levels 8 and 9, of 70 x 30 cm in levels 5, 6 and 7, of 85x30 cm in levels 3 and 4, of 95x35cm in levels 1 and 2. The dimensions and properties of columns and beams of model 2 (with K form steel diagonals and ADAS type energy dissipation elements, both directions; see Figs. 1.a and 1.b) are: columns of 50 x 50 cm for the 5, 6, 7 , 8 and 9 levels, of 65 x 65 cm for levels 3 and 4, and 80 x 80 in the remaining levels; beams are 60 x 30 cm in all the levels. It was checked in order that the angular story height deformation would not exceed 0.006 in both directions. For the steel diagonal design, the resistance and load factor criteria (LRFD) was used, considering Type 1 sections.

3. SEISMIC DESIGN AND ANALYSIS CRITERIA

The studied structure is regular and symmetric in stiffness and resistance in plant as well as in height. Because of the kind of soil (soft, seismic zone type III_b) and structure (B group), the seismic coefficient, without the reduction of Q, was of 0.45. For its design, the Q=3 seismic behavior factor was used. The seismic design and the analysis were performed according to the RDF-04 and its corresponding Complementary Technical Norms. The loads and the weight calculation were made based on the typical office requirements; the ETABS program was used. For the step by step non-lineal dynamic analysis the DRAIN-2DX and ETABS were used. The ADAS energy dissipation elements, to reduce the earthquake transmitted forces, were included in order to give additional external damping as well as stiffness. These new structural elements should be capable of having enough deformation capacity, not to deteriorate in its resistance as well as not to degrade in its stiffness facing cyclic loads application. Therefore they allow to dissipate the energy by the steel plates inelastic behavior, in X shape, that presents bending in a double curvature around its minor axe, due to the relative displacement of the superior side in order to the inferior. For its design it is convenient that: a) to absorb a percentage of story shear force (for instance it could be of 50 percent), that depends of the bays number with steel diagonals; b) The maximum ductility developed is from 5 to 8, because the dissipation elements stiffness is reduced significantly for bigger values; c) The structure rides in the inelastic range, and that there is also energy dissipation by non-linear behavior; d) That the interstory relative maximum displacement is not bigger than the code permissible limit. For the ADAS devices design it is necessary to determine the resistance values F_y and Δ_y according to the studied structure.

4. ELASTIC RESPONSES

The structural model 1 was designed for $\gamma_p \leqq 0.012$ and Q= 3, accomplished with the Code for ductile frames.

In the Table 1, the three translation vibration period values of the three-dimensional model, with and without the diagonal elastic stiffness and ADAS energy dissipation elements participation are shown. Fig. 2 compares the design spectra for the III_b zone for seismic behavior factors equal to 1 and 3. Fig. 3 compares the ratios of relative lateral displacement between the story-height (Δr_i/ h_i) without and with steel braces, earthquake in X direction. The reinforcements design was made according to the Code specifications; for this model (Q= 3), reinforcement steel areas were calculated with ductile frames requirements. For model 1, initially dimensioned to accomplish the 0.012 times the story-height limit, designing the reinforcement steel, the sections were slightly bigger than needed, according to the service limit state, having a more rigid structure.

Table 1. Vibration periods, 9 levels building

	X direction (short)	Y direction (long)
Vibration mode	Period, T_i (seconds)	Period, T_i (seconds)
1	1.628 (1.394) [1.535]	1.572 (1.389) [1.526]
2	0.641 (0.516) [0.570]	0.626 (0.516) [0.566]
3	0.388 (0.310) [0.360]	0.382 (0.310) [0.359]

( ) Results with steel diagonals
[ ] Results with steel diagonals and ADAS energy dissipation elements

5. INELASTIC RESPONSES

Fig. 4 shows the SCT-EW-85 record, typical accelerogram of the 1985 soft soil earthquakes in Mexico City. Fig. 5 shows C axe lateral displacements envelopes, with and without inelastic behavior. The differences between both behaviors are significant, with smaller results for the non-linear response case. In the first structural case (only frames), the given resistances in beams and columns were exceeded by the internal actions calculated by the step-by-step dynamic analysis, which means that such structure presented a non-linear behavior practically generalized of yield over PB columns and N1 to N9 beams, as observed in Fig. 6. The local ductility maximum demands developed in beams and columns were of 8.29 and 8.12 for positive and negative bending in beams, and of 3.00 in columns when calculated without the axial load and 2.89 when it is considered. To quantify the local ductility demands in the structural members yield zones, the concept of curvature was used considering a plastic length of l_p= d (effective depth). The results are only presented for C axe, X direction seismic behavior. The inelastic behavior of model 1, designed with Q= 3, tends to the beam mechanism. Checking the longitudinal direction responses (2 Axe), the pattern of behavior is similar regarding the observed in transversal direction. After seismically analyzing the building of structural pattern 2 with only diagonals, the following responses were observed: the horizontal displacements of the elastic and inelastic step-by-step analysis, as well as the spectral modal dynamic analysis, for comparative purposes, present differences little significant; with the roof displacements histories registered in A axe (short exterior axe) with and without post-elastic behavior, it is noticed that there is indeed raid in the inelastic range; the plastic hinges distribution and the ductility maximum demands developed in beams and columns show values of 8.95 and 20.80 for negative and positive bending, respectively, for beams and of 11.47 for calculated columns as beams and very big ones if we consider the axial load due to its failure by tension. Fig. 7 presents the horizontal displacements envelopes of C axe (interior axe) with diagonals, where it can be noticed that it could be considering that there was no inelastic behavior; this is because of the diagonals presence, which due to their participation absorb in a considerable way seismic energy in the exterior axes. The plastic hinges global distribution shows that the lower level beams are the ones that present inelastic behavior, as expected, due to the diagonals presence as noticed in Fig. 8. Regarding the ductility demands in beams and columns it can be noticed the lightly difference between the inelastic and elastic behavior, where only in beams there was a rare inelastic behavior of 1.78. Afterwards in structure pattern 2 with braces, the ADAS energy dissipation elements were placed. For their design it was necessary to define the F_y and Δ_y values, depending of the seismic energy magnitude to dissipate by such elements yield, it is checked how beams and columns behave after making the ADAS work. Regarding the local ductility demands in A axe beams and columns for positive and negative bending in beams the values are in 20.27 an 21.86 respectively; and in columns of 13.11 when the axial load participates it is not considered and extremely big values when it is considered, due to yield presented in load to tension; as expected, the dissipation elements have a better work in the inelastic range, but due to its small F_y, the concrete structure and the diagonals have to work in a bigger quantity. The fist story ADAS presented the biggest number of times in which the hysteretic cycles occur, as expected, due to such story has height double, as noticed in Fig. 9, where the hysteresis diagrams (ratios of shear force-lateral displacement) of energy dissipation elements in levels 9, 7, 5, 3 and 1 are shown, and where the height distribution is appreciated. It is important not to forget that in the diagonals, columns and beams design it was given a Q = 3. It is obvious that it is necessary to review other ADAS possible distributions to achieve a better global seismic behavior.

6. CONCLUSIONS

When a structure is designed for interstory angular deformation $\gamma_p \leq 0.012$ and the reinforcement steel areas are determined with a ductility factor of 3 or higher, it leads to the formation of a high number of plastic hinges. To avoid the fragile failure modes, and in order to develop the desired ductility, sufficient transversal reinforcement should be placed in beams and columns in order to achieve that the concrete nucleus remains sufficiently confined at the moment of facing the cyclic action of seismic forces, but, this does not avoid the damage. While checking the seismic inelastic behavior with the ADAS energy dissipation elements located in model 2, it is noticed that there is an important diminish of internal actions in beams and columns of the conventional structure (model 1), when the elements are collocated; as long as they have a high resistance F_y, taking care that they really get to yield enough. It is notorious that there is an interaction very important between what happens with the ADAS and with the rest of the structure as it was expected. In general, the requirements specified in the Mexico City Code appear to be congruent for similar structures in this work. Never the less, it is recommended that the design for these structures gets done with a global ductility factor of 2 or even 3, and with an relation of the relative lateral displacement between story height no higher of 0.006, depending of the importance of them avoiding structural damages for severe earthquakes. The studies of the seismic effects influence of the dissipation elements must continue, for new and existent structures; its collocation, distribution and characteristics definition F_y and Δ_y, must be done with care, always based in the analytic studies that consider the adequate hysteresis laws and three-dimensional seismic behavior.

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Complementary Technical Norms (NTC), NTC-Concrete, RDF-04.
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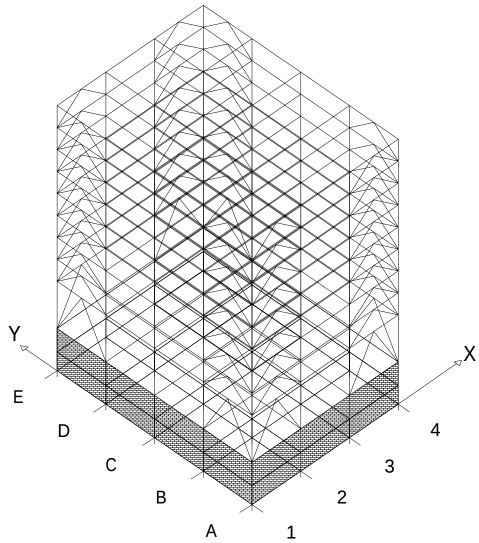

Figure 1.a Model 2 structure (with braces and ADAS)

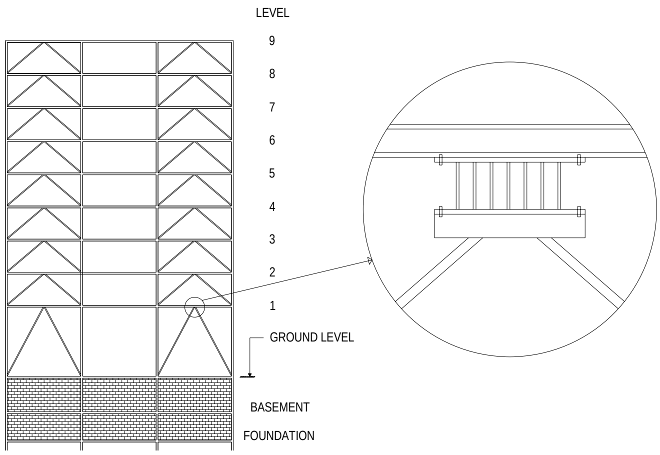

Figure 1.b Transversal direction frame, model 2 (with braces and ADAS)

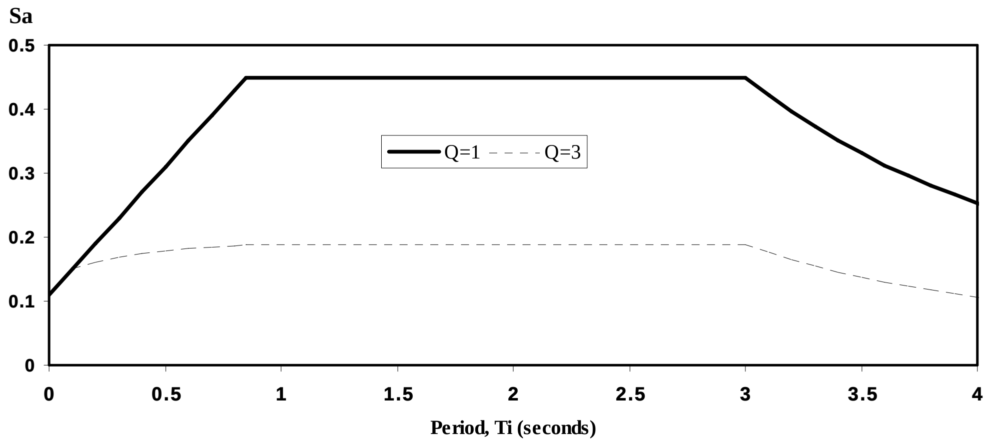

Figure 2. Design spectra, seismic zone III_b, Q=1 y Q=3, Mexico City Code (RDF-04)

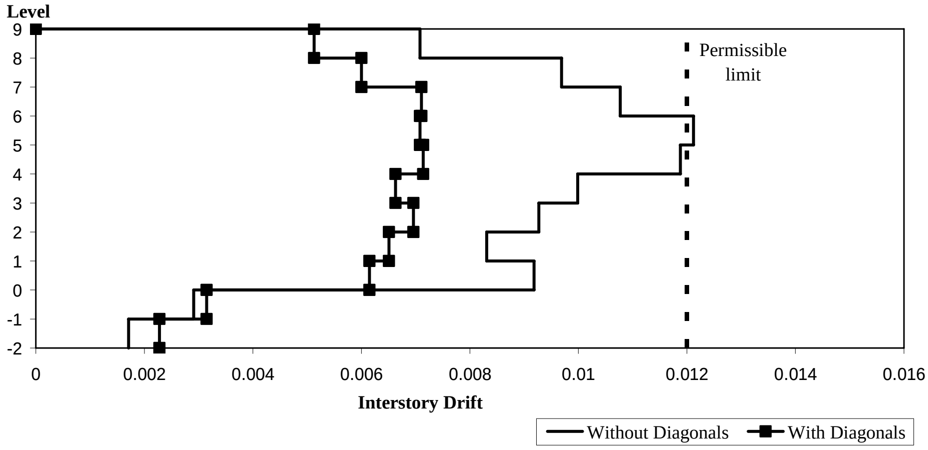

Figure 3. Ratios of relative lateral displacement between the story-height ($\Delta r_i / h_i$), earthquake in direction X

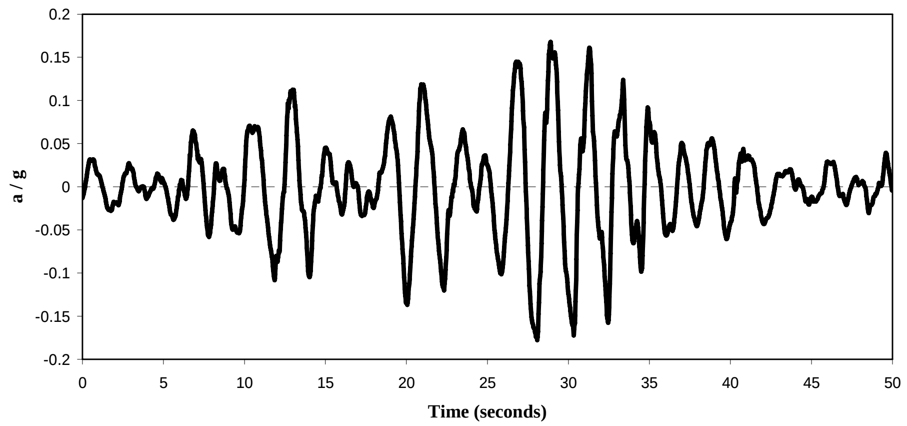

Figure 4. SCT-EW record (September 19, 1985)

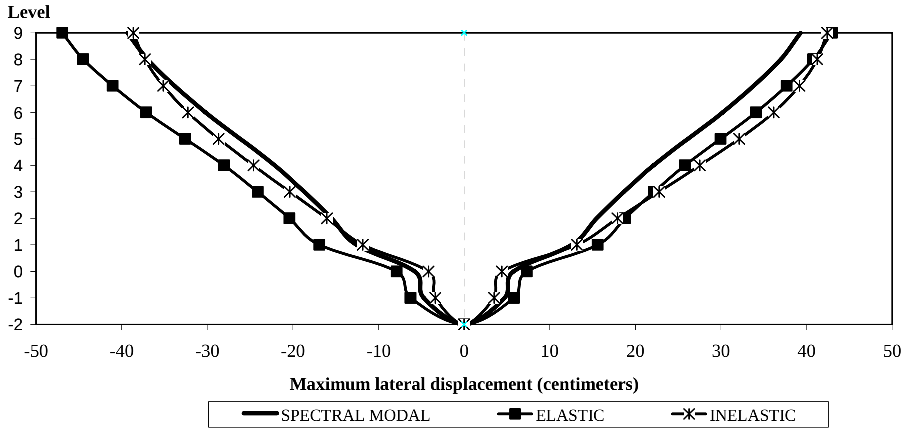

Figure 5. Maximum lateral displacements, C axe (transversal direction) without braces

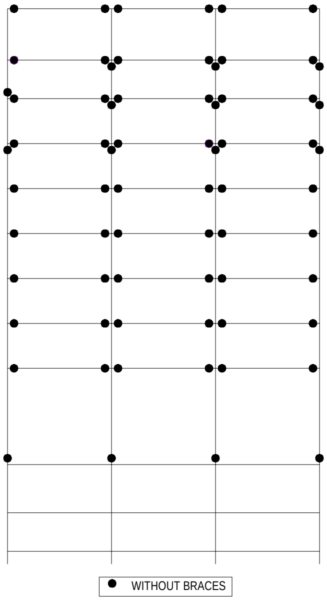

Figure 6. Plastic hinges global distribution, C axe (transversal direction) without braces

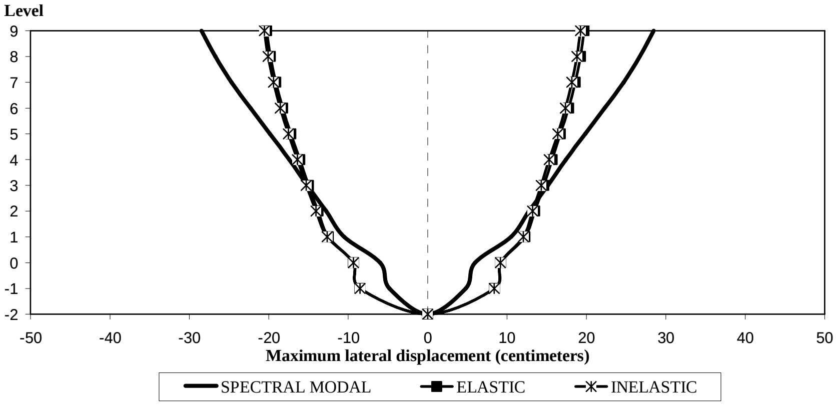

Figure 7. Maximum lateral displacements, C axe (transversal direction) with braces

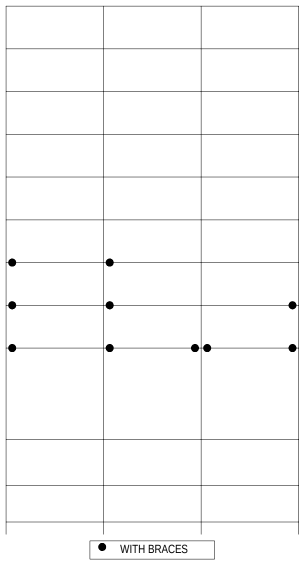

Figure 8. Plastic hinges global distribution, C axe (transversal direction) with braces

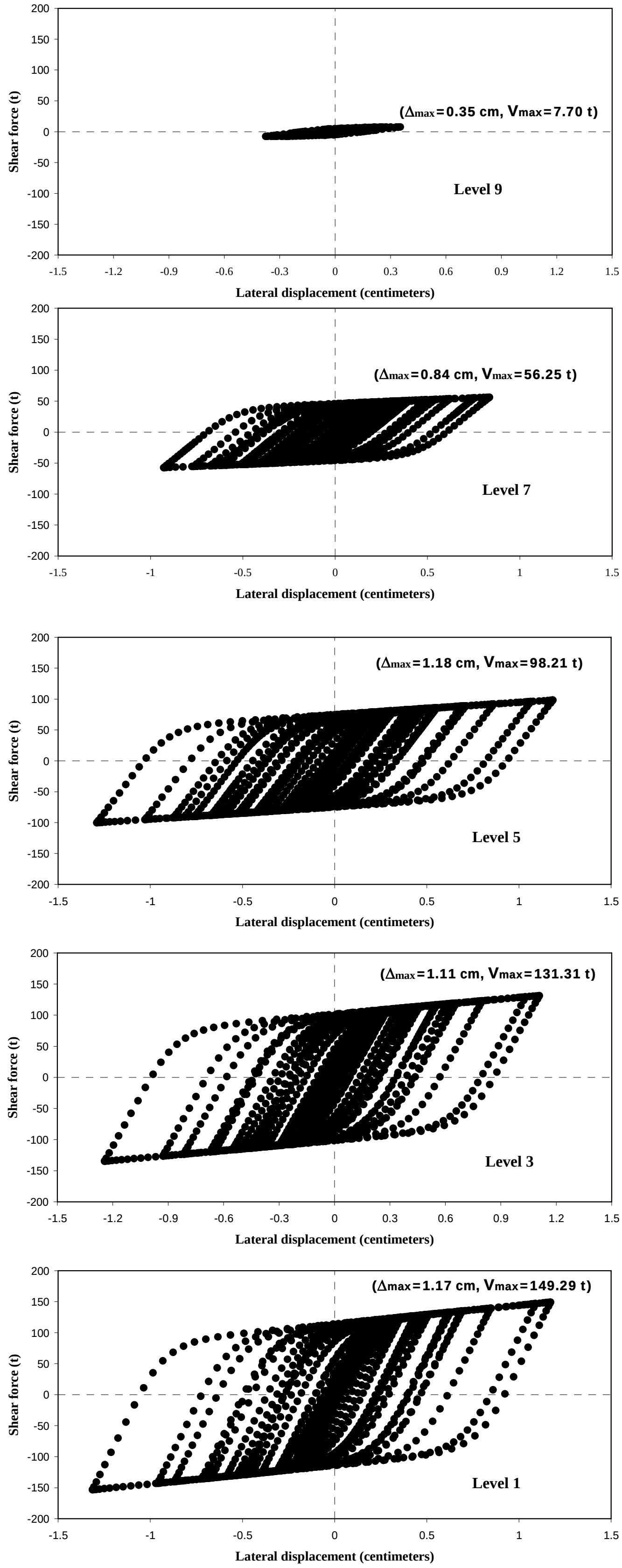

Figure 9. Ratios of shear force-lateral displacement of energy dissipation elements in levels 9, 7, 5, 3 and 1