Efficiency of Helical Springs and Viscodampers in Base Isolation

Semih S. TEZCAN
Bogazici University, Istanbul, Turkiye
Ahmet ÇIVI
Yapi Merkezi Inc., Istanbul, Turkiye

ABSTRACT

Results of an experimental testing are presented for a five-storey steel frame model, subjected to horizontal and vertical earthquake vibrations with varying intensities.

The dynamic testing included the fixed base conditions, as well as the full isolation by means of neoprene pads and helical springs, coupled with or without viscous dampers.

The response of the structural model to both horizontal and vertical vibrations has been thoroughly recorded, and these records have been correlated with those of the analytical investigations.

The primary conclusion of the study is that the vertical vibrations may unexpectedly cause response amplifications at very high undesirable levels, especially when the structure is base isolated by means of rubber pads. No such deficiency exists however, when helical springs and viscodampers are used.

SMiRT 11 Transactions Vol. K (August 1991) Tokyo, Japan, © 1991

1.- INTRODUCTION

The concept of vibration isolation has been utilized in connection with rotating machinery and delicate instruments for over a century *(Den Hartog, 1956)*. However, only within the last decade, base isolation and other autocontrol devices have been introduced as practical techniques for earthquake resistant design of structures.

Rubber elements *(Petrovski, 1982)* have been widely used as vibration isolators in the construction of some conventional structures and nuclear power plants. Many other base isolation systems such as ball bearings and floating platforms are still in the stage of theoretical development. A comprehensive summary of base isolation and other similar techniques is presented in a recent publication *(Anderson, 1990)*.

The vibration isolation provided by the rubber pads is limited to the horizontal direction only. Because the rubber elements, although very flexible in the horizontal direction, are very stiff in the vertical direction it is not possible to eliminate the amplification of the vertical accelerations in the superstructure, due to high rigidity of these elements in the vertical direction.

In a nuclear power plant building, sitting on rubber pads, the secondary structural elements, piping systems, machinery and other equipment would be subjected to excessive amount of vertical components of the seismic response. Thus, although the horizontal response is significantly reduced, the overall safety of the structure would be hindered on account of the existence of such large vertical amplifications. Moreover, due to insufficient damping in the rubber elements, horizontal displacements may also become unacceptably large.

Earthquakes excite structures not only horizontally, but also vertically, i.e. in a three dimensional way. In order to achieve vibration isolation in all three directions, a number of new vibration isolation systems with appropriate elastic properties in all directions have been introduced.

Helical springs and velocity proportional dampers proved to be very efficient in providing vibration isolation practically in all possible directions of motion *(Tezcan et al, 1979, 1980 and Hüffman, 1980).*

The helical springs, made out of steel, are very suitable for vibration isolation of earthquake excitations, since the ratio between their vertical and horizontal stiffnesses may be easily varied to meet the necessary damping is supplied by means of viscodampers so that both the acceleration and displacement responses of the structure are reduced to any desired levels.

In order to emphasize the importance of vertical vibrations, a series of experimental tests have been conducted as explained in the following sections, and the test results have been correlated with those of the analytical studies.

All shaking table tests have been conducted at the *Dynamics Laboratories of the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, Yugoslavia.* The necessary financing as well as the base isolation devices, in the form of steel laminated neoprene pads, helical springs, and also the viscodampers have been supplied by the *Gerb Gesellschaft für Isolierung, Berlin, Germany.*

2.- LABORATORY INVESTIGATIONS

The experimental studies consist of testing two distinct types of energy-absorbing systems, most favorable for seismic isolation, *(a) helical springs* coupled with *viscodampers*, and *(b) rubber pads.*

In order to investigate the behaviour of these two different isolation systems and also to study their respective advantages over the other systems, experimental tests have been conducted on a steel frame, identical to the one tested earlier in the *University of California at Berkeley, USA,* with rubber base isolation systems *(Kelly et al, 1980).*

The purpose of selecting a frame model the same as the frame previously tested at

Berkeley, USA, is to compare the relative performances of the rubber pads and spring-dashpot isolation systems.

Both types of base isolation, as well as the fixed base configuration, have been subjected to simultaneous action of biaxial excitations.

3.- TEST FRAME

The experimental model used is shown in *Fig. 1*. It is a five-storey three-bay steel frame mounted on two heavy base girders, which are supported at the shaking table for simulation of the fixed base model. In order to simulate the base isolated cases however, sets of *spring-dashpot* units as well as *rubber* elements are used at the corners of base girders.

Although, the structural members have different cross sectional properties, the *IZIIS* test frame has similar dynamic characteristics to the test frame used in *Berkeley, California USA* for testing of rubber base isolation.

The dead load is provided by means of steel blocks tied down to the frame at each floor level. The dead weight at upper floors is *4 700* kg. The total dead load at the upper floors is approximately *23.5* tons, while the weight of the two frames including the base girders and the bracing is *2.5* tons. An additional dead weight of *6.4* tons is attached onto the base girders, thus exerting a total of 32.4 tons weight on four springs.

The dead load provided by the steel blocks produces stress levels comparable to those in a fulll-scale structural frame. The geometrical scale factor of the model is roughly *1* to *4*. The corresponding time scale factor is consequently the square root of *4*, which is *2*.

The experimental program includes four cases of structural support conditions. The first series refer to the *fixed base* model in which the floor girders are fixed to the shaking table. The other three cases correspond to the base isolated models, two of which are with *spring-dashpot* units and one is with *rubber* elements.

4.- *SPRING-DASHPOT* UNITS

The first spring-dashpot system consists of four springs and four dashpot units *(4D-case)* placed under the base floor girders. The second system consists of four springs and eight dashpot units *(8D-case)*. The dashpots are placed at each end of the model along the end column lines. The total weight of the vibration isolation devices in the *4D-case* is *3* tons, thus the total weight of the model and the isolation elements on the shaking table becomes *35.4* tons.

The spring constants of a single helical spring are $k_v = 0.748$ kN/mm and $k_h = 0.395$ kN/mm in vertical and horizontal directions, respectively. The damping coefficients of the viscodampers, at an ambient temperature of *20* °C, are assumed to be $c_v = 30$ kNs/m, and $c_h = 25$ kNs/m for vertical and horizontal directions, respectively.

5.- EXPERIMENTAL PROGRAM

The experimental program has been prepared to provide as much data as possible necessary for an accurate interpretation of the dynamic behaviour of the structure with and without base isolation.

The input motions were selected to be the most representative to the most common destructive earthquakes. The following two earthquakes were selected:

1- *1940 El Centro*, California earthquake.
2- *1979 Montenegro Petrovac*, Yugoslavia earthquake.

The simulation of each earthquake has been achieved at *3* to *4* different levels of accelerations given to the shaking table. Altogether, *73* tests have been carried out using the selected earthquakes as the simulated input motion.

In order to provide an easy reference, each test has its own identification number consisting of *8* digits. The first two digits identify the base condition. For instance, *FB* = Fixed base model, *D4* and *D8* = Models with four and eight dashpot elements, respectively. The next two digits identify the type of earthquake, as follows:

EN = *El Centro* earthquake, real time (Δt = 0.02 sec)
EB = *El Centro* earthquake, time scaled (Δt = 0.01 sec)
PN = *Petrovac* earthquake, real time (Δt = 0.02 sec)

The earthquake component has been denoted by the fifth and the sixth digits of the identification number, such as;

NS = North-south component
VK = Vertical component

The numerical values like *200, 300* or *400* beside the earthquake identification code, indicate the *span* of the shaking table, which is a measure for the input displacement amplitude, on the basis of a *span* of *1000*, corresponding to ∓*12.5* cm.

6.- PEAK RESPONSES AT FLOOR LEVELS

The records of all thirty channels for *73* different runs are stored on magnetic tapes. In this study, only a minimum number of the most essential data important for understanding the structural model behaviour is presented. An extensive description of test data and their evaluations may be obtained from another reference *(Çivi, 1985)*.

Figs. 2 and *3* show the maximum values of the horizontally measured real accelerations and relative displacements at each floor level for different base conditions and earthquakes.

It is evident from these results that the base isolation systems in the form of springs and dashpots act as energy absorbers and significantly decrease the acceleration values along the height of the model. The rate of reduction in maximum accelerations under base isolation conditions is different and for some levels it is as large as twenty times.

It is also interesting to note that in the case of base isolation with four dashpots, the acceleration reduction level is considerably higher compared to the base isolation with eight dashpots. This is a consequence of the increased stiffness of the system due to the additional viscodampers. As opposed to the accelerations, the displacement amplitudes of the base isolated model with eight dashpots are smaller than those recorded under the same conditions with four dashpots.

Peak floor accelerations and displacements, corresponding to the *El Centro* real time *(EN NS 20)* and *Petrovac* real time *(PN NS 20)* earthquakes for different base conditions, are illustrated in *Figs. 4* and *5*, respectively. It is seen that although the floor accelerations of the rubber base isolation case are within the acceptable range, the horizontal displacements become excessively large even at relatively moderate earthquake intensities.

It is very important to note that in the case of spring supported system the horizontal displacements grow from base to top of the model similar to the fixed base model. At the spring level the horizontal deflections are negligible. However, horizontal displacements become significantly larger along the height of the structure due to coupling of rocking and horizontal motions.

Contrary to the considerable amount of relative interstorey displacements in the fixed base case however, the structural model with base isolation behaves almost like a rigid body with almost no interstorey displacements.

7.- DISCUSSION OF RESULTS

It is evident that in the case of base isolation which consists of four dashpots, the acceleration reduction level is considerably higher, almost two times, compared to the base isolation with eight dashpots. This is due to the increase in rigidity at the base level of the system caused by increasing the energy absorption capacity, by adding more dashpots.

The acceleration level continually decreases going from the base to the third floor and then starts to increase again. This shows that the deformational mechanism of the test model, in the case of base isolation, is complicated. It could be assumed that the type of deformation is controlled by the rocking, however, for higher levels there is an influence of horizontal inertia forces.

The above advantages in the form of the reduction of accelerations are off-set by the problem of larger horizontal and vertical displacements, which result from the rocking effect at the base of the model. Although, the scale of these displacements is in the order of several centimeters, they can be controlled by a special viscodamper system, which reduces incredibly the level of the rocking effect at the base level.

It is observed that with increase in energy absorption capacity the displacement amplitude level decreases considerably. The additional viscodampers reduce the effects of rocking, resulting in the decrease of horizontal displacements.

Due to the position of the rocking center near to the spring level, and the governing motion being in the rocking mode, the horizontal displacement of the springs are negligible. In none of the tests conducted, the vertical displacements ranging from *1* cm to *3* cm, were less than one quarter of the overall static deflections of the springs.

For simultaneous horizontal and vertical excitations, the results were practically similar to those corresponding to the results of individual nonconcurrent excitations. Based on the series of biaxial tests, it may be concluded that there is no considerable interaction between the horizontal and vertical excitations. The results of independent simulations in each direction are easily available and sufficiently accurate to represent the results of biaxial excitation.

The time history response of the roof, is given in *Fig. 6*, for fixed base and spring base isolation cases.

8.- MEASURED v.s. CALCULATED RESPONSES

Parallel to the experimental testing, the test frame is extensively analyzed under the action of the same earthquake loads in order to correlate the results of tests with theory. For purposes of simplicity, only the maximum amplitudes of the analytical and test results are compared.

It is clearly demonstrated by both analytical and experimental studies that when helical springs and viscodampers are used, both the vertical and horizontal components of acceleration to any given ground excitation are significantly reduced.

In general, the peak response values determined by analytical studies are in acceptable ranges with those obtained from the shaking table tests. In the case of the *1940 El Centro* real time earthquakes however, the correlation is not satisfactory regarding the peak accelerations of the fixed base model. The analytical results are higher almost by a factor of two. This is particularly attributable to the nonlinear behavior of the frame during the tests, which is considered to be linear in the analytical investigations. The peak accelerations of the analyses and tests for the vibration isolated models, however, are in very good agreement with each other.

Similarly, the *1979 Petrovac, Yugoslavia* earthquake results indicate that accelerations of the base isolated system are in very good agreement with those of theoretical analyses, for both low and high damping values. For the fixed base model however, the correlation is not satisfactory for the reason of linear assumption of behavior in the analyses.

The measured and calculated displacements for the fixed base case are consistently in good agreement with theory, at all earthquake input motions.

Although, the analytical studies have been performed for four different structural and damping conditions, only the peak response values of the "*4D-case*" with $T=1.47$ sec natural period are used in constructing the comparative figures. The peak floor response values of the analytical studies are also compared illustratively with those of the shaking table test results for some of the input motion data in *Figs. 7* and *8*.

It is obvious that the displacements are very much controlled by the amount of damping existing in the structure. The differences in the displacements therefore may be caused by the discrepancies of damping assumptions not necessarily corresponding to the real values existing in the tests.

Finally, certain other differences may exist between the measurement and the analysis, especially when the coupling of the shaking table with the test model is considered.

Considerable coupling of the mass of the shaking table *(32 tons)* may exist with that of the model frame, *(also 32 tons)*. The table pitching is also measured during the tests. Slight alterations of the predictable peak response, are observed in both the top floor and base beam horizontal accelerations, when the scaled time, $t = 0.01$ sec interval is used in conjunction with either the *1940 El Centro* or the *1979 Petrovac, Yugoslavia* earthquakes. It appears that, this phenomenon resembles, to a certain extent, to the presence of an appendix or a set-back superstructure on top of a tall building.

9.- RESPONSE IN VERTICAL DIRECTION

In order to investigate the relative performance of base isolation systems in vertical motion, vertical components of the *1940 El Centro* and *1979 Petrovac* earthquake motions have been considered using real time interval of $\Delta t = 0.02$ *sec.*

The responses of the test structure to these input motions, at the base, are illustrated in *Figs. 9* and *10*.

In general, it is determined that the spring-dashpot system considerably decreases the vertical acceleration amplitudes of the model and provides adequate energy absorption in reducing displacement response values. In the case of rubber isolation however, the vertical accelerations are found to be excessively large even at relatively low magnitude input motions.

It is seen that for the *1940 El Centro* earthquake, the vertical accelerations are reduced to about *50 %* of their shaking table values in the case of helical springs, but they are excessively amplified to about $445/45 \cong 10$ times their shaking table values, in the case of rubber pads.

This particular test therefore, indicates very clearly the superiority of helical springs over their rubber counterparts, in providing the best base isolation in the vertical direction. This is a very significant conclusion from the view point of efficiency of helical springs.

10.- ACKNOWLEDGEMENTS

The writers gratefully acknowledge the guidance and financial support supplied by *Dr. G. Hüffman,* Vice-president, Gerb Gesellschaft for Isolierung, Berlin, Germany and also the technical cooperation supplied by *Dr. J. Petrovski,* and *Dr. D. Jurukovski.,* former and current directors, respectively of the Institute of Earthquake Engineering and Engineering Seismology, Skopje, Yugoslavia.

11.- REFERENCES

Anderson, T.L., (editor), 1990 "*Theme Issue : Seismic Isolation*", Earthquake Spectra, *The Professional Journal of the Earthquake Engineering Research Institute,* 6431 Fairmount Ave., Suite 7, El Cerito, Calif., 94530, USA, May 1990.

Çivi, Ahmet, (1985), "*Vibration Isolation Concept in Aseismic Design of Structures,*" Ph. D. Thesis, Department of Civil Engineering, Bogaziçi University, Bebek-Istanbul, Türkiye, June 15, 1985.

Den Hartog, J.P. (1956), *"Mechanical Vibrations",* McGraw-Hill Book Co., New York.

Hüffmann, G., (1980), "*Spring-Damper Systems for the Support of Structures to Prevent Eartquake Damage,*" Proceedings of the 7th World Conference on Earthquake Engineering, Istanbul, Türkiye, Vol. 8, pp. 167-168.

Kelly, J.M., Skinner, M.S., and Beucke, K.E., (1980), "*Experimental Testing of an Energy Absorbing Base Isolation System*", Report No. *UCB/EERC-80/35,* Earthquake Engineering Research Center, University of California, Berkeley, USA.

Petrovski, J. and Simovski, V. (1982), "*Dynamic Response of a Base Isolated Building*", Proceedings of the 7th European Conference on Earthquake Engineering, Athens, Greece, Vol. 4, pp. 449-454.

Tezcan, S.S., and Çivi, A., (1979), "*Reduction in Earthquake Response of Structures by means of Vibration Isolators*", Proceedings of the 2nd U.S. National Conference on Earthquake Engineering, Stanford University, Stanford, California, USA, pp. 433-442.

Tezcan, S.S., and Çivi, A., and Hüffmann, G. (1980), "*Advantages of Spring Dashpot Systems as Vibration Isolators*", Proceedings of the 7th World Conference on Earthquake Engineering, Istanbul, Türkiye, Vol. 8, pp. 53-60.

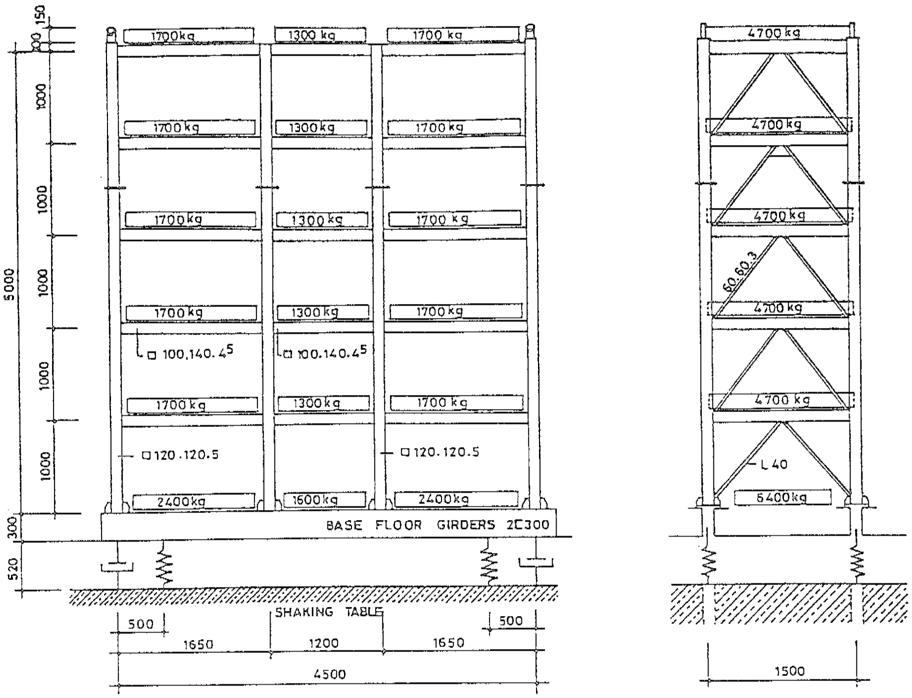

FIG. 1.- THE TEST FRAME ON THE SHAKING TABLE

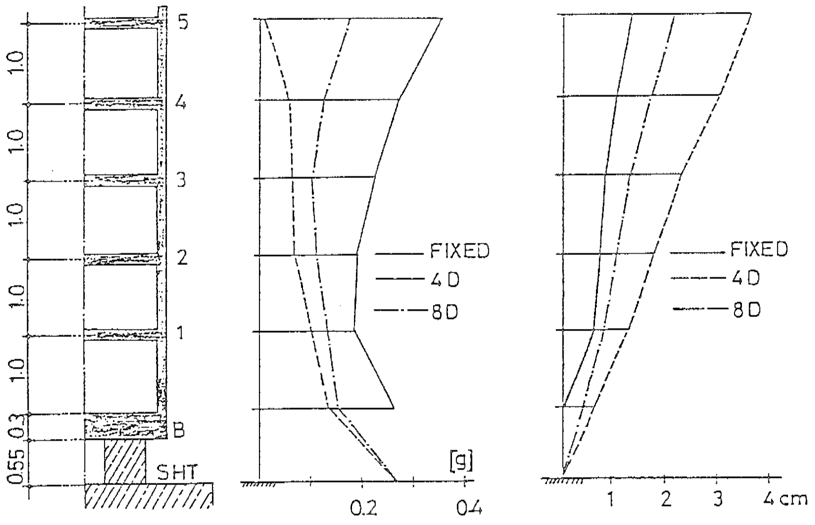

FIG. 2.- PEAK ACCELERATIONS AND DISPLACEMENTS - *El Centro (EN 400)*

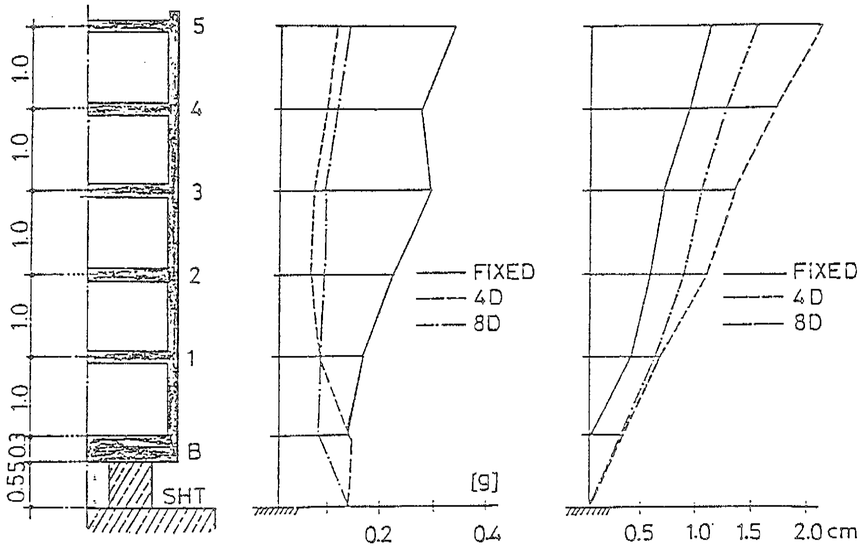

FIG 3.- PEAK ACCELERATIONS AND DISPLACEMENTS - *Petrovac (PN 200)*

May 18, 1940 EL CENTRO EARTHQUAKE Δt= 0.02 sec

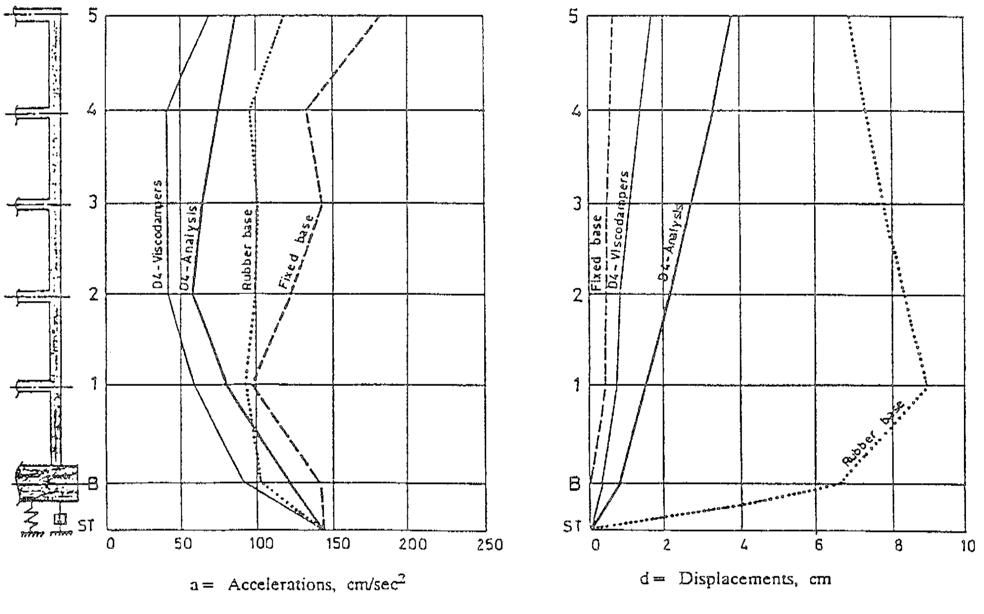

FIG. 4.- PEAK RESPONSE VALUES - *El Centro (EN NS 200)*

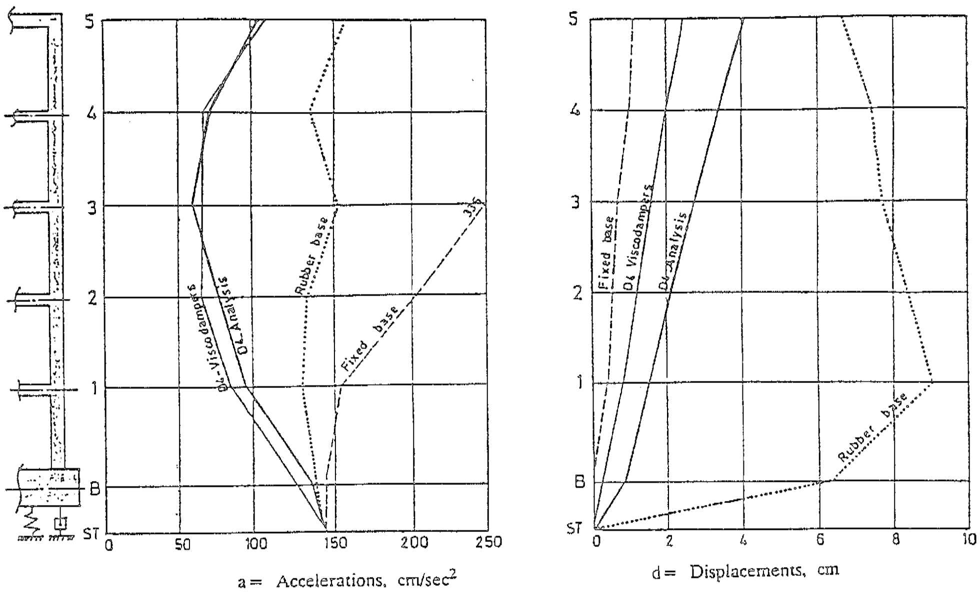
April 15, 1979 PETROVAC EARTHQUAKE, Δt= 0.02 sec

FIG. 5.- PEAK RESPONSE VALUES - *Petrovac (PN NS 20)*

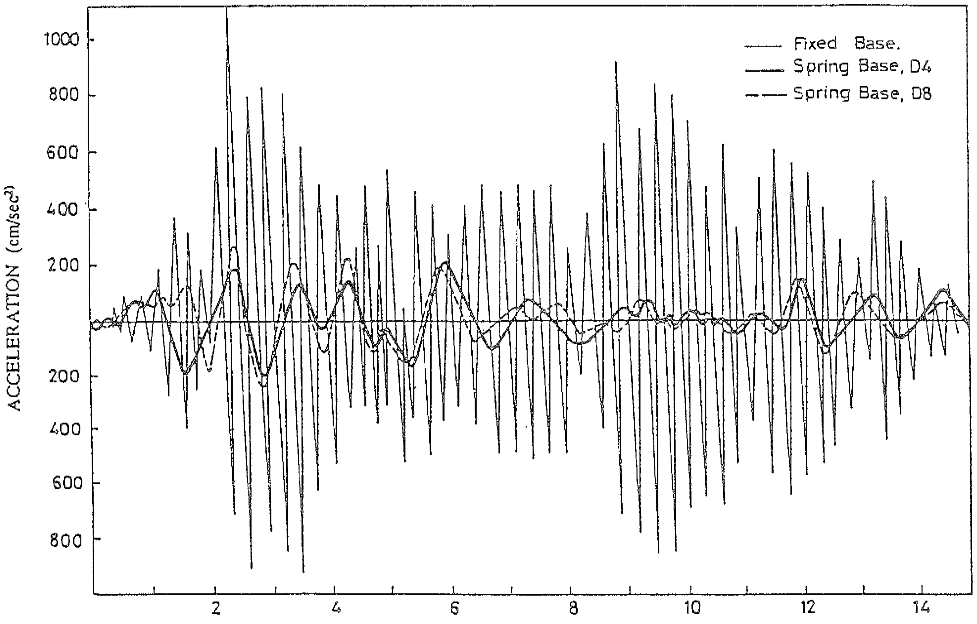

FIG. 6.- ACCELERATION RESPONSE OF ROOF TO *EL CENTRO,* REAL

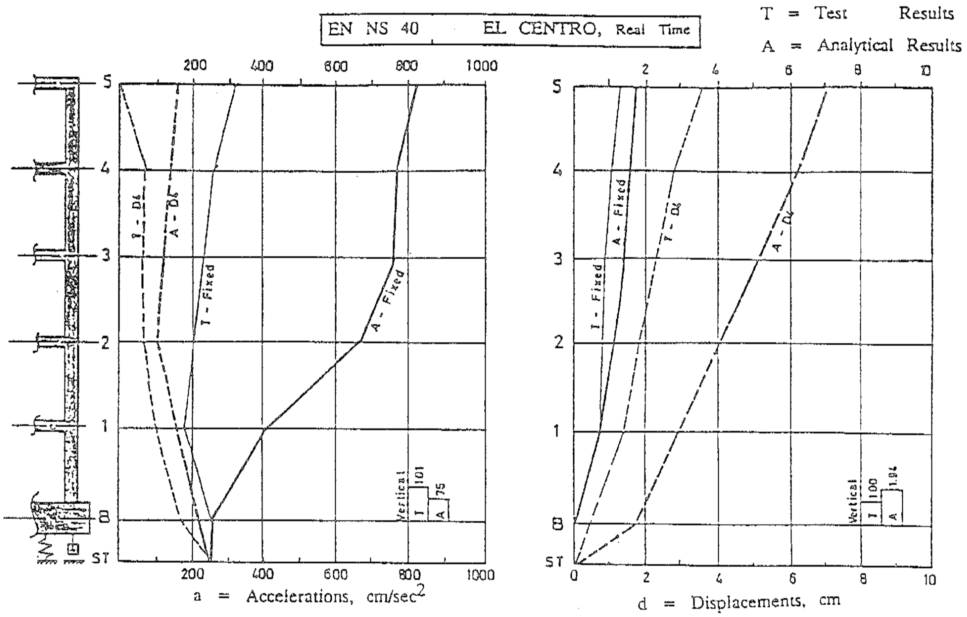

FIG. 7.- RESPONSE COMPARISONS, *(Four dampers vs Fixed base)*

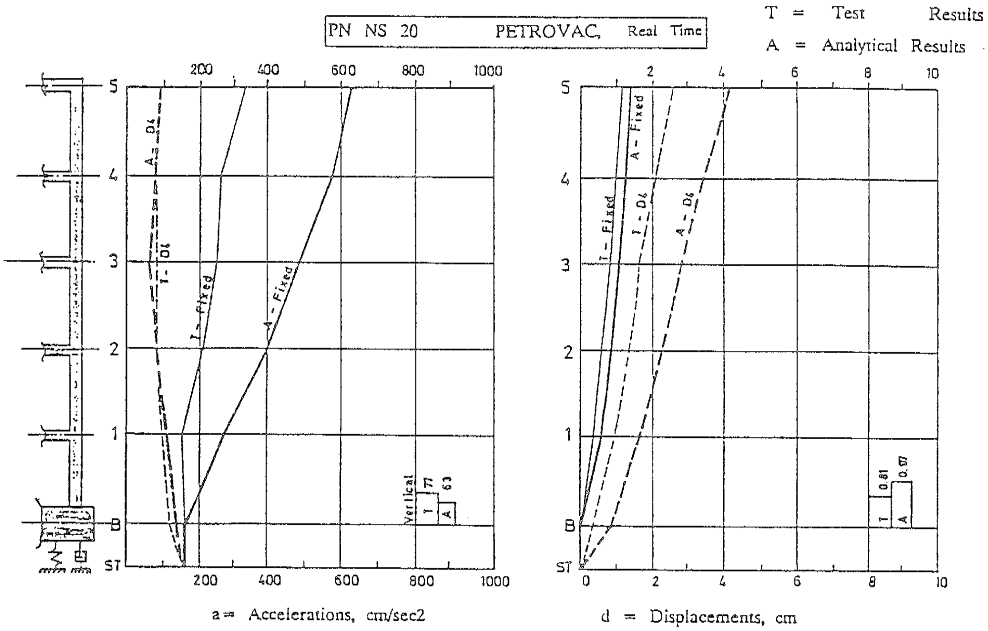

FIG. 8.- RESPONSE COMPARISONS, *(Four dampers vs Fixed base)*

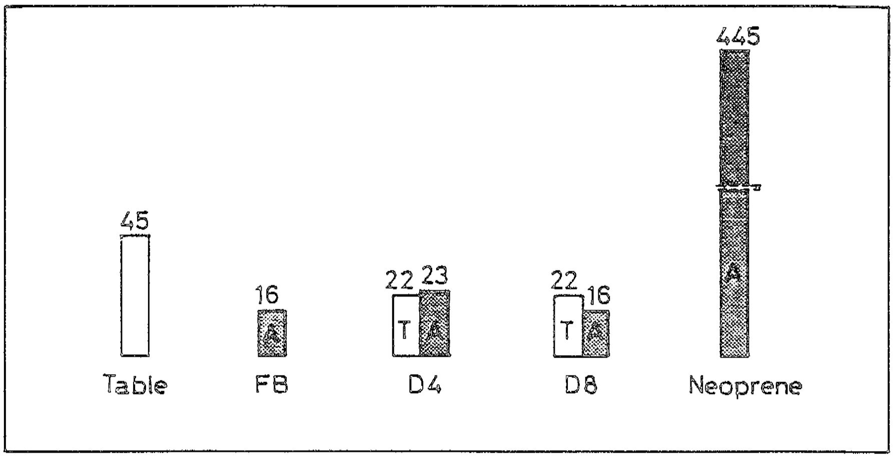

FIG. 9.- VERTICAL ACCELERATIONS, *1940 EL CENTRO REAL TIME (cm/sec^2)*

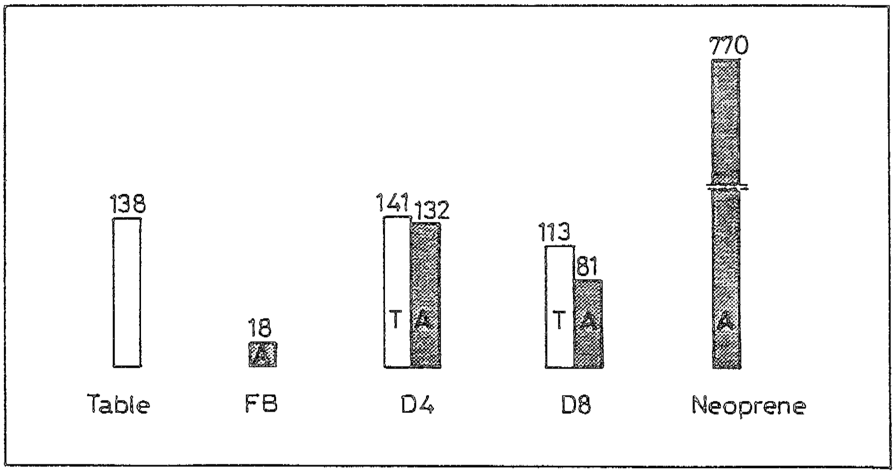

FIG. 10.- VERTICAL ACCELERATIONS, *1979 PETROVAC REAL TIME (cm/sec^2)*