EFFECTS OF GRAVITY LOADS AND VERTICAL GROUND ACCELERATION ON THE SEISMIC RESPONSE OF MULTISTORY FRAMES

by

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SYNOPSIS

The inelastic response of a ten story unbraced steel frame, subjected to a horizontal component of earthquake and to combinations of this component with gravity load, and the vertical component of the earthquake, is evaluated using numerical methods. The inclusion of gravity load results in a significant increase in the ductility requirements of the upper story girders and of the lower story columns. Inclusion of the vertical component of ground motion can result in a further increase in the ductility requirements of these elements and can also increase significantly the ductility requirement of the upper story columns.

INTRODUCTION

Current building codes place heavy reliance on the ductile, inelastic behavior of structural systems in resisting strong ground motions. At present, most codes ignore the effect of the vertical component of ground motion, and most dynamic analyses of structural response are performed using only one horizontal component of acceleration. Furthermore, in many analyses, the gravity loads are not included simultaneously with the ground motion although it is well known that the principle of superposition does not apply in the case of significant inelastic behavior. Since large inelastic deformations are expected in conventional buildings when they are subjected to strong ground motion, it is important to be able to predict the nonlinear response under the combined action of all the ground motion components and gravity load. In an earlier study(1), the authors found that the inclusion of gravity loads with the horizontal component of ground motion resulted in a significant increase in the ductility requirements of both the girder and column elements. In a more recent study, Iyengar and Shinozuka(2) considered a vertical cantilever model and found that inclusion of self weight and vertical acceleration could cause either a significant increase or decrease in the peak responses.

The San Fernando earthquake of February, 1971, is of particular engineering significance because it produced more than two hundred usable records of ground and building motions. Most of these records show very significant vertical accelerations which might be due to the fact that this earthquake was generated by thrust faulting rather than strike -slip faulting. An accelerograph located on a rock ridge adjacent to the Pacoima Canyon Dam, which is directly above the plane of the fault thrust, recorded the largest peak accelerations so far measured during earthquakes, the vertical component being 0.7g. These data place a new emphasis on the need to evaluate the effects of the vertical forces, which may be present and/or

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develop during strong earthquakes, on the inelastic seismic response of multistory buildings. The investigation reported in this paper is an attempt to evaluate these effects.

SELECTION OF THE STRUCTURE, ITS DESIGN, MODELLING AND ANALYSIS

This study considers an unbraced, single bay frame of ten stories. Following current seismic design practice, the frame was designed for seismic loads specified in the Uniform Building Code(3) and the members were proportioned following the allowable stress design procedures described in the AISC Specifications(4) although more efficient seismic design methods have been proposed by the authors(5,6). The following load combinations are considered in the design: (a) dead plus live load; (b) dead plus live load plus wind; and (c) dead plus live plus seismic load. The overall dimensions of the frame along with the member sizes are shown in Fig. 2(a).

The dynamic model used in this study is shown in Fig. 2(b). It is a general finite element model in which each node has three degrees of freedom. This permits incorporation of all the significant modes of vibration of the actual structure. In the case of strong vertical motion, both the vertical column modes and the vertical floor modes must be considered; thus a node is placed at the midspan of the floors in order to include the fundamental vertical mode of the floor system. The mass which is lumped at this point is adjusted to give the floor system the same period as a distributed mass system. The remainder of the floor mass is lumped at the column nodes. The fundamental periods of the three different vibration modes are as follows: (1) horizontal mode, 2.0 sec; (2) vertical floor mode, 0.18 sec; and (3) vertical column mode, 0. 15 sec.

Because the elastic and especially the inelastic seismic responses are sensitive to the amplitude, frequency content, and duration of the ground motion, it was considered necessary to evaluate the response for at least two earthquakes offering different ground motion characteristics, but with approximately the same peak vertical acceleration of about 0.31 g. The first ground motion is a modified version of the first eleven seconds of ground acceleration recorded at Pacoima Dam during the San Fernando earthquake(7). To obtain a maximum vertical acceleration of 0.31 g, the measured intensities of the accelerations in the vertical direction have been reduced by multiplying them by 0.4. Using this same reduction coefficient for the measured accelerations in the S74W direction, its peak value has been reduced to 0.5 g. The second record selected is a modified version of the first fourteen seconds of the ground acceleration recorded at Taft, California on July 21, 1952. The modification consists of multiplying the S69E accelerations by two and the vertical accelerations by three. This results in an earthquake having a maximum acceleration of 0.32 g in both the horizontal and vertical directions. The response spectra for elastic systems for the four ground motions considered in this study are shown in Fig. 1.

The analysis procedure is similar to that used by Anderson and Gupta(5), incorporating the following assumptions and features: (a) The mass of the system is lumped at the nodal points in the manner described previously (Fig. 2(b)); (b) The effects of rotary inertia are neglected; (c) All elements are assumed to form concentrated plastic hinges at their ends whenever the effective plastic moment of each end section is reached.

To achieve this the two component element suggested by Clough et al[8] is used, and the moment curvature at the end of each element is assumed to follow a bilinear hysteresis loop in which the rate of strain hardening is taken as 5%; (d) The effective plastic moment of each end section of an element is calculated considering the effect of the axial force using the axial-flexural interaction relationship suggested by AISC[4] for strong axis bending of short columns; (e) Gravity loading is represented by equivalent fixed end forces.

For the purpose of this study it is assumed that the damping matrix can be represented as being linearly proportional to the mass matrix. The proportionality factor is selected to give 5% of critical damping in the fundamental horizontal mode. It should be noted that this representation results in negligible damping in the vertical modes. Later studies will consider the effect of introducing a small amount of damping into the vertical modes. The ductility requirements of the individual members are computed on the basis of the curvature ductility ratio[9]. For bilinear systems, this ratio can be expressed in terms of moment as follows:

$$\mu = 1 + \frac{M_{max} - M_p}{pM_p}$$

where M_{max} = the maximum moment in the element;
M_p = the plastic moment capacity of the element; and
p = the rate of strain hardening.

DISCUSSION OF RESULTS

To evaluate the effects of gravity load and vertical component of ground motion on the response of multistory frames, the results of the following three loading conditions are compared for each of the two earthquakes: horizontal ground motion alone (H); horizontal ground motion with gravity load (HG); and horizontal ground motion with gravity load and vertical ground motion (HGV). The above abbreviations are used later to identify the response curves. All comparisons are presented in graph form and the following response parameters are considered.

Maximum Acceleration: The maximum vertical acceleration at each nodal point is shown in Fig. 3. Note the almost linear amplification in the columns due to exciting the column modes. The fundamental column mode is approximately 0.15 sec. Contrast this response to the beam accelerations which are almost constant at the beam mode of 0.18 sec. It can also be seen that the vertical response of the frame to the two ground motions is quite similar.

Story Displacement: The envelope of maximum lateral story displacement is shown in Fig. 4. It can be seen that there is not too much variation between the three loading conditions. This is because the lateral displacement envelope is a rather insensitive parameter which does not reflect the behavior of the individual elements of the frame. It is of interest to note that the refined analysis, which considers the three loadings simultaneously, results in the minimum displacement envelope for both earthquakes. As could be expected from analysis of the spectra curves given in Fig. 1(a), the modified Taft motion results in the larger horizontal displacement even though the maximum horizontal acceleration is 36% less than that of the modified Pacoima record. This result clearly points out that larger peak intensity of ground motion does not necessarily imply more severe structure response. This is especially true in cases where large inelastic deformations are involved.

Relative Story Displacement: The envelopes of the maximum relative displacement between adjacent floors are illustrated in Fig. 5, where the maximum relative drift of each story is plotted. Again, there is no striking difference between the values of this parameter for the three loading conditions. However, if one considers that an efficient seismic design should have a relative drift index that has a gradual, linear increase with height, some general observations can be made from these results. Considering Fig. 5(a) for the Pacoima motion, it can be seen that the ninth floor has a larger relative drift than the others. This indicates that critical regions of some members located adjacent to the ninth floor will have increased ductility requirements. Fig. 5(b) shows a similar result for both the second story and the ninth story. This fact is not reflected at all in the results shown in Fig. 4. Because all values of Δ/h are well below .02, drift of the frame and overturning moment due to axial loads are of minor importance in the structure response to the ground motions considered in this study.

Girder Ductility Requirement: The maximum ductility requirements of each girder at the faces of the columns are shown in Fig. 6. Results for the Pacoima motion, shown in Fig. 6(a), indicate that while the response under the horizontal component alone is elastic, the inclusion of gravity load demands ductilities up to 2 at the upper floor girders. Inclusion of vertical ground motion results in an additional increase of more than 50% in the ductility requirements of the upper girders. A similar result is shown in Fig. 6(b) for the Taft motion; however, in this case, the difference between the inclusion of gravity load and gravity load plus vertical motion is not as striking, the main increase being due to gravity load. Results of Fig. 6 show that neglect of the vertical forces can lead to a very significant and dangerous underestimation of the ductility requirement. The ductility requirements at the midspan of the girders are shown in Fig. 7. It can be seen in Figs. 7(a) and 7(b) that the vertical component of motion has a significant effect on the ductility requirement at this location, particularly in the upper floors. In the case of the Pacoima motion, the midspan ductility is the controlling value for the girders at the ninth and tenth floors. In all cases, the inclusion of gravity load and vertical component of motion tends to increase significantly the ductility requirements of the upper floor girders. This is because in current design procedures the design of the upper girders is controlled by the gravity load.

Column Ductility Requirements: The column ductility requirements are presented in Fig. 8. It can be seen in Fig. 8(a) that for the Pacoima motion, plastic deformations are induced only when the vertical component of the motion is included. A similar effect can be seen in the upper stories for the Taft motion (Fig. 8(b)), where the ductility requirement of the upper story columns can reach a value of 2. However, in this case, it can also be seen that inclusion of gravity load causes an increased ductility requirement in the lower stories. In all cases, the increased ductility results from a decrease in moment capacity of the section due to an increase in the axial loads. Underestimation of the ductility requirements of the columns can be dangerous since a partial failure of these critical members can lead to a catastrophic failure of the whole structure.

Plastic Hinge Rotation Requirement: Curvature ductility is perhaps the best basic parameter for comparing the response of frames. However, due to the way of modelling the actual inelastic behavior of members (two elements in parallel), the values of required ductility obtained in the analysis could be considerably smaller than the actual ones. Although it is possible to evaluate the correct values of the curvature ductility from the model results, in general, it requires tedious computations[10]. For design, and especially for the detailing of critical regions, a better parameter than the curvature ductility is the required plastic hinge rotation. The envelope of these values for the girders is given in Fig. 9. Inclusion of gravity load and vertical acceleration has a significant influence on this parameter for both ground motions. It is of interest to note that the maximum rotation of approximately 0.017 radians is considerably smaller than the plastic rotation that girders of compact sections can develop[11]. The envelopes for the plastic rotations at the columns are shown in Fig. 10. While the increase in the inelastic rotation at the upper columns is mainly due to the vertical component of the ground motion, the increase observed in the lower story columns is due mainly to the gravity load.

CONCLUSIONS

The following conclusions have been drawn from the results just reported and are, therefore, limited by the assumptions involved in this study.

1. Ductility requirements at the critical regions of structural elements cannot be accurately evaluated by neglecting the effects of the gravity load and of the vertical ground motion.

2. The inclusion of gravity loads causes a significant increase in the ductility requirements of the girder elements. This is particularly true in the upper floors where the design is controlled by these loads. Gravity loads can also increase the ductility requirements of the columns of the lower floors due to the reduced moment capacity of these members when loaded in axial compression.

3. The inclusion of vertical component of ground motion increases the ductility requirements in both the columns and girders of the upper stories. Vertical motion is particularly significant in causing inelastic action at the midspan of the girders. Inelastic action in the columns is increased by the amplification of the vertical motion in these members and by the amplified vertical response of the girders.

4. The relative importance of the vertical motions is dependent on the main characteristics of the complete time histories of both the horizontal and vertical components of the earthquake. In this study, inclusion of vertical motions had a more significant effect on the behavior of the frame subjected to the Pacoima motion. This was true even though the maximum horizontal acceleration of Taft was considerably smaller (0.31 g vs. 0.5 g). This further illustrates the importance of duration and frequency content, as well as maximum acceleration in determining the effect of earthquakes on structures.

5. Ductility requirements at the critical regions of individual members cannot be evaluated with accuracy from just analyzing maximum lateral displacements and maximum relative story drifts.

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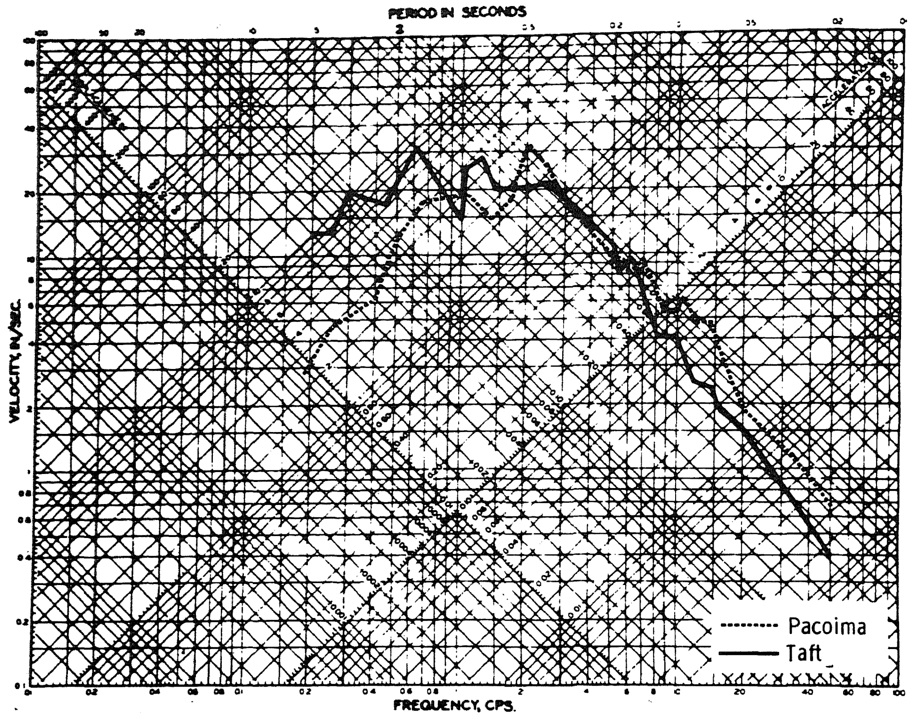
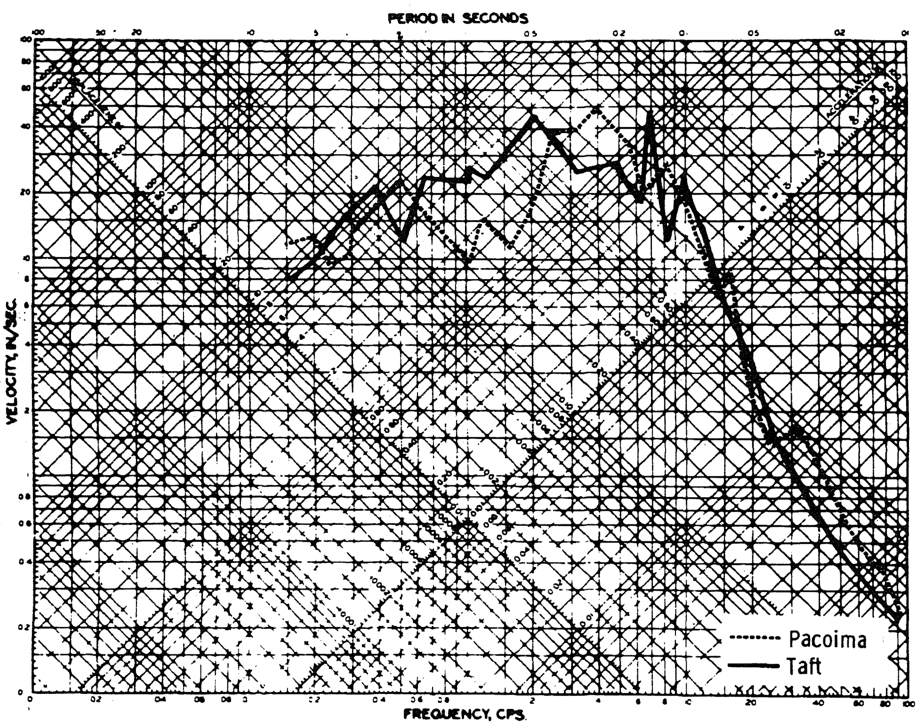


(a) Horizontal Component, 5% Damping



(b) Vertical Component, 0% Damping

FIG. 1. RESPONSE SPECTRUM FOR ELASTIC SYSTEM

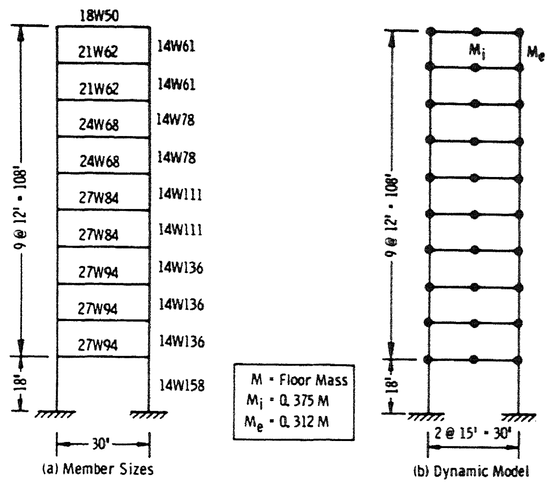


FIG. 2. ANALYTICAL MODEL

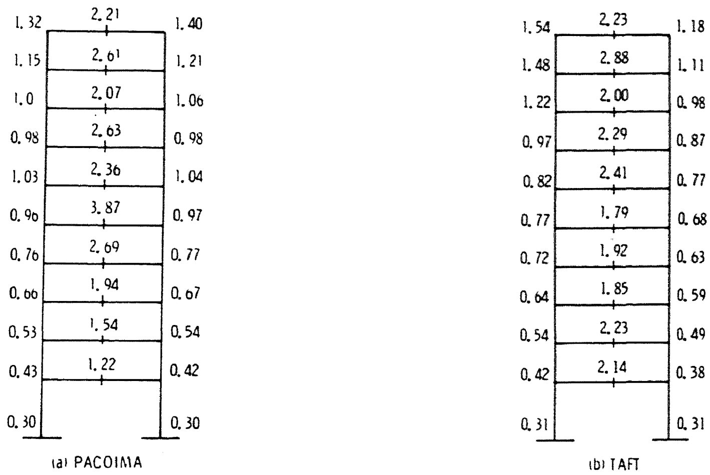


FIG. 3. MAXIMUM VERTICAL ACCELERATIONS

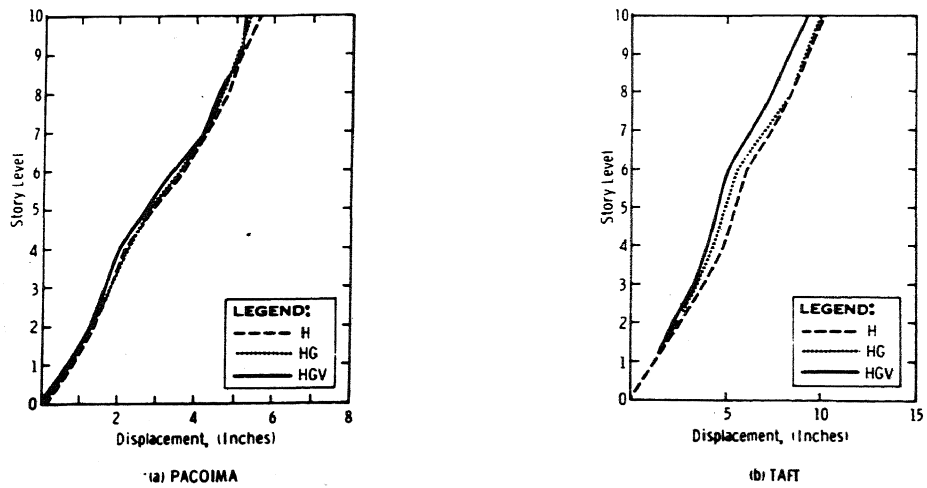


FIG. 4. MAXIMUM STORY DISPLACEMENT

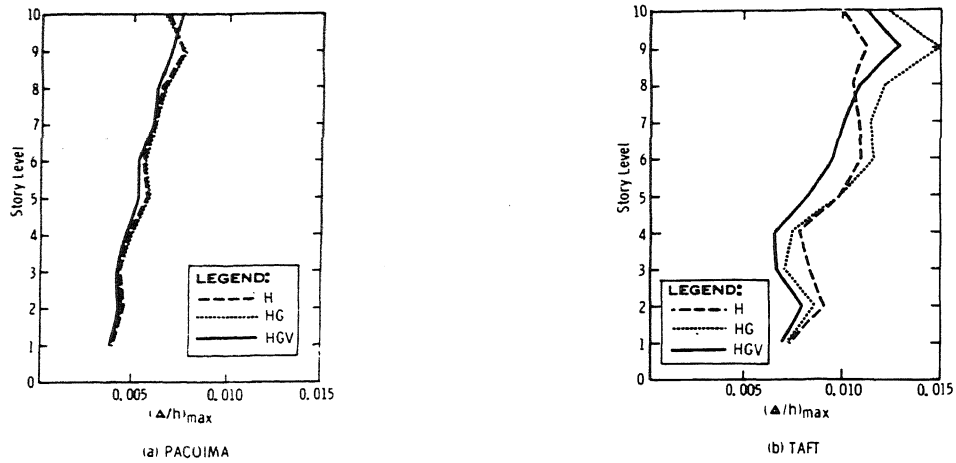


FIG. 5. MAXIMUM RELATIVE DISPLACEMENT

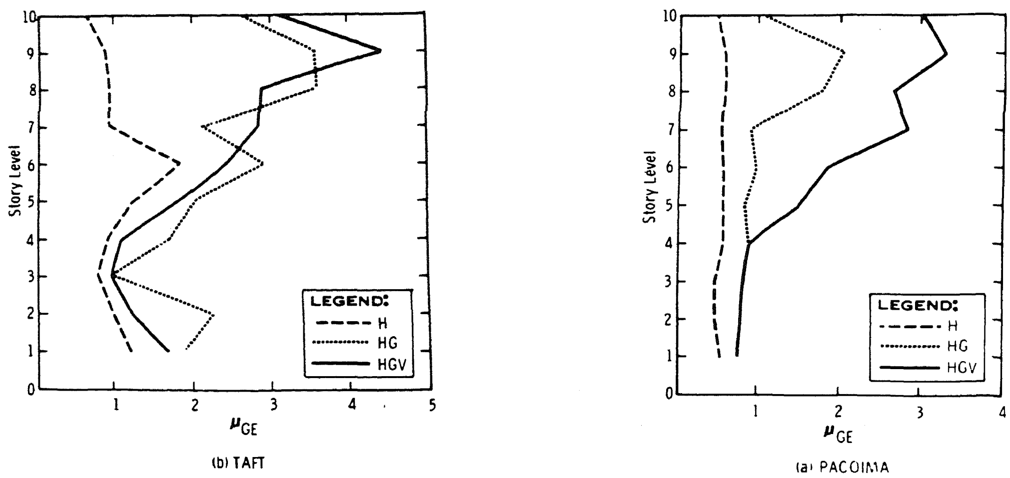


FIG. 6. MAXIMUM GIRDER DUCTILITY AT FACE OF COLUMN

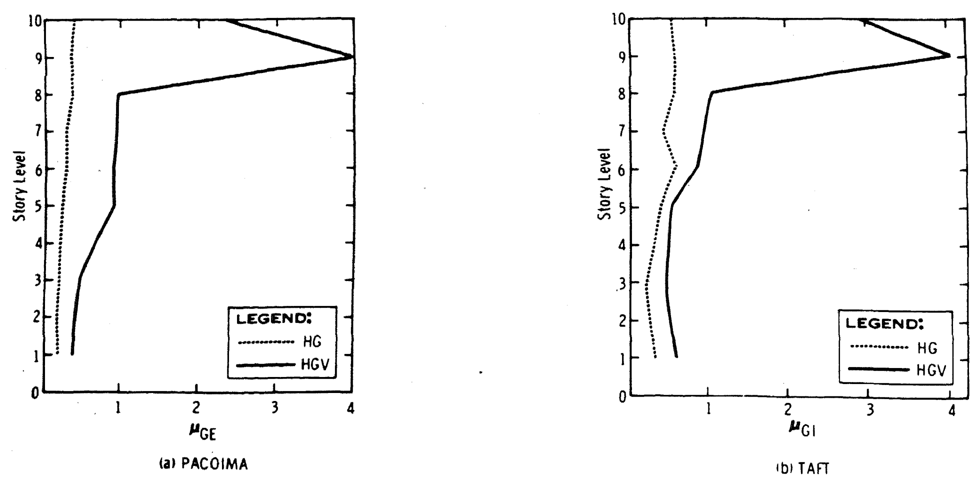


FIG. 7. MAXIMUM GIRDER DUCTILITY AT MIDSPAN

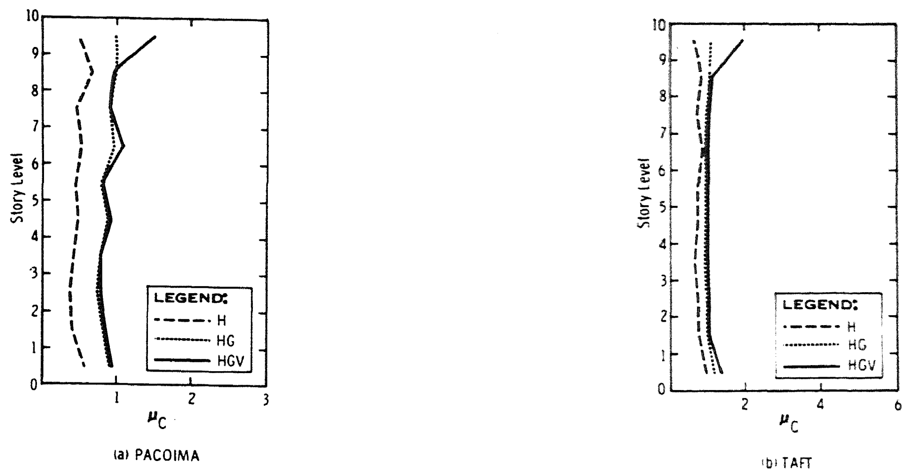


FIG. 8. MAXIMUM COLUMN DUCTILITY

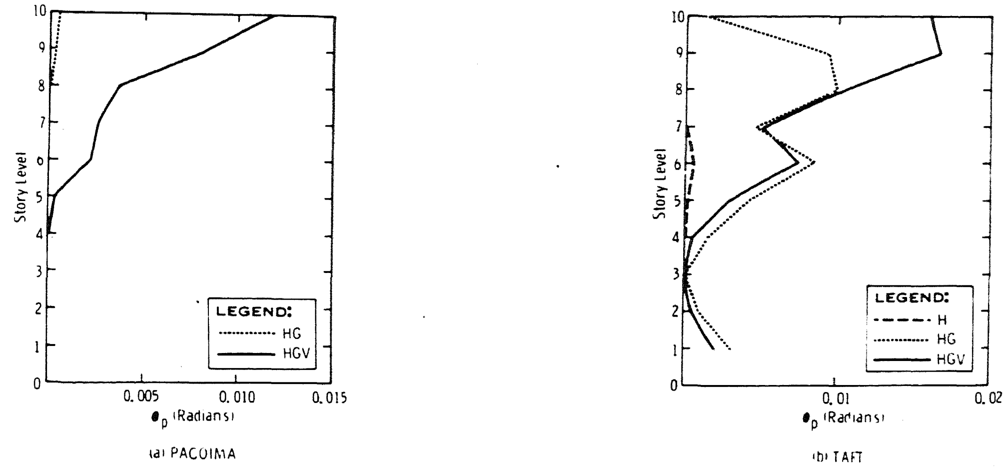


FIG. 9. MAXIMUM PLASTIC HINGE ROTATION, GIRDERS

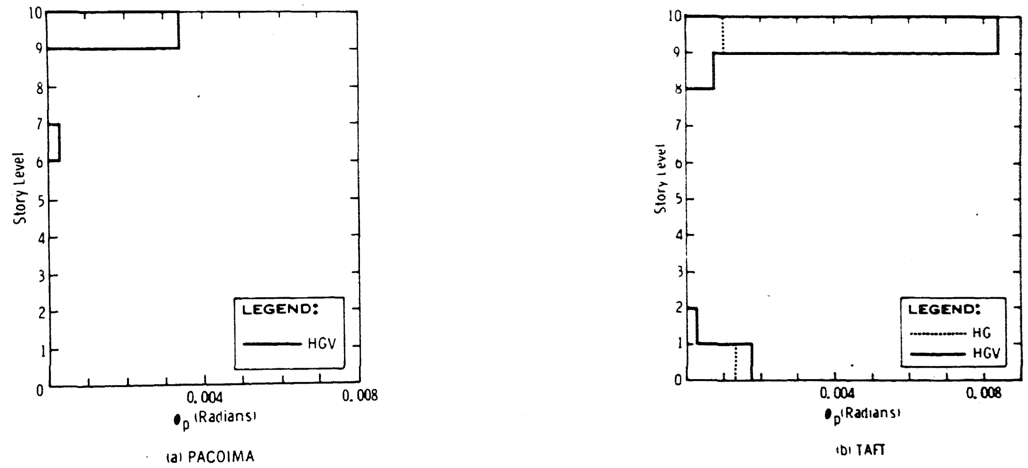


FIG. 10. MAXIMUM PLASTIC HINGE ROTATION, COLUMNS.