SECTION 6

COMPARISON OF RESULTS

All of the isolated structures in this report were analyzed by a linear response spectrum analysis and a rigorous dynamic nonlinear time history analysis. Furthermore, results were obtained by the static analysis procedure of SEAOC/UBC.

In order to quantify the results and make comparisons between the analyses, plots of the response quantities have been created. In section 6.1, comparisons are made between story shear forces from the analyses and in section 6.2, comparisons are made between center bearing displacements and corner bearing displacements from the analyses.

6.1 Comparison of Results on Story Shear Forces

Plots have been constructed to show the variation of story shear force vs. story as determined by the three analysis procedures. The results are presented as follows. The results of the SEAOC/UBC static analysis procedure are referred to as "SEAOC STATIC". The results of the response spectrum analysis procedure are referred to as "RESPONSE SPECTRUM". The results of the nonlinear dynamic time history analysis are presented in terms of the mean of the maximum longitudinal and transverse direction results. This quantity has been used for comparisons since it represents the absolute maximum result of the nonlinear analyses regardless of the direction of input excitation. This value is called "MEAN OF MAX L,T". Furthermore, the mean of maximum L,T plus one standard deviation of the results is presented in order to provide an upper bound to both the response spectrum results and the static analysis results. This quantity is referred to as "MEAN + 1 σ". It should be noted that all results on story shear forces and base shear force were not reduced by factors R_{WI} and 1.5, respectively, to obtain the design level forces.

Figures 6-1 to 6-6 compare the distribution of shear force over story level in the analyzed 8-story isolated structure. The isolation systems which do not meet the criteria of SEAOC/UBC allowing the response spectrum analysis procedure (see Table 5-I) have been appropriately labeled in the figures. The results of Figures 6-1 to 6-6 demonstrate that:

1. The results of the static and response spectrum analysis procedures are, in general, in close agreement.
2. The results of the static and response spectrum analysis procedures either predict well or underestimate the mean of story shear forces as predicted by the time history analysis. The degree of underestimation is significant in all isolation systems which do not meet the SEAOC/UBC criteria allowing response spectrum analysis. In these systems, with typical effective damping of the isolation system β larger than 30%, the time history analysis predicted significantly more shear force in the upper stories. This is the result of significant contribution from the higher modes of the isolated structure. This behavior is typical of highly nonlinear isolation systems.
3. The underestimation of the story shear force by the static and response spectrum analysis procedures is also significant in isolation systems No. 4, 7 and 10 on soil type S_1 and No. 3, 10 and 12 on soil type S_2. These isolation systems meet the criteria of SEAOC/UBC for allowing response spectrum analysis and have effective damping in the isolation system in the range of 15% to 27% of critical. In these systems, the shear force in the upper stories of the isolated building is underestimated by the static and response spectrum procedures by a factor which is in the range of 2 to 3.

Table 6-I presents a comparison of the base and story shear forces of the 1-story isolated structure as computed by the three analysis procedures. Again, it is observed that the static and response spectrum procedures produce nearly identical base shear forces. The difference in the first story shear force (by a factor of 2) is just a result of equations (2.5) and (2.6) which, without the reduction factors 1.5 and R_{WI}, give identical base and first story shear forces. The response spectrum analysis procedure underpredicts the mean of time history analyses on the story shear force in all but four of the 22 analyzed isolation systems. The degree of underestimation was,

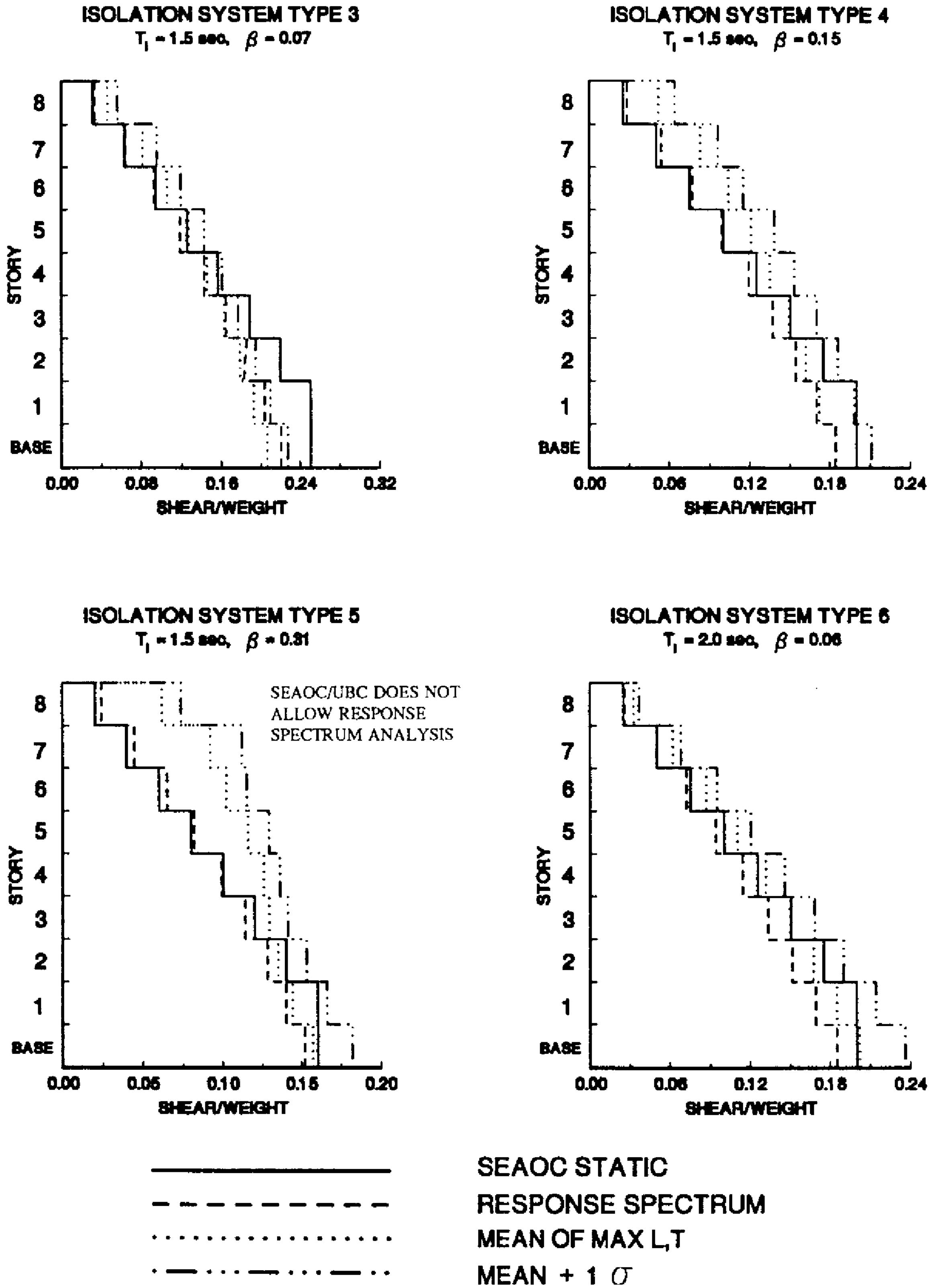

FIGURE 6-1 Distribution of Story Shear Forces for Isolation System Types 3, 4, 5 and 6 on S_1 Soils

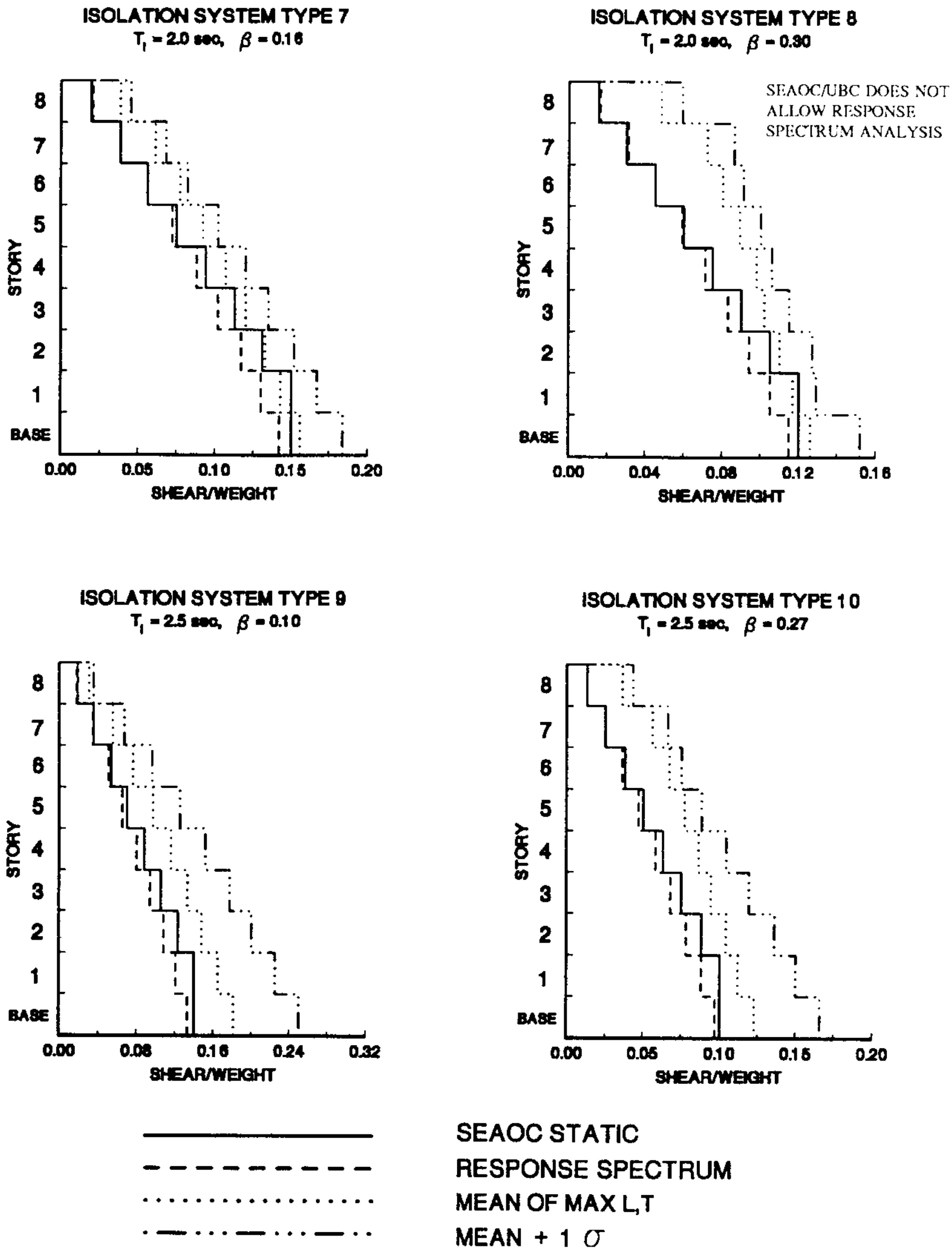

FIGURE 6-2 Distribution of Story Shear Forces for Isolation System Types 7, 8, 9 and 10 on S_1 Soils

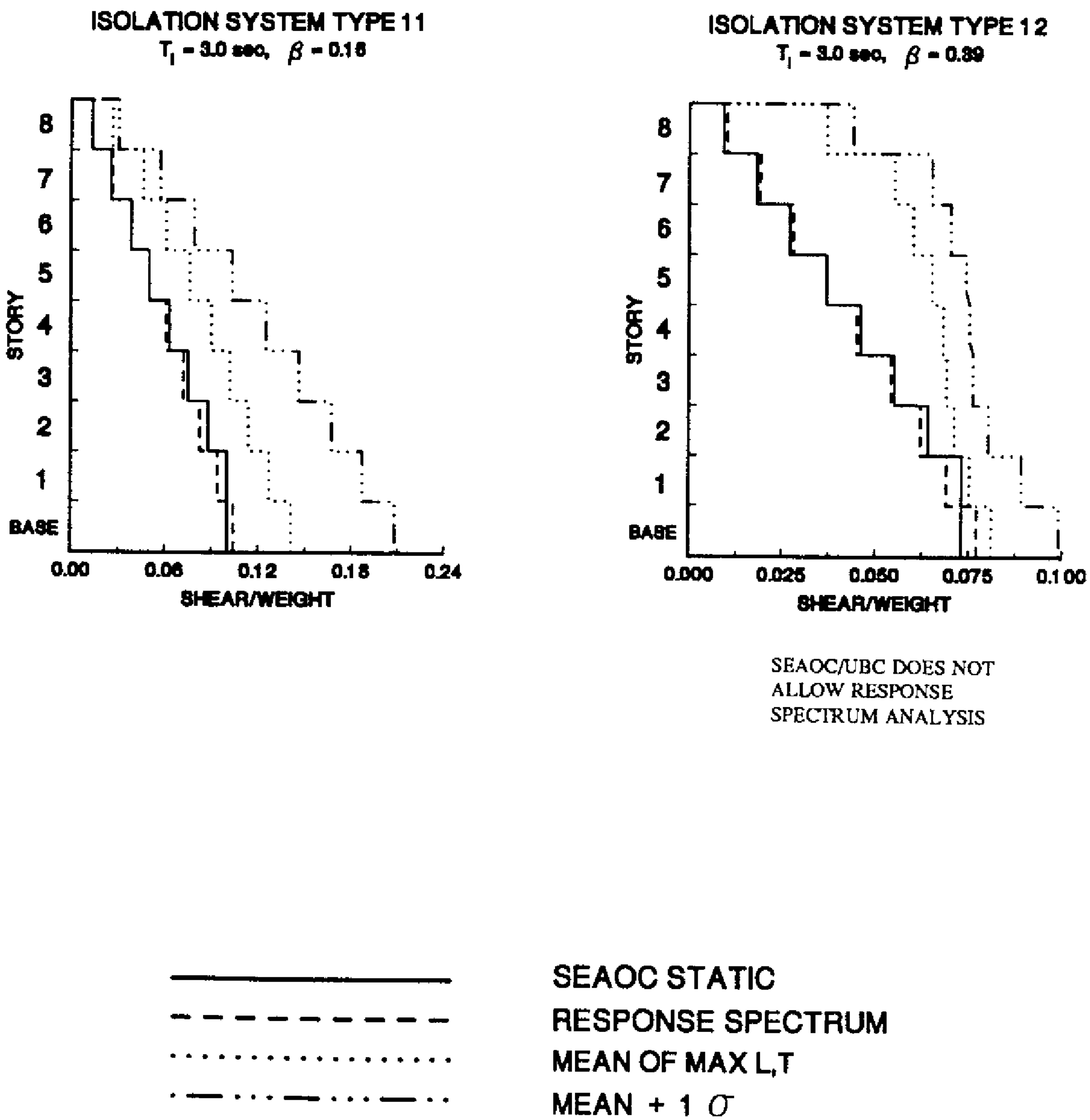

FIGURE 6-3 Distribution of Story Shear Forces for Isolation System Types 11 and 12 on S_1 Soils

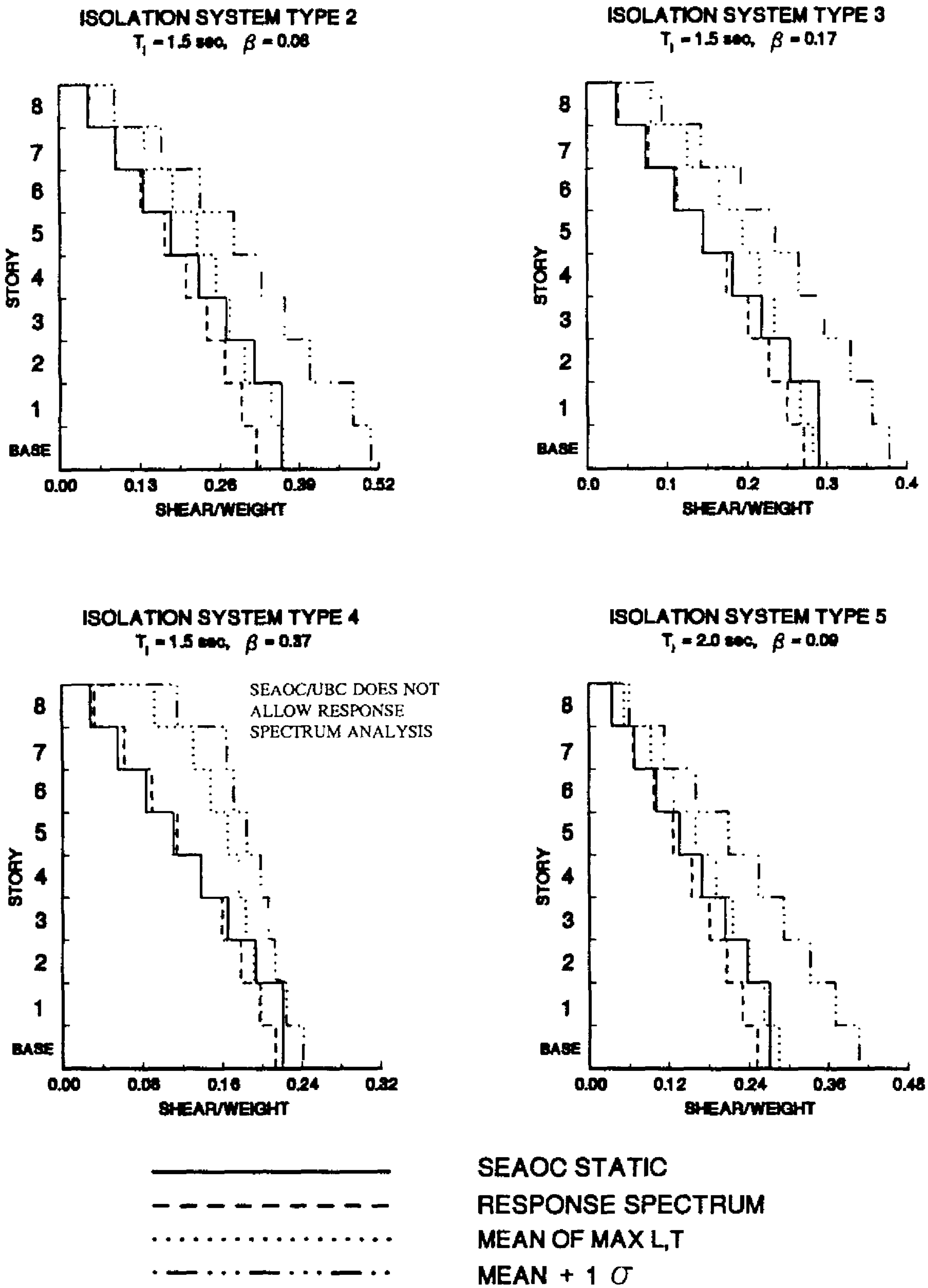

FIGURE 6-4 Distribution of Story Shear Forces for Isolation System Types 2, 3, 4 and 5 on S_2 Soils

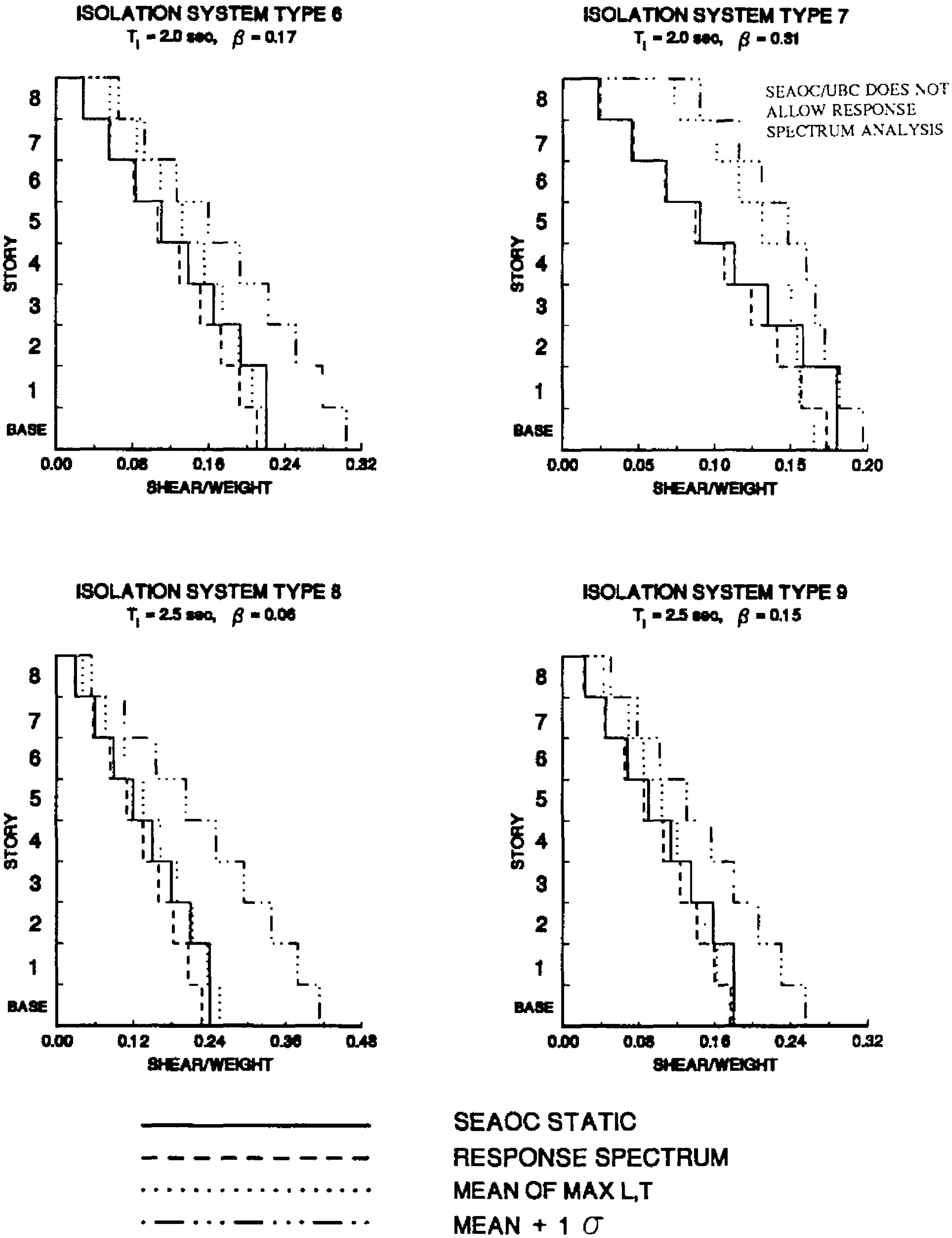

FIGURE 6-5 Distribution of Story Shear Forces for Isolation System Types 6, 7, 8 and 9 on S_2 Soils

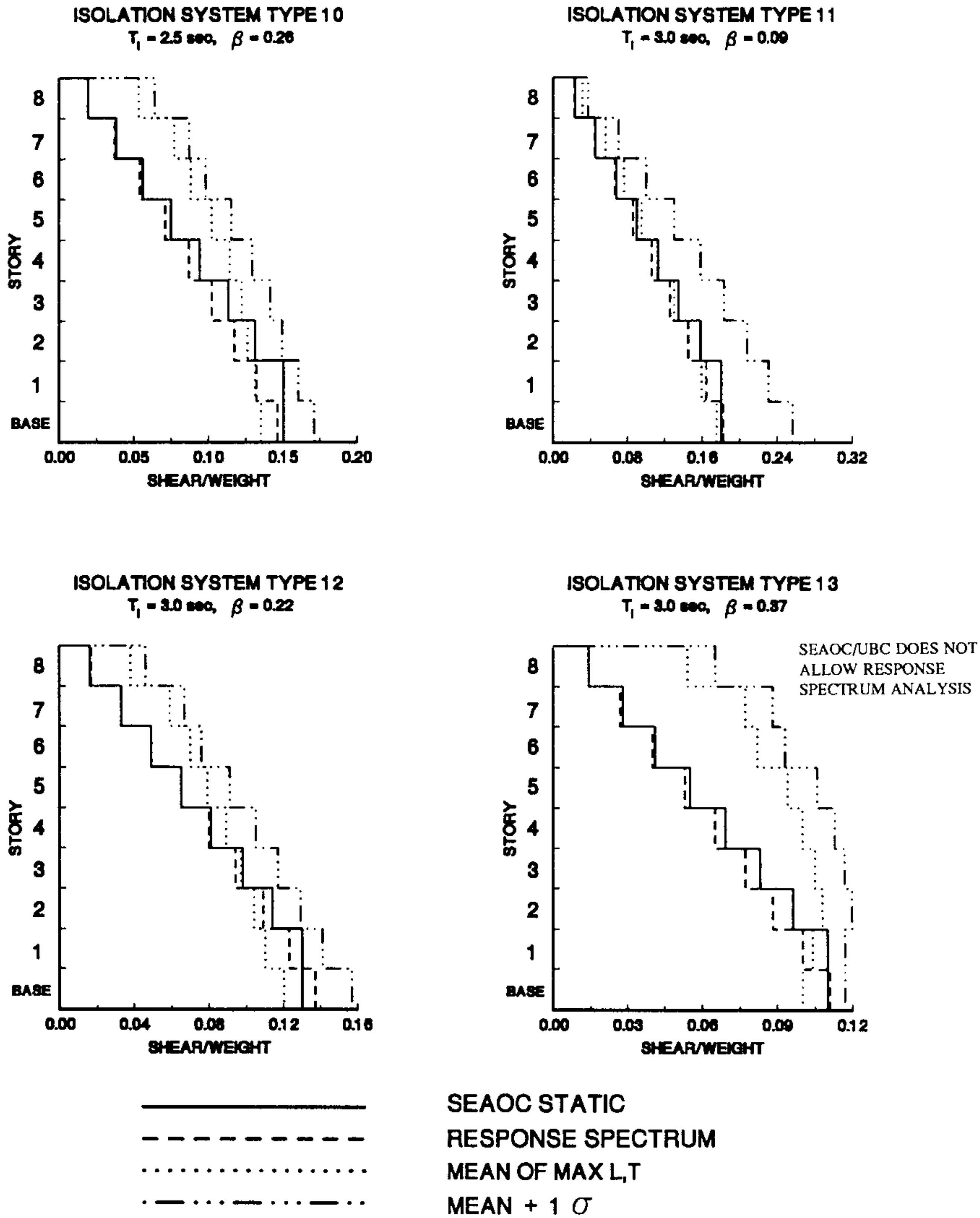

FIGURE 6-6 Distribution of Story Shear Forces for Isolation System Types 10, 11, 12 and 13 on S_2 Soils

TABLE 6-I Comparison of Base Shear (BS) and Story Shear (SS) Force Results for 1-story Isolated Structure. Weight = 2560 kips.

SOIL TYPE	ISOLATION SYSTEM TYPE	SEAOC STATIC		RESPONSE SPECTRUM		MEAN OF MAX L, T		MEAN + 1 σ	
		BS/WEIGHT	SS/WEIGHT	BS/WEIGHT	SS/WEIGHT	BS/WEIGHT	SS/WEIGHT	BS/WEIGHT	SS/WEIGHT
S_1	3	0.250	0.250	0.252	0.127	0.232	0.118	0.281	0.142
	4	0.200	0.200	0.200	0.101	0.179	0.092	0.212	0.108
	5	0.160	0.160	0.161	0.082	0.150	0.080	0.170	0.090
	6	0.200	0.200	0.195	0.098	0.214	0.108	0.256	0.129
	7	0.150	0.150	0.147	0.074	0.158	0.081	0.183	0.093
	8	0.120	0.120	0.117	0.059	0.120	0.062	0.142	0.072
	9	0.140	0.140	0.135	0.068	0.187	0.094	0.253	0.127
	10	0.100	0.100	0.098	0.049	0.121	0.061	0.161	0.081
	11	0.100	0.100	0.100	0.050	0.143	0.072	0.208	0.104
	12	0.073	0.073	0.073	0.036	0.080	0.042	0.096	0.048
S_2	2	0.360	0.360	0.351	0.177	0.377	0.205	0.513	0.283
	3	0.290	0.290	0.282	0.142	0.298	0.158	0.399	0.203
	4	0.220	0.220	0.216	0.109	0.207	0.127	0.222	0.143
	5	0.270	0.270	0.263	0.132	0.306	0.156	0.424	0.214
	6	0.220	0.220	0.215	0.108	0.224	0.116	0.301	0.153
	7	0.180	0.180	0.175	0.088	0.166	0.095	0.192	0.102
	8	0.240	0.240	0.233	0.177	0.283	0.142	0.430	0.215
	9	0.180	0.180	0.177	0.089	0.187	0.096	0.273	0.137
	10	0.150	0.150	0.146	0.073	0.135	0.073	0.167	0.086
	11	0.180	0.180	0.176	0.088	0.184	0.093	0.269	0.135
	12	0.130	0.130	0.130	0.065	0.120	0.063	0.157	0.080
	13	0.110	0.110	0.108	0.054	0.099	0.059	0.115	0.066

generally, less than 30% of the mean of time history analysis. Interestingly, the largest difference was observed in isolation system No. 9 on S_1 soils, which has an effective damping, $\beta = 10\%$.

6.2 Comparison of Results on Bearing Displacements

Figures 6-7 to 6-10 compare the results on the center bearing and corner bearing displacements as determined by the static and response spectrum analysis procedures of SEAOC/UBC and the mean of time history analysis results. The latter is the mean of the maximum response in either the longitudinal or the transverse direction of the structure. The calculated displacements are presented as a function of the isolation system period, T_I, and grouped according to the effective damping of the isolation system, β.

The results demonstrate:

1. The static and response spectrum procedures of SEAOC/UBC predict almost identical center bearing displacement.
2. The response spectrum procedure predicts corner bearing displacements which are typically larger than those predicted by the static procedure. Differences of the order of 15% of the value predicted by the static procedure are observed at an isolation system period of 3 seconds.
3. The center bearing displacement, as predicted by the static and response spectrum procedures, is in good agreement with the mean displacement of the nonlinear time history analyses for Soil Type S_2. However, they are substantially less than the mean of the time history analyses for Soil Type S_1 and for isolation system periods larger than or equal to 2.5 seconds. The source of this discrepancy is the existence of two records with strong long-period components in the set of earthquake motions used in the time history analysis. These records were identified by Theodossiou and Constantinou (1991).
4. The corner bearing displacement as predicted by the static and response spectrum procedures, is in good agreement with the mean of results of time history analysis for isolation system periods of 2 seconds or less. At higher values of effective period, the

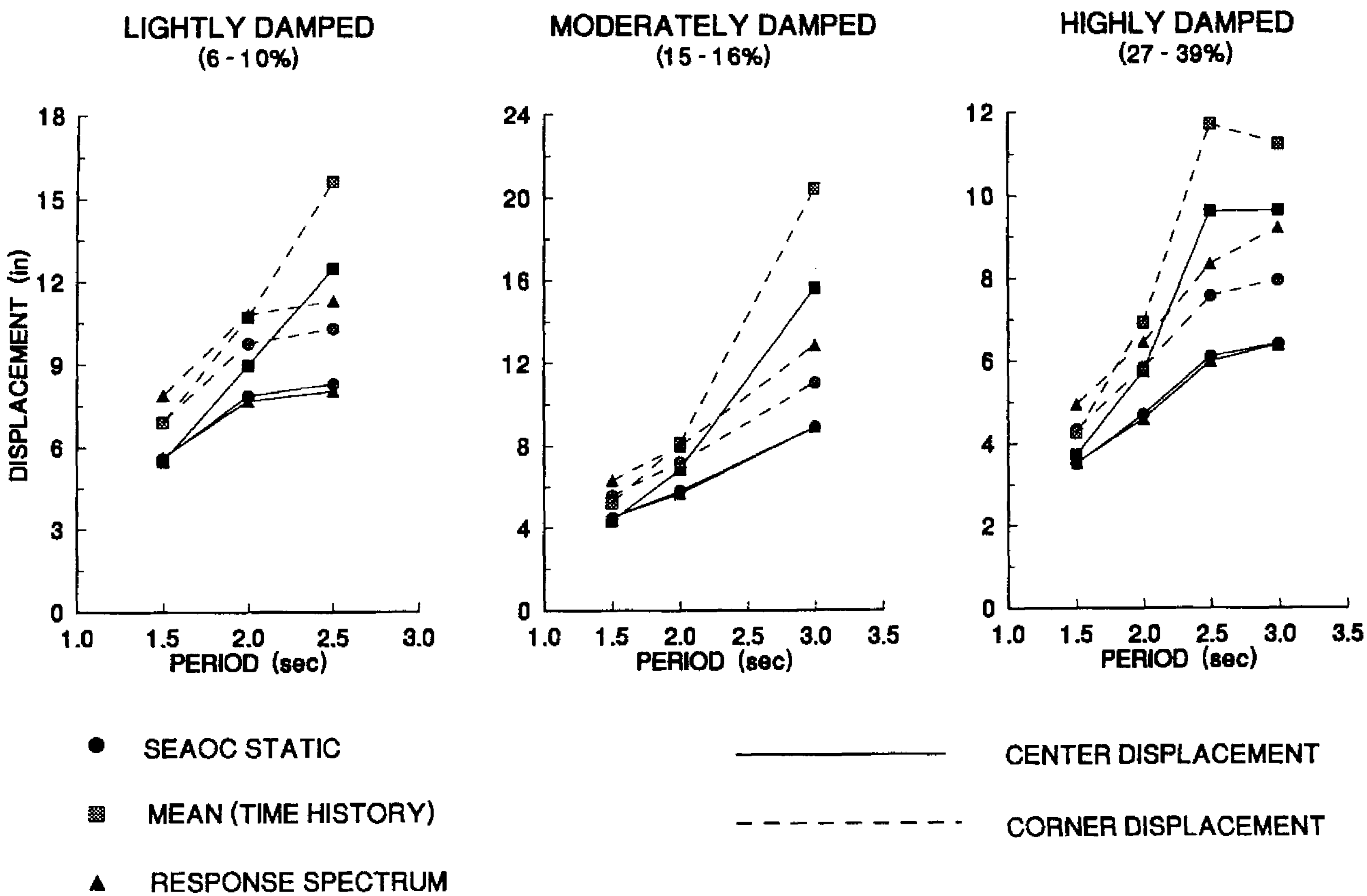

FIGURE 6-7 Results of Center and Corner Bearing Displacements for 1-story Isolated Structures on S_1 Soils

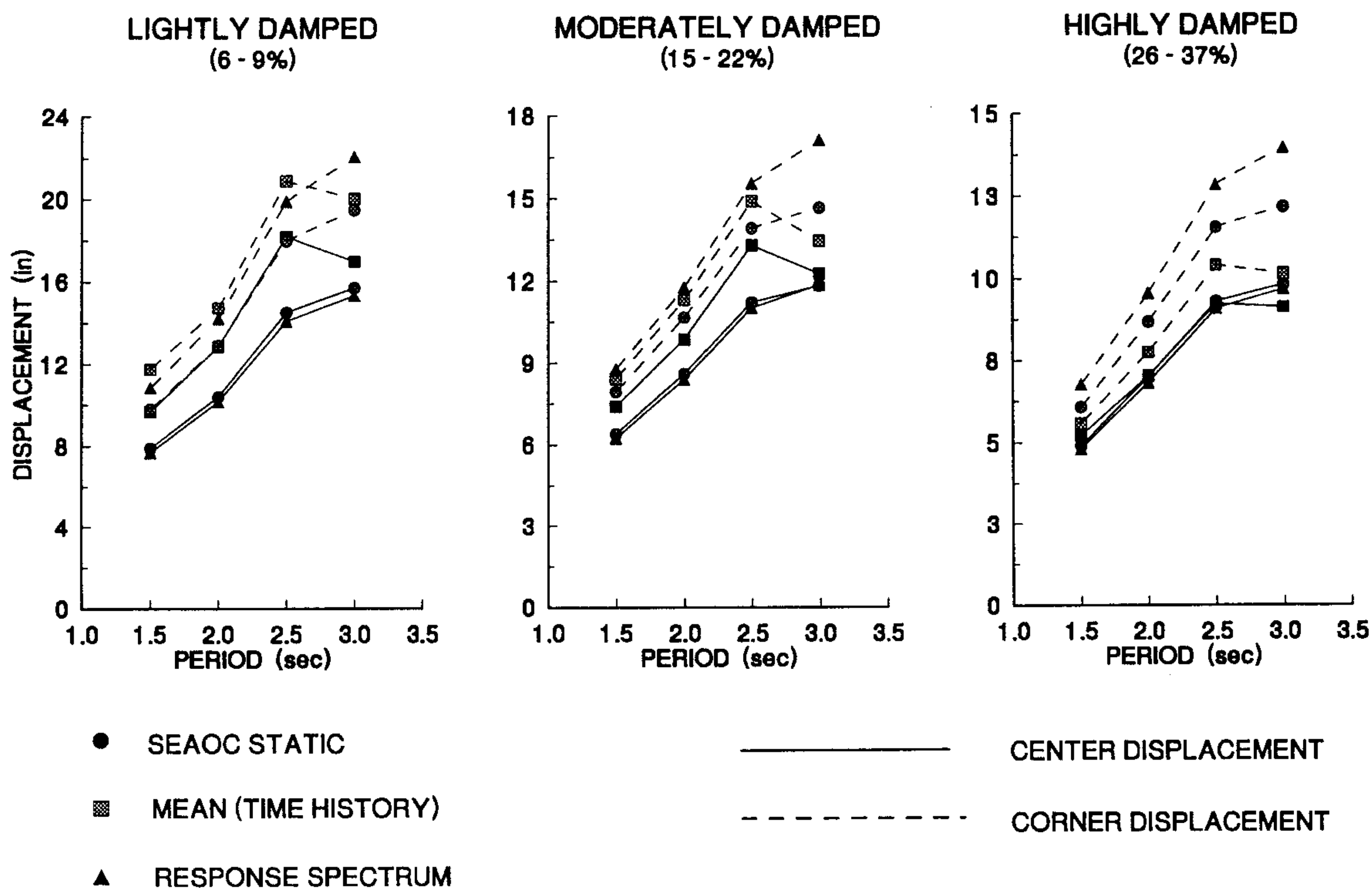

FIGURE 6-8 Results of Center and Corner Bearing Displacements for 1-story Isolated Structures on S_2 Soils

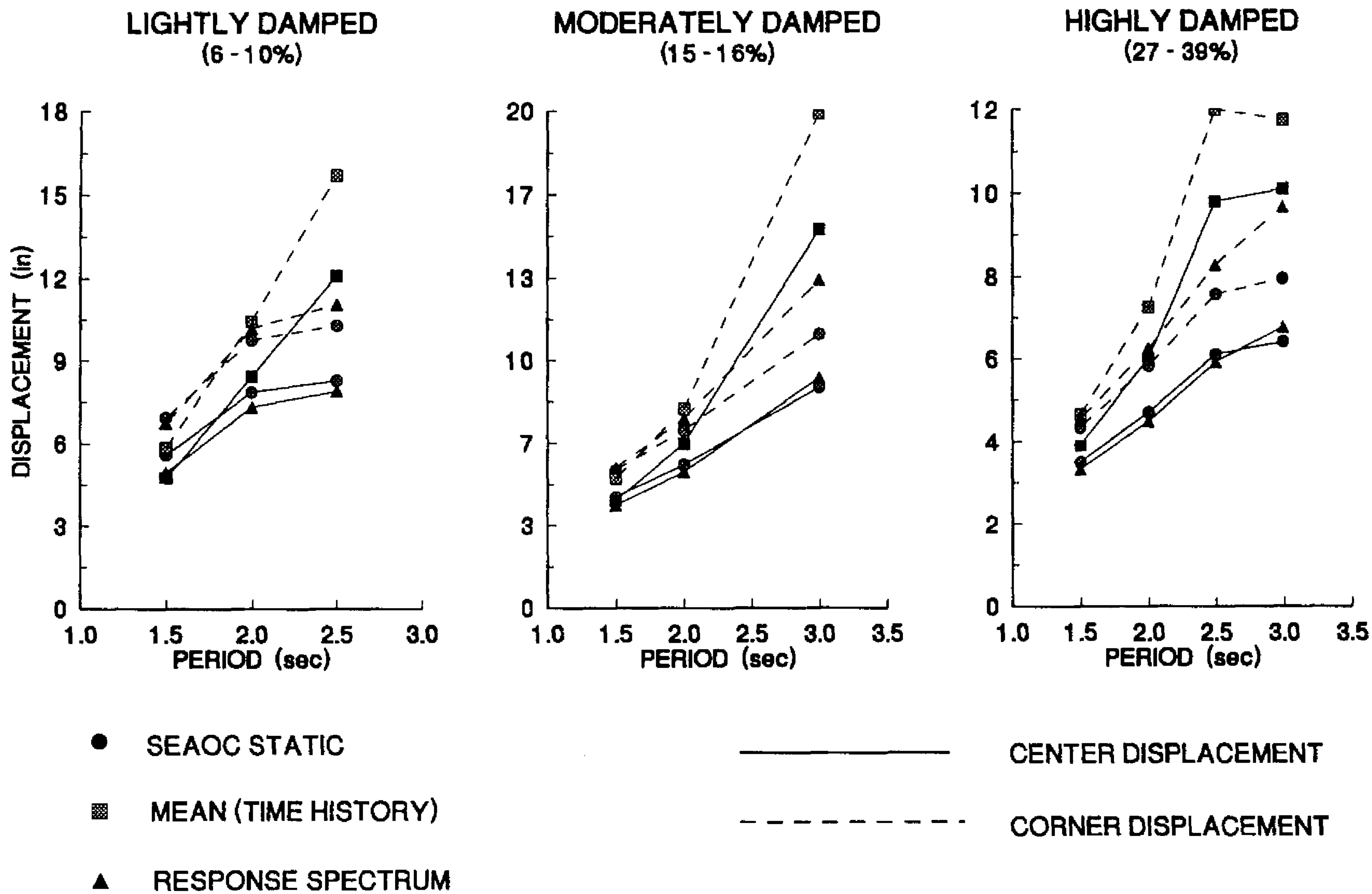

FIGURE 6-9 Results of Center and Corner Bearing Displacements for 8-story Isolated Structures on S_1 Soils

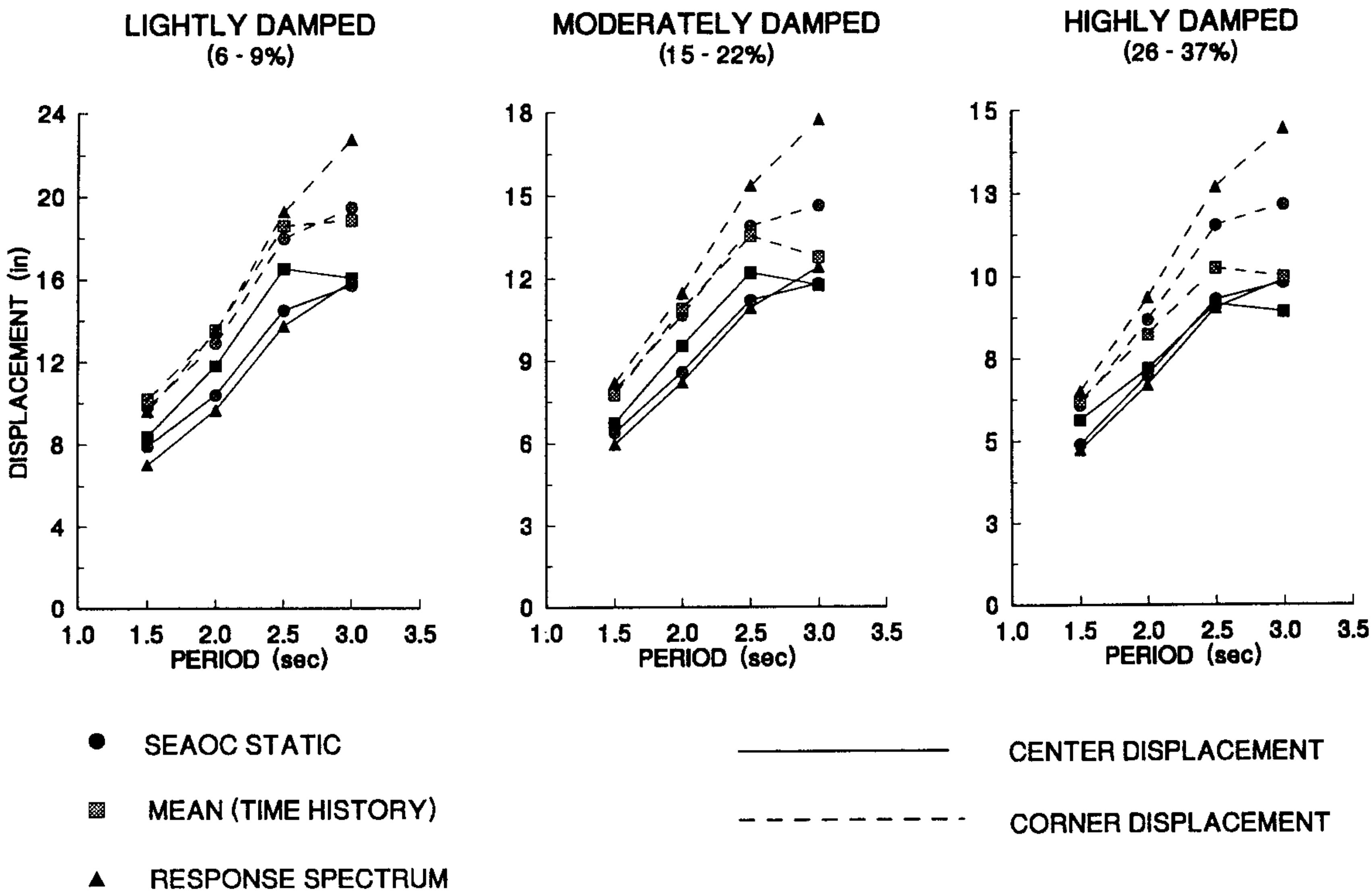

FIGURE 6-10 Results of Center and Corner Bearing Displacements for 8-story Isolated Structures on S_2 Soils

predictions of the static and response spectrum procedures are conservative for Soil Type S_2 and unconservative for Soil Type S_1.

An interesting observation is made with regard to the bearing displacements of the 8-story and 1-story isolated structures. Concentrating on the mean of the time history results (see Appendices A and B), we observe that the center bearing displacement of the 8-story structure is less than the corresponding displacement of the 1-story structure. The difference is rather small and it is observed in most, but not all, analyzed isolation systems. This phenomenon is recognized in the proposed changes for the 1994 Uniform Building Code (Seismology Committee, 1992). It is proposed in the 1994 UBC that the displacement of the isolation system, D', is determined as

$$D' = \frac{D}{\sqrt{1 + \left(\frac{T}{T_I}\right)^2}} \tag{6.1}$$

where D is given by equation (2.1), T_I is the period of the isolated structure (eq. 2.2) and T is the period of the fixed-based superstructure. The derivation of equation (6.1) is based on the theory presented in section 5.2.

Figure 6-11 compares the predictions of equation (6.1) to the mean (calculated in time history analysis) of the ratio of center bearing displacement of the 8-story isolated structure to the center bearing displacement of the 1-story isolated structure. The comparison demonstrates the validity of equation (6.1). However, it may be seen in Figure 6-11 that equation (6.1) is sufficiently accurate for all damping levels provided that $T_I / T \geq 2.0$. Equation (6.1) is actually valid over a wider range of ratio of T_I / T when the effective damping in the isolation system is within certain limits. For example, the equation is valid for $T_I / T \geq 1.3$ when $\beta \leq 0.10$ (lightly damped isolation systems) and for $T_I / T \geq 1.75$ when $0.15 \leq \beta \leq 0.22$ (moderately damped isolation systems).

The dependency of the accuracy of equation (6.1) on the effective damping of the isolation system is apparently, a result of the nonlinearity of the isolation system and the associated excitation of higher mode response. It should be noted that equation (6.1) is based on the linear theory of section 5.2 and consideration of only the effects of the first mode of vibration of the isolated structure.

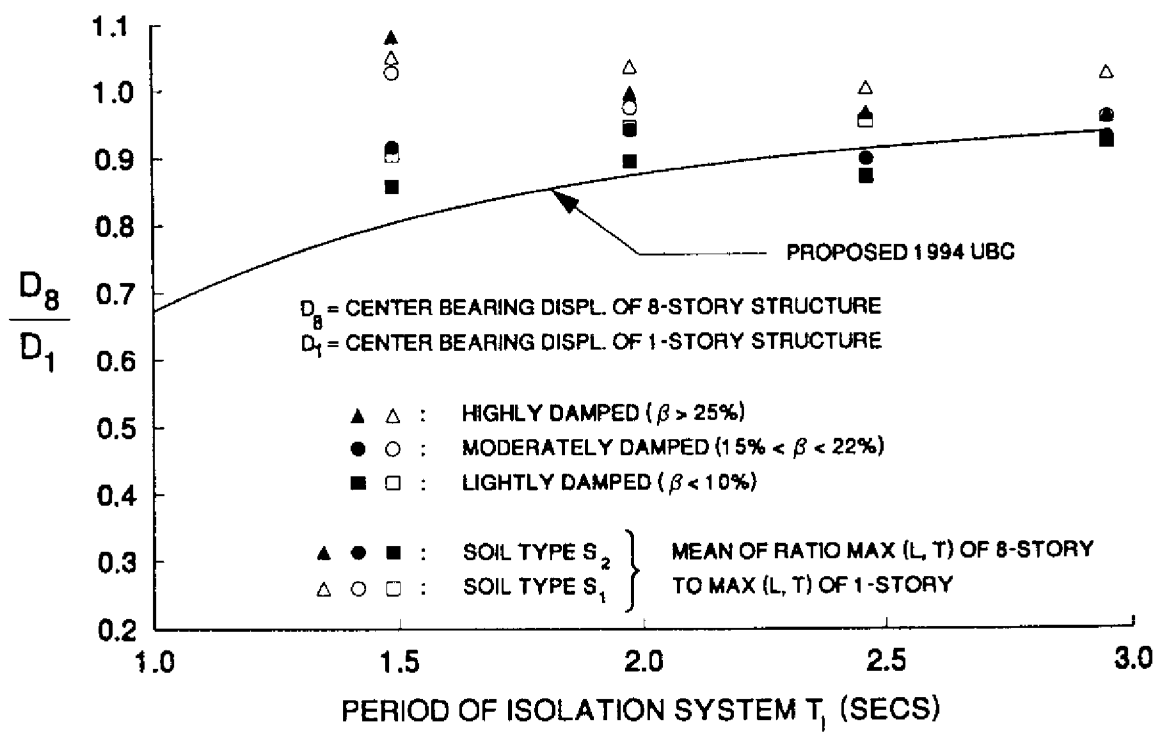

FIGURE 6-11 Ratio of the Center Bearing Displacement of the 8-story and 1-story Isolated Structures

SECTION 7

SUMMARY AND CONCLUSIONS

In this study, comparisons have been made between dynamic nonlinear time history analysis and the SEAOC/UBC static and response spectrum analysis procedures for seismic isolated structures. The response of isolated structures with stiff and flexible superstructures founded on soil types S_1 and S_2 in Seismic Zone 4 has been examined.

The isolation systems varied in properties to account for a wide range of conceivable isolation schemes. The isolation systems had period, T_I (per SEAOC/UBC), in the range of 1.5 to 3 seconds and effective damping, β (per SEAOC/UBC), in the range of 6% to 39% of critical.

The time history analysis results were obtained by the use of 29 pairs of earthquake orthogonal components which were scaled so that they represented Seismic Zone 4 and soil types S_1 and S_2 excitations. The response spectrum analysis results were obtained by the procedures of SEAOC/UBC and using modified response spectra to account for the damping ratios other than 5% of critical in the various modes of the isolated structure.

Two methods of modifying the 5%-damped response spectra were used. The two methods gave nearly identical response results even though the modified spectra were very different at short periods. In the first method, only the long period spectral ordinates were modified for damping different than 5% of critical. In the second method, the entire spectrum was modified in accordance with analytically calculated estimates of the first three periods and corresponding damping ratios of the isolated structure. In both methods, **the 5%-damped response spectrum was reduced (divided) by the factor B (see Table 2-IV) in the neighborhood of the first mode period of the isolated structure, T_1, and in accordance with the damping ratio of the first mode of the isolated structure, ξ_1.** In general, period T_1 is larger than period T_I of the isolation system and damping ratio ξ_1 is less than the effective damping β of the isolation system. The relation between T_1 and T_I and ξ_1 and β has been explored in section 5.2 based on the theory of Kelly (1990). Simplified code type relations, valid for **T/T_I less than 0.6** are easily obtained from the results of section 5.2 to be

$$T_1 = T_I \left[1 + \frac{1}{2} \left(\frac{T}{T_I} \right)^2 \right] \tag{7.1}$$

$$\xi_1 = \beta \left[1 - \frac{3}{2} \left(\frac{T}{T_I} \right)^2 + \frac{1}{2} \left(\frac{T}{T_I} \right)^4 \right] \tag{7.2}$$

where T = period of the fixed based superstructure.

The comparison of results of the time history analysis and the SEAOC/UBC static and response spectrum procedures revealed that:

1. The static and response spectrum analysis procedures predict almost identical center bearing displacement and distribution of shear force with height. However, the response spectrum analysis procedure predicts corner bearing displacements which are larger by no more than 15% of the displacements predicted by the static analysis procedure.
2. The static and response spectrum analysis procedures predict center bearing displacements which are in good agreement with the mean of time history results for soil type S_2 but they are substantially less than the mean of time history results for soil type S_1 and isolation system period $T_I \geq 2.5$ secs. This discrepancy was primarily caused by two records with strong long-period components in the set of earthquake motions representative of soil type S_1.
3. The static and response spectrum analysis procedures predict corner bearing displacements which are in good agreement with the mean of time history analysis results for periods of isolation system less than or equal to 2 seconds. For periods larger than 2 seconds,

the static and response spectrum procedures are conservative for soil type S_2 and unconservative for soil type S_1.

4. The flexibility of the superstructure tends to reduce the isolation system displacement in accordance with equation (6.1) of the proposed 1994 UBC, provided that $T_I / T \geq 2.0$.

5. The results of the response spectrum analysis procedure on the distribution of shear force over the height of the isolated structure agree with the mean of time history analyses for all lightly damped isolation systems (that is, systems with effective damping $\beta < 10\%$). For higher values of effective damping of the isolation system, the shear force in the upper stories of the structure is underpredicted by the response spectrum procedure by factors exceeding two. In particular, systems which meet the current SEAOC/UBC criteria allowing response spectrum analysis (that is, systems with $\beta < 0.30$), the degree of underprediction of shear force in the upper ⅓ of the structure ranged from 2 to 3. Considering that the top of a building is not, usually, the most critical failure point of the building, underpredicting the response by a factor of 2 might be acceptable for design. However, underprediction of the shear force by a factor of 3 is unconservative.

It is clear from the results of this study that the current SEAOC/UBC criteria for allowing response spectrum analysis (effectively allowing use of the procedure when $\beta < 0.30$) should be modified to prevent the prediction of unconservative shear forces at the top of an isolated building.

SECTION 8

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