EQUIVALENT NUMBER OF LOADING CYCLES FOR THE SEISMIC TESTING OF PASSIVE ENERGY DISSIPATION DEVICES

Fahim Sadek[1] and Michael A. Riley[2]

ABSTRACT

Prototype testing of passive energy dissipation devices is required to verify their response characteristics and demonstrate their capacity to withstand the design loads. These tests usually consist of loading the devices with a defined number of cyclic loads, with frequency and amplitude based on the design properties. The objective of this research was to develop recommendations for the required number of sine-wave-equivalent loading cycles that a device will be subjected to during the design earthquake. For this purpose, several linear and nonlinear single-degree-of-freedom (SDOF) structures were analyzed with a large number of earthquake records and the required number of cycles was computed based on two criteria. The first criterion is the "equivalent total energy," where the energy dissipated by the passive energy dissipation device during seismic excitation is equal to that absorbed by the device during cyclic testing. The second criterion is the "equivalent cumulative displacement," where the cumulative displacement experienced by the device during seismic excitation is equal to that experienced by the device during cyclic testing. Two sets of earthquake records were included in this study: a general set and a near-source set. The results of the various analyses indicated that the number of loading cycles computed using the displacement criterion is significantly larger than that based on the energy criterion. Comparing the number of cycles computed for linear and nonlinear structures, it is found that increased nonlinearity results in a smaller number of cycles using both criteria, due to the energy dissipated through inelastic action. The results also indicate that similar numbers of cycles are required for near-source and far-field ground motions in the short-period range, while for longer periods (T > 1 s), near-source excitations require fewer cycles.

Introduction

Structural control is quickly gaining acceptance as a cost effective way of protecting buildings, bridges, and other structures from earthquakes and strong winds; however, structural

---

[1] Research Associate, National Institute of Standards and Technology, Gaithersburg, MD 20899.
[2] Research Structural Engineer, National Institute of Standards and Technology, Gaithersburg, MD 20899.

control devices are still generally custom designed and produced on a per-project basis, with limited production of a particular size or design. Since these devices, which include seismic isolation systems and passive dampers, are not "off-the-shelf" items, testing has become an essential step in the design and manufacturing process, in order to validate that the devices will perform as expected. Testing of these devices is required by the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures (FEMA 368, 2001) and the NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273, 1997). Such testing is likely to be part of most future codes and guidelines that are based on the NEHRP provisions. In addition, the National Institute of Standards and Technology (NIST) has issued a set of guidelines for testing passive energy dissipation devices (Riley et al., 2001).

The above guidelines all require two classes of project specific testing: prototype tests and quality control (production) tests. Prototype tests are generally conducted on a few samples to verify the design properties, the response characteristics, and the device's capacity to withstand the design seismic loads. Quality control tests are conducted to verify the quality of manufacture and the as-built characteristics of each of the completed devices.

Prototype tests generally consist of cyclic tests of the device for a given number of cycles to the design earthquake displacement at the fundamental frequency of the structure. Different testing guidelines specify different number of test cycles. For example, the FEMA 273 guidelines specify loading the devices with twenty fully reserved cycles, while the newer FEMA 368 provisions require five cycles. The NIST guidelines leave the required number of cycles to the discretion of the structural engineer, but require a minimum of three cycles to the design earthquake displacement.

The objective of this study was to develop recommendations for the required number of sine-wave-equivalent loading cycles that the device will be subjected to during the design level earthquake. For this purpose, several single-degree-of-freedom (SDOF) structures were analyzed under a large number of earthquake records and the required number of cycles was computed based on two criteria. The first criterion is the "equivalent total energy," where the energy dissipated by the passive energy dissipation device during seismic excitation is made equal to that absorbed by the device during cyclic testing. The second criterion is the "equivalent cumulative displacement," where the cumulative displacement experienced by the device during seismic excitation is made equal to that seen by the device during cyclic testing.

Criteria for Computing Number of Cycles

The required number of sine-wave-equivalent loading cycles that the device will be subjected to during the design earthquake can be computed by the following two criteria:

1. *Equivalent total energy criterion.* Since the premise behind the use of passive energy dissipation devices is to dissipate a portion of the seismic energy in the structure, the devices should be cycled to absorb the same amount of energy during testing. This criterion should be applicable for devices exhibiting viscous or velocity-dependent behavior such as fluid viscous and viscoelastic dampers. The total energy dissipated by a device with damping coefficient c during seismic excitation is equal to:

$$E_{D,s} = \int_0^x c\dot{x}dx = \int_0^{t_f} c\dot{x}^2 dt \qquad (1)$$

Here x and $\dot{x}$ are the relative displacement and velocity, respectively and t_f is the total duration of excitation. The total energy consumed by the device during one cycle of sinusoidal excitation with period T (same as the natural period of the structure) and displacement D (same as the peak earthquake response) is equal to:

$$E_{D,c} = \frac{2\pi^2 c}{T} D^2 \qquad (2)$$

In order to make the total energy during cyclic loading (Equation 2) equivalent to that during seismic excitation (Equation 1); the number of sinusoidal cycles should be equal to:

$$N_E = \frac{T\int_0^{t_f} \dot{x}^2 dt}{2\pi^2 D^2} \qquad (3)$$

2. *Equivalent cumulative displacement criterion.* For some devices whose performance might degrade with repeated cycling, such as metallic yielding devices, it is essential that the device will experience a cumulative displacement during testing similar to that expected during the design earthquake. For this case, the number of sinusoidal cycles can be computed as:

$$N_{CD} = \frac{\int_0^x |dx|}{4D} \qquad (4)$$

Note that if testing is conducted at displacement, $\widetilde{D}$, or period, $\widetilde{T}$, other than the peak earthquake displacement, D, or the natural period of the structure, T, the computed number of cycles should be modified. Using the equivalent total energy criteria, the computed number of cycles, N_E, should be multiplied by $(\widetilde{T}/T)(D/\widetilde{D})^2$. If the cumulative displacement criteria is used, the computed number of cycles, N_{CD}, should be multiplied by $(D/\widetilde{D})$.

Analytical Procedure

The procedure used to determine the number of test loading cycles consisted of analyzing a number of linear SDOF structures with natural periods, T, ranging from 0.1 s to 4.0 s, and an inherent damping ratio, ξ, of 5 %. The structures were equipped with supplemental dampers; adding a viscous damping ratio, β, of 5 %, 10 %, 20 %, 30 %, and 40 %. Since structures are expected to experience nonlinear behavior during severe ground motions; even when equipped with passive energy dissipation devices, nonlinear SDOF structures with the same elastic periods (prior to yielding) and the same inherent and supplemental damping ratios were also analyzed. The structures had an elastic-plastic load-deformation relationship where the yield force, F_y, is

identified using a strength factor, η, such that:

$$F_y = \frac{mS_{ae}}{\eta}$$

(5)

Here m is the mass of the structure, and S_{ae} is the spectral acceleration of the 5 % damped linear elastic system. Note that $\eta = 1$ indicates linear behavior. The strength factor η is an indirect measure of the response modification factor, R, commonly used in seismic design codes and provisions. Values of the factor η used in this study were 2, 5, and 10.

The structures were subjected to a set of 72 horizontal components of accelerograms from 36 stations in the western United States. These records include a wide range of earthquake magnitudes, epicentral distances, peak ground accelerations, and soil conditions. A complete list of these records may be found in Sadek et al. (1999). This set of records will be referred to as the *general set*. Since the nature of near-source ground motions vary significantly from far-field motions due to the impulsive nature of the near-source excitations, the structures were also analyzed using a set of near-source ground motion accelerograms. This set included 22 near-source records from 11 stations. The horizontal distance from the recording site to the surface projection of the rupture for the stations in this set ranges from 0 to 5 kilometers. These records are listed in Table 1. This set of records will be referred to as the *near-source set*.

For each natural period, supplemental damping ratio, and strength factor, the response of the structure and the number of equivalent sinusoidal cycles were computed using the two criteria. The mean and the mean + standard deviation of the number of cycles were computed for each of the structures and for the two sets of ground motion.

Table 1. List of near-source earthquake records used in the study.

Earthquake	Mag.	Station Name	Distance[*] (km)
San Fernando, 1971	6.7	Pacoima Dam	< 1
Tabas, Iran, 1978	7.4	Tabas	3
Landers, 1992	7.2	Lucerne Valley Station	1
Offshore Eureka (Petrolia), 1994	7.2	Cape Mendocino	1.8
Northridge, 1994	6.7	Los Angeles Dam Right Abutment	< 1
		Arleta - Nordhoff Ave Fire Station	4
		Newhall – LA County Fire Station	5
		Rinaldi Receiving Station	< 1
		Sylmar Converter Station	< 1
		Sylmar County Hospital	2
		Tarzana - Cedar Hill Nursery	5

[*] Distance is defined as the approximate horizontal distance from the recording site to the surface projection of the rupture (Hall et al., 1995).

Numerical Results

Results with the General Set of Ground Motions

Based on the results of the numerical simulations, the mean number of cycles and the mean + one standard deviation were computed using the equivalent total energy criterion. These results are shown in Figures 1 and 2 for the linear SDOF structures ($\eta = 1$). The results indicate that the number of equivalent cycles varies with the structural period and supplemental damping ratio. For structures with supplemental damping ratios of 20 % and less, the number of cycles is greatest for periods of 0.3 s and shorter, and the number of cycles drops as the periods become longer. Alternately, for larger damping ratios, the number of cycles is smallest for periods shorter than 0.3 s, and largest for periods longer than 2.0 s.

Figures 3 and 4 present the results based on the cumulative displacement criterion. These results indicate that the number of cycles drops substantially with the increase in period. This is expected, since structures with short periods tend to have a larger number of response cycles than long-period structures during typical seismic excitations. Comparing the results shown in Figures 1 and 2 with those in Figures 3 and 4, it is observed that the number of loading cycles computed using the displacement criterion is significantly higher than that using the energy criterion for all periods and supplemental damping ratios.

For structures with nonlinear behavior, the mean number of cycles using the energy and cumulative displacement criteria, respectively, for $\eta = 2$ are shown in Figures 5 and 6. The results for higher values of η showed a consistent trend that increasing the value of η results in a significantly smaller number of cycles using both criteria. For the total energy approach the increased η results in larger inelastic response and, consequently, more energy is dissipated though the inelastic response of the structure. Hence, the amount of energy absorbed by the device is reduced. For the cumulative displacement approach, the increased yielding leads to a smaller number of response cycles, and, consequently, less cumulative displacement. The ratio between the number of cycles estimated for a linear structure and the number for nonlinear ones tend to approach unity for longer periods ($T > 1$ s). This indicates that the number of cycles computed from the nonlinear analysis is similar to linear structures in the long-period range.

Results of the Near-Source Set

Analyses similar to those conducted for the general earthquake set were carried out for the near-source set. Figure 7 presents the mean number of cycles using the energy criterion for the linear SDOF structures ($\eta = 1$), while Figure 8 presents the means based on the cumulative displacement criterion. The trends in these results are similar to those of the general set.

It was noted that the results for the two records from the Lucerne Valley station of the Landers earthquake of 1992 had a substantially larger number of cycles in the short-period range (0.1 s $< T < 0.3$ s) than the other records. Based on the energy criterion for $T = 0.1$ s and $\beta = 5$ %, the number of cycles for the Lucerne records were approximately 15 and 20; while the other records ranged between 2 and 10. Using the cumulative displacement criteria for the same

period and damping ratio, the numbers of cycles using the Lucerne records were approximately 61 and 52; while those for other records ranged between 7 and 37. These results may be due to the records having an uncharacteristically high energy content in the short-period range, or due to the method used to correct the accelerogram (Iwan and Chen, 1994).

After excluding the Lucerne records from the statistical analysis, it may be concluded that similar numbers of cycles are required for near-source and far-field ground motions in the short-period range when the energy criterion is used. For longer periods (T > 1 s), near-source excitations require fewer cycles. Using the cumulative displacement criterion similar conclusions can be reached.

Analyses conducted for nonlinear structures using the near-source records indicated that the reductions in the number of cycles were similar to the reductions with the general set.

Conclusions

The results of the analyses presented here indicate that the number of sine-wave-equivalent loading cycles required to meet the equivalent cumulative displacement criterion is significantly larger than that required to meet the equivalent total energy criterion. Comparing the number of cycles required for linear and nonlinear structures, it was found that increased nonlinearity results in a smaller number of cycles using both criteria, due to the energy dissipated through inelastic action. The results of the study also indicate that similar numbers of cycles are required for near-source and far-field ground motions in the short-period range, while for longer periods (T > 1 s), near-source excitations require fewer cycles.

References

FEMA 273 (1997). "NEHRP Guidelines for the Seismic Rehabilitation of Buildings." Building Seismic Safety Council, Washington, D.C.

FEMA 368 (2001). "NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures." Building Seismic Safety Council, Washington, D.C.

Hall, J. F., Heaton, T. H., Halling, M. W., and Wald, D. J. (1995). "Near-Source Ground Motion and its Effects on Flexible Buildings," Earthquake Spectra, Vol. 11(4), pp. 569-605.

Iwan, W. D., and Chen X. D. (1994). "Important Near-Field Ground Motion Data from the Landers Earthquake," *Proceedings of the 10th European Conference on Earthquake Engineering*, Vienna, Austria.

Riley, M. A., Sadek, F., and Mohraz, B., (2002), "Guidelines for Testing Passive Energy Dissipation Devices," *Technical Report NISTIR xxxx,* National Institute of Standards and Technology, Gaithersburg, MD.

Sadek, F., Mohraz, B., and Riley, M. A. (1999). "Linear Static and Dynamic Procedures for Structures with Velocity-Dependent Supplemental Dampers," *Technical Report NISTIR 6329,* National Institute of Standards and Technology, Gaithersburg, MD.
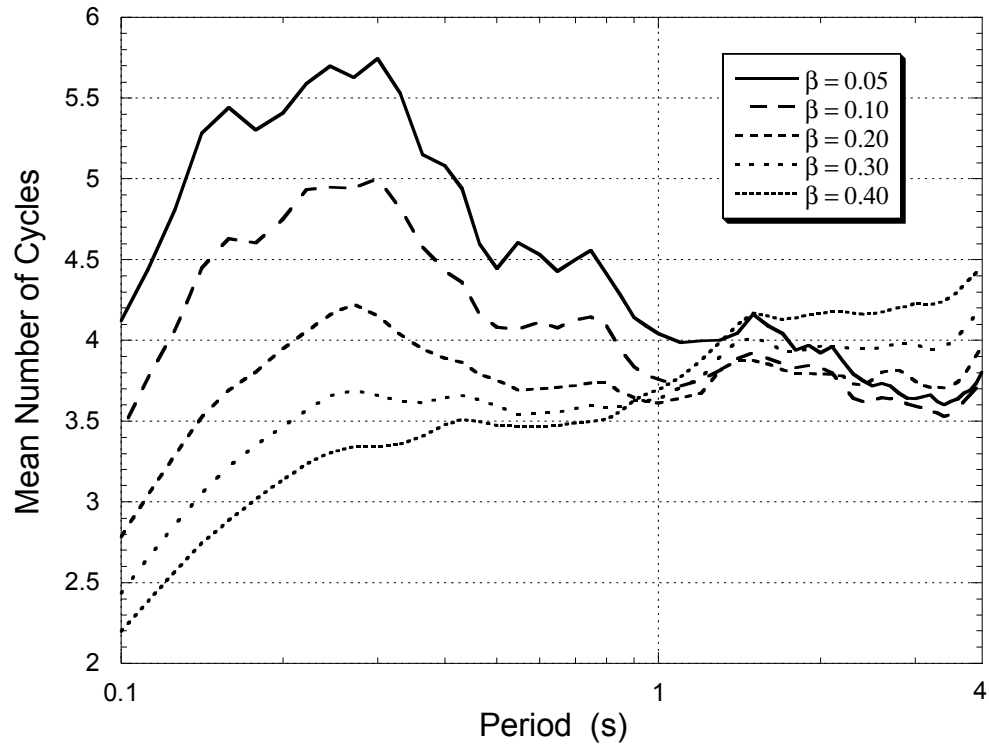
Figure 1. Mean number of cycles for linear structures using energy criterion.
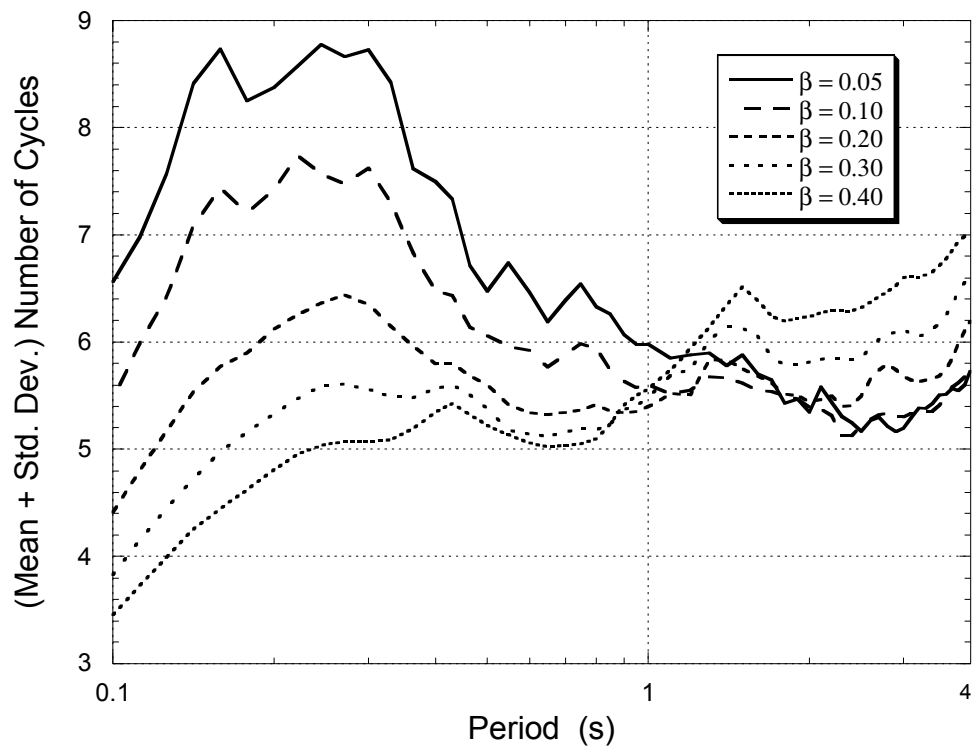

Figure 2. Mean + standard deviation of the number of cycles for linear structures using energy criterion.
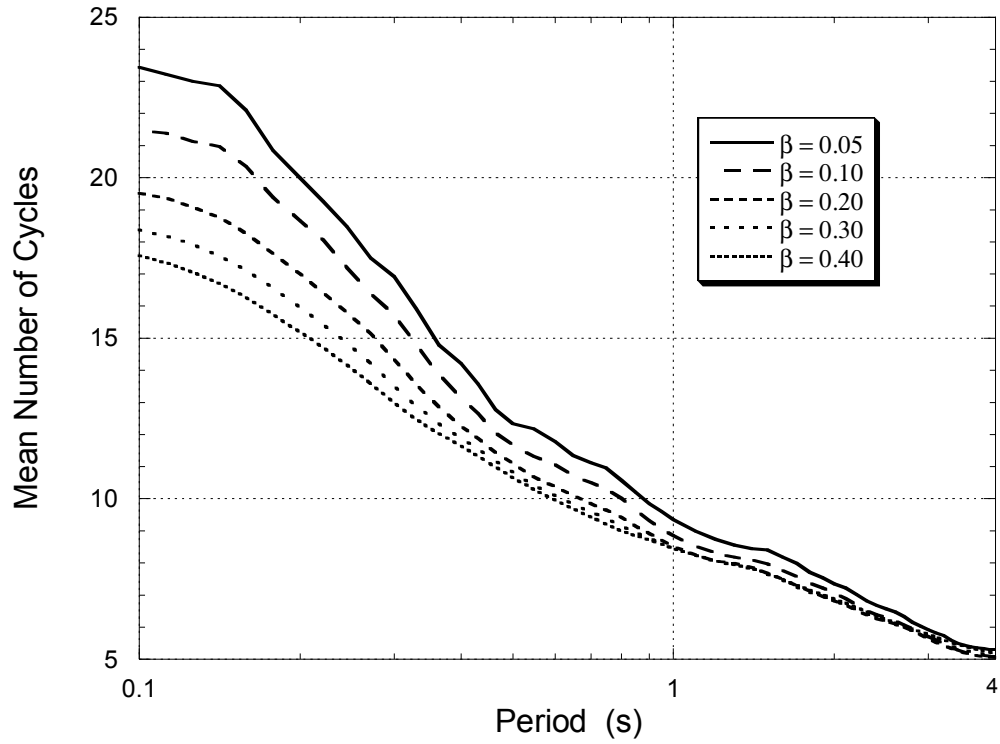
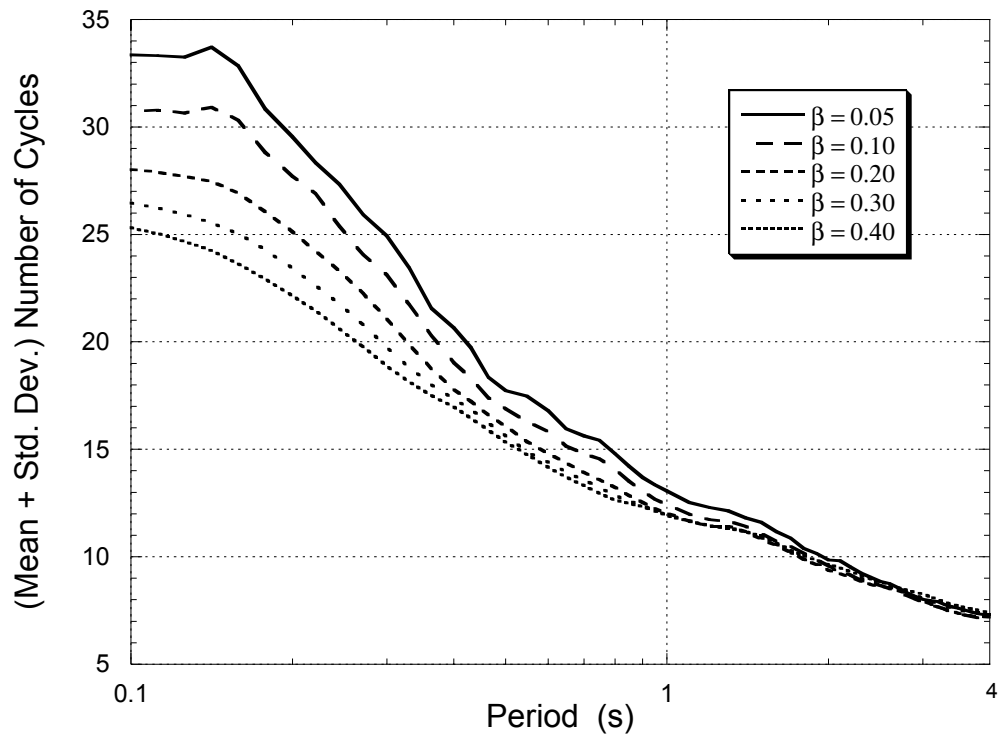Figure 3. Mean number of cycles for linear structures using displacement criterion.

Figure 4.   Mean + standard deviation of the number of cycles for linear structures using displacement criterion.
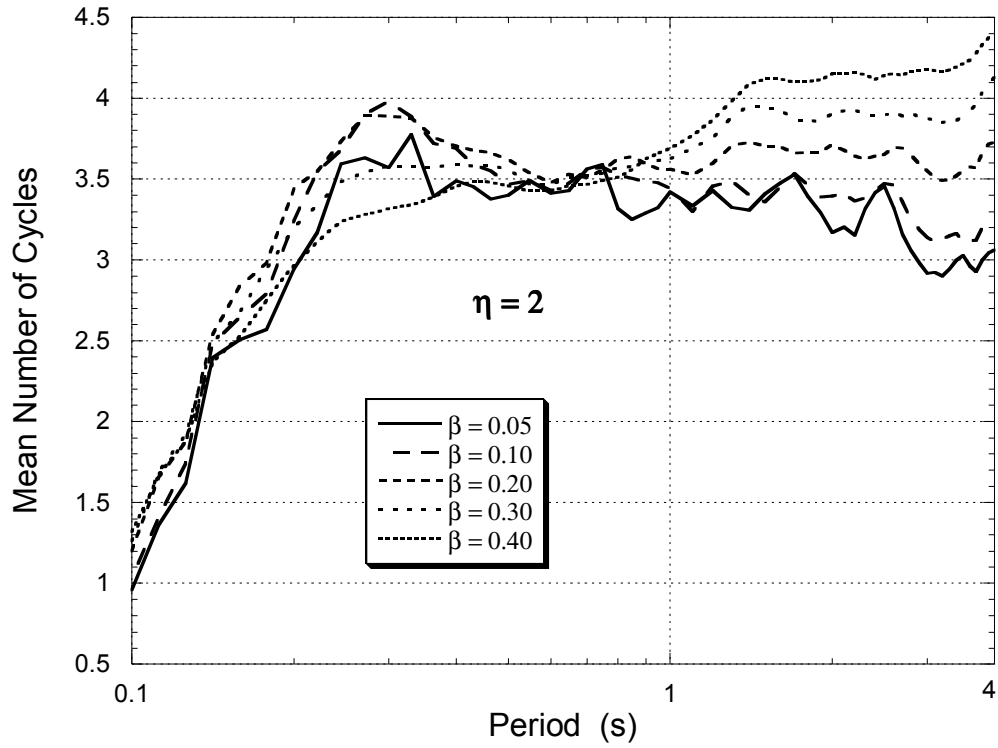
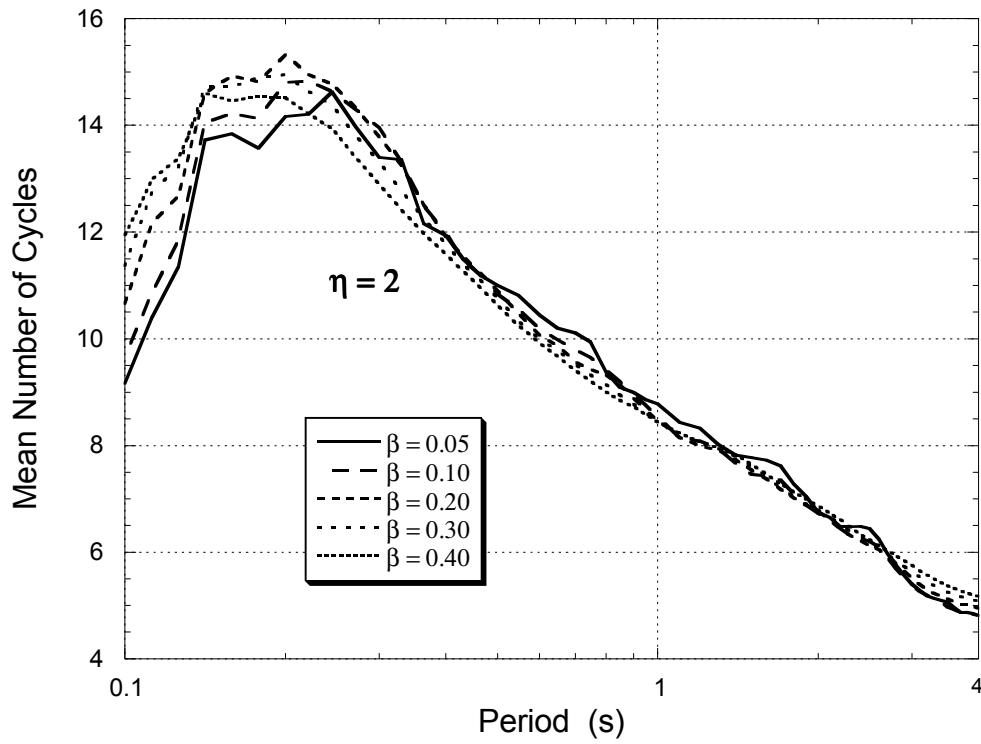Figure 5. Mean number of cycles for nonlinear structures using energy criterion.

Figure 6. Mean number of cycles for nonlinear structures using displacement criterion.
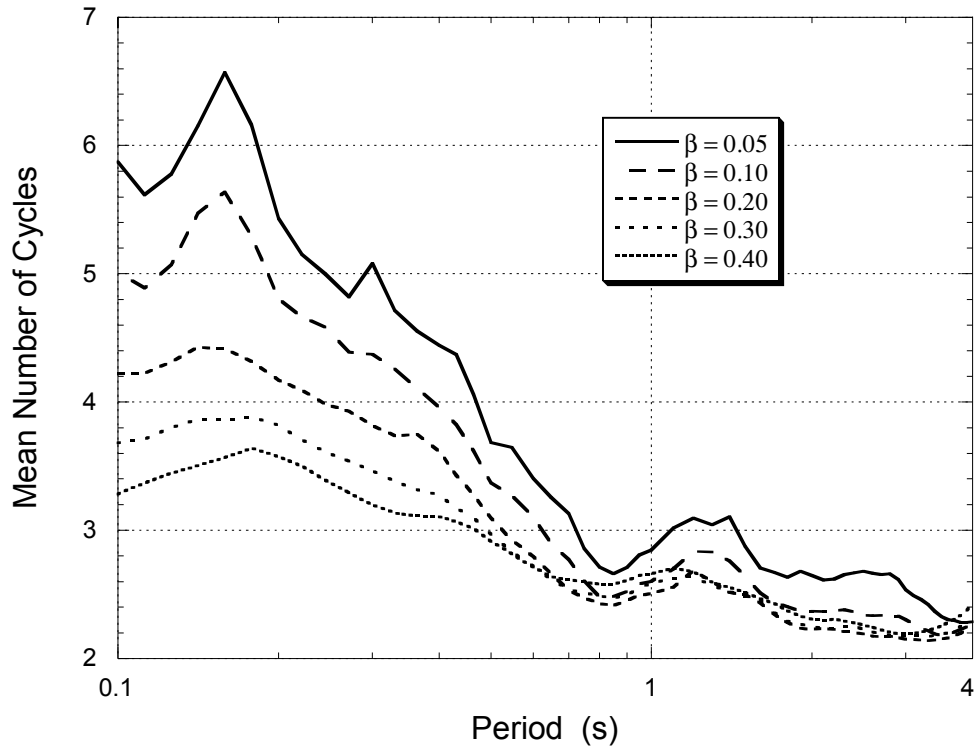
Figure 7.   Mean number of cycles for linear structures under near-source records using energy criterion.
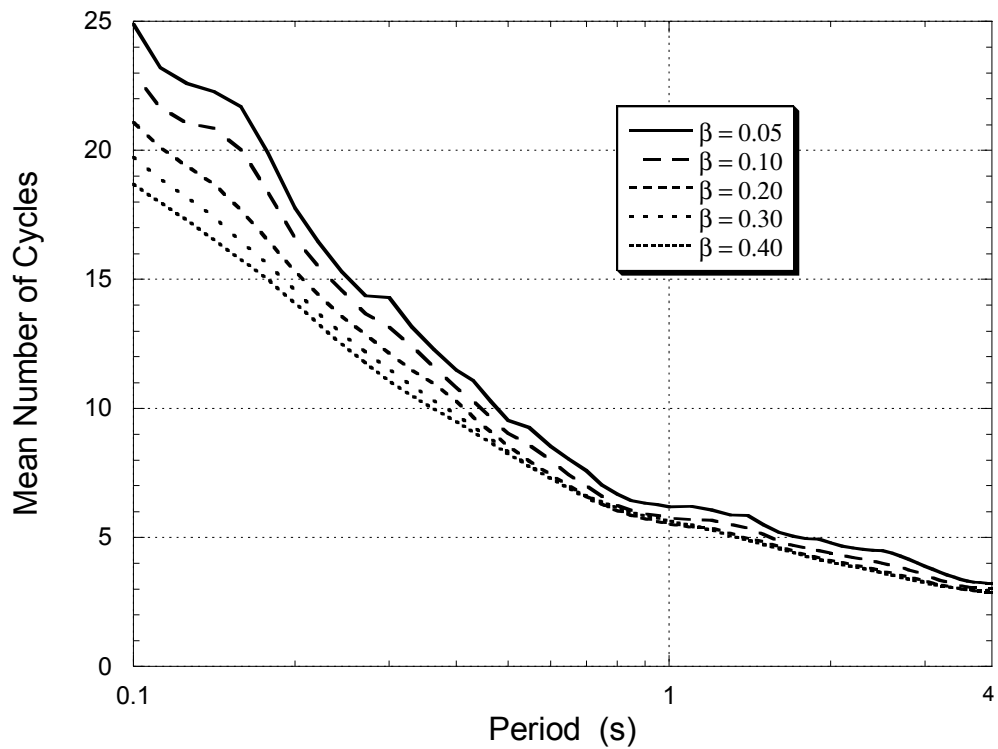

Figure 8.   Mean number of cycles for linear structures under near-source records using displacement criterion.