Required Number of Records for ASCE/SEI 7 Ground-Motion Scaling Procedure

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By Juan C. Reyes[1] and Erol Kalkan[2]

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Abstract

The procedures and criteria in 2006 IBC (International Council of Building Officials, 2006) and 2007 CBC (International Council of Building Officials, 2007) for the selection and scaling ground-motions for use in nonlinear response history analysis (RHA) of structures are based on ASCE/SEI 7 provisions (ASCE, 2005, 2010). According to ASCE/SEI 7, earthquake records should be selected from events of magnitudes, fault distance, and source mechanisms that comply with the maximum considered earthquake, and then scaled so that the average value of the 5-percent-damped response spectra for the set of scaled records is not less than the design response spectrum over the period range from $0.2T_n$ to $1.5T_n$ sec (where T_n is the fundamental vibration period of the structure). If at least seven ground-motions are analyzed, the design values of engineering demand parameters (EDPs) are taken as the average of the EDPs determined from the analyses. If fewer than seven ground-motions are analyzed, the design values of EDPs are taken as the maximum values of the EDPs. ASCE/SEI 7 requires a minimum of three ground-motions. These limits on the number of records in the ASCE/SEI 7 procedure are based on engineering experience, rather than on a comprehensive evaluation. This study statistically examines the required number of records for the ASCE/SEI 7 procedure, such that the scaled records provide accurate, efficient, and consistent estimates of “true” structural responses. Based on elastic-perfectly-plastic and bilinear single-degree-of-freedom systems, the ASCE/SEI 7 scaling procedure is applied to 480 sets of ground-motions. The number of records in these sets varies from three to ten. The records in each set were selected either (i) randomly, (ii) considering their spectral shapes, or (iii) considering their spectral shapes and design spectral-acceleration value, $A(T_n)$. As compared to benchmark (that is, “true”) responses from unscaled records using a larger catalog of ground-motions, it is demonstrated that the ASCE/SEI 7 scaling procedure is overly conservative if fewer than seven ground-motions are employed. Utilizing seven or more randomly selected records provides a more accurate estimate of the EDPs accompanied by reduced record-to-record variability of the responses. Consistency in accuracy and efficiency is achieved only if records are selected on the basis of their spectral shape and $A(T_n)$.

Introduction

When nonlinear response history analysis (RHA) is required for design verification of building structures, the International Building Code (2006) and California Building Code (2007) refer to the ASCE/SEI 7 Section 16-2[1] (ASCE, 2005, 2010). According to these documents, earthquake records should be selected from events of magnitudes, fault distance, and source mechanisms that comply with the maximum considered earthquake.

For two-dimensional analysis of symmetric-plan buildings, ASCE/SEI 7 requires intensity-based scaling of ground-motion records using

[1]Ground motion selection and scaling procedure for two-dimensional analysis of structures are same in both ASCE/SEI 7-05 and 7-10 documents; therefore in the remaining of this report, we simply refer to this method as the ASCE/SEI 7 scaling procedure.

appropriate scale factors, so that the average (that is, mean[2]) value of the 5-percent-damped response spectra for the set of scaled records is not less than the design response spectrum over the period range from $0.2T_n$ to $1.5T_n$ (where T_n is the elastic first-“mode” vibration period of the structure). For three-dimensional analyses, ground-motions should consist of pairs of appropriate horizontal ground-motion acceleration components. For each pair of horizontal ground-motion components, a square root of the sum of the squares (SRSS) spectrum should be constructed by taking the SRSS of the 5-percent-damped response spectra of the unscaled components. Each pair of motions are then scaled with the same scale factor such that the mean of the SRSS spectra from all horizontal component pairs does not fall below the corresponding ordinate of the target spectrum in the period range from $0.2T_n$ to $1.5T_n$. The design value of an engineering demand parameter (EDP)—member forces, member deformations or story drifts—is taken as the mean value of the EDP over seven or more ground-motions, or as its maximum value over all ground-motions, if the system is analyzed for fewer than seven ground-motions. This procedure requires a minimum of three records. The limits on the number of ground-motions in ASCE/SEI 7 were based on engineering experience rather than on a comprehensive evaluation (Charlie Kircher, oral commun.).

This study, for the first time, statistically examines the required number of records for the ASCE/SEI 7 procedure such that the scaled records provide accurate, efficient, and consistent estimates of “true” median structural responses. The adjective “accurate” refers to the discrepancy between the “true” responses and those computed from the scaling procedure. The adjective “efficient” refers to the record-to-record (that is, intra-set) variability of responses, and the adjective “consistent” refers to the ground-motion set-to-set (that is, inter-set) variability of accuracy and efficiency. Smaller values of inter- and intra-set dispersion of responses indicate that the scaling procedure is more efficient and consistent.

Based on elastic-perfectly-plastic and bilinear single-degree-of-freedom (SDF) systems, the accuracy, efficiency, and consistency of the ASCE/SEI 7 ground-motion scaling procedure are evaluated by applying it to 480 sets of ground-motions. The number of records in these sets varies from three to ten. The scaled records in each set were selected in three different ways: (i) randomly and (ii) minimizing discrepancy between scaled spectrum of a record and the target spectrum over the period range from $0.2T_n$ to $1.5T_n$ (this approach will be referred to as “Best1”) and (iii) minimizing discrepancy between scaled spectrum of a record and the target spectrum over the period range from $0.2T_n$ to $1.5T_n$, and then the final set of records was identified with spectral-acceleration values at T_n close to that of the design spectrum (this approach will be referred to as “Best2”).

Ground-Motions Selected

The thirty records selected for this investigation (listed in table 1) were recorded from seven shallow crustal earthquakes compatible with the following scenario:

- Moment magnitude: $M_w = 6.7 \pm 0.2$
- Joyner-Boore distance: $R_{JB} = 25 \pm 5$ km
- NEHRP[3] soil type: C and D
- Highest usable period≥4 sec

Shown in figure 1 are the 5-percent-damped geometric-mean response spectra for the *x*-component (identified as the maximum horizontal component) of the unscaled ground-motions. The geometric-mean spectrum of thirty records is taken as the design spectrum (that is, target spectrum) for purposes of this investigation.

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[2]In the remaining, “mean” is used in lieu of “arithmetic mean”.

[3]National Earthquake Hazard Reduction Program

Description of Inelastic SDF Systems

The structures considered are 16 SDF systems with vibration periods T_n equal to 0.2, 0.5, 1, and 2.5 sec, and yield strength reduction factors R equal to 1, 2, 4, and 8. The design base shear is determined as the mass of the system (assumed to be 1 kip-sec^2/in) times the geometric-mean pseudo-acceleration at T_n reduced by R. The damping ratio of the selected SDF systems is 5-percent.

Two constitutive models, used for the inelastic SDF systems, are: (1) an elastic-perfectly-plastic model, and (2) a bilinear model with a strength hardening ratio of 10 percent.

Methodology

According to the ASCE/SEI 7 procedure for two-dimensional (or planar) analyses of "regular" structures, the ground-motions should be scaled such that the mean value of the 5-percent-damped response spectra for the set of scaled motions is not less than the design spectrum over the period range from $0.2T_n$ to $1.5T_n$ sec. The ASCE/SEI 7 scaling procedure does not insure a unique scaling factor for each record; various combinations of scaling factors can be defined to insure that the mean spectrum of scaled records remains above the target spectrum over the specified period range. To achieve the desirable goal of scaling each record with a minimum scale factor closest to unity, we implemented the ASCE/SEI 7 scaling procedure for randomly selected ground-motions as follows:

1. For each of the thirty records listed in table 1, calculate the 5-percent-damped response spectrum $A(T)$ and the vector $\mathbf{A}$ of spectral values at 300 logarithmically spaced periods T over the period range from $0.2T_n$ to $1.5T_n$ sec.
2. Obtain a target (that is, "design") pseudo-acceleration spectrum $\hat{A}(T)$ as the geometric-mean spectrum of thirty records. Define $\hat{\mathbf{A}}$ as a vector of target spectral values $\hat{A}_i$ at periods T over the period range from $0.2T_n$ to $1.5T_n$ sec.
3. Compute the scaling factor SF_1 to minimize the difference between the target spectrum $\hat{A}(T)$ (Step 2) and the response spectrum $A(T)$ (Step 1) by solving the following minimization problem for each ground-motion:

   $$\min_{\mathrm{SF}_1} \left\| \log \hat{\mathbf{A}} - \mathrm{SF}_1 \times \log \mathbf{A} \right\| \Rightarrow \mathrm{SF}_1$$

   where $\|\cdot\|$ is the Euclidean norm. Required for this purpose is a numerical method to minimize scalar functions of one variable; such methods are available in textbooks on numerical optimization (for example, Nocedal and Stephen, 2006). This minimization ensures that each scaled response spectrum is as close as possible to the target spectrum, as shown schematically in figure 2.
4. Randomly select a set of m ground-motions to be used in nonlinear RHA of the systems described previously. No more than two records from the same event should be included in a single set, so that no single event is dominant within a set.
5. Determine the vector $\hat{\mathbf{A}}_{\mathrm{scaled}}$ for the mean scaled spectrum defined as the mean of the scaled spectra ($\mathrm{SF}_1 \times \mathbf{A}$) of the set of m records. The ordinates of this mean scaled spectrum could be smaller than the ordinates of the target spectrum at the same periods.
6. Calculate the maximum normalized difference $\varepsilon_{\mathrm{ASCE}}$ (fig. 3*a*) between the target spectrum $\hat{\mathbf{A}}$ and the mean scaled spectrum $\hat{\mathbf{A}}_{\mathrm{scaled}}$ over the period range from $0.2T_n$ to $1.5T_n$; that is, $\varepsilon_{\mathrm{ASCE}} = \max_{0.2T_1 \le T_i \le 1.5T_1} (\hat{A}_i - \hat{A}_{\mathrm{scaled},i}) \div \hat{A}_i$, where $\hat{A}_i$ and $\hat{A}_{\mathrm{scaled},i}$ are the ordinates of the target and the mean scaled pseudo-acceleration spectra

at vibration period T_i, respectively. Define the scale factor $\mathrm{SF}_2 = (1 - \varepsilon_{\mathrm{ASCE}})^{-1}$.

7. Determine the final scale factor $\mathrm{SF} = \mathrm{SF}_1 \times \mathrm{SF}_2$ for each ground-motion. Scaling ground-motions by the scaling factor SF ensures that the mean value of the response spectra for the set of scaled motions is not less than the target spectrum over the period range from $0.2T_n$ to $1.5T_n$ (fig. 3*b*).

To select ground-motions using the approach “Best1”, where the discrepancy between scaled spectrum of a record and the target spectrum over the period range from $0.2T_n$ to $1.5T_n$ is minimized, Step 4 is modified as follows:

4. Rank the scaled records based on their $\left\| \log \hat{\mathbf{A}} - \mathrm{SF}_1 \times \log \mathbf{A} \right\|$ value; the record with the lowest value is ranked the highest. From the ranked list, select a set of *m* records to be used in nonlinear RHA of the systems described previously.

Selection of ground-motions using the approach “Best2” requires that Steps 4-7 are iteratively implemented until the errors, defined as $\left\| \log \hat{\mathbf{A}} - \mathrm{SF}_1 \times \log \mathbf{A} \right\|$ and $\left| A(T_n) - \mathrm{SF} \times A(T_n) \right|$, are minimized. At the end of Steps 1 to 7, the scaling factors for the sets of *m* ground-motions would have been determined. Nonlinear RHA is then used to obtain final EDP values. If at least seven ground-motions are analyzed ($m \geq 7$), the design values of EDPs are taken as the mean or median[4] of the EDPs over the ground-motions used. If fewer than seven ground-motions are analyzed, the design values of EDPs are taken as the maximum values of the EDPs.

[4]Because the geometric mean and median of a lognormal distribution are the same, we decided to employ the term “median” instead of geometric mean, as is commonly done.

Benchmark Inelastic Deformations

Benchmark values of inelastic deformations (D_n) were determined by using nonlinear RHA of the SDF systems described previously subjected to each of the 30 unscaled ground-motions, and computing the median and mean value of the data set.

Hancock and others (2008) noted that the empirical ground-motion models that are used to derive the target spectrum assume the ground-motions to be lognormally distributed; therefore, the use of the median response spectrum of the records as a target spectrum is more consistent with the specification of the target spectrum. Similarly, it commonly is assumed that EDPs are lognormally distributed (Cornell and others, 2002); for this reason, it is more appropriate to represent the “mean” structural response by the median, a conclusion that is widely accepted. However, the ASCE/SEI 7 procedure states that the mean values of EDPs are used if at least seven ground-motions are considered. We decided to use both the median and the mean of the inelastic deformations as the benchmark values. In all cases of benchmark computations, the mean is larger than the median of inelastic deformations, indicating that the distribution of D_n is positively skewed. The percent differences between the two are in the ranges of 15 to 63, 23 to 39, 38 to 48, and 42 to 63 for elastic-perfectly-plastic systems with R equal to 1, 2, 4, and 8, respectively. For bilinear systems the percent differences are 11 to 26, 12 to 32, 20 to 45, and 27 to 56 for the same R values. Note that the difference between mean and median increases with increasing R value.

Evaluation of ASCE/SEI 7 Scaling Procedure - Fewer Than Seven Ground-Motions

The ASCE/SEI 7 scaling procedure was implemented for the inelastic SDF systems of this investigation subjected to one component of ground-motion (table 1). The accuracy of the ASCE/SEI 7 procedure was evaluated first by comparing the maximum value of the inelastic deformation D_n due to seven sets of 3 to 6 scaled records against the benchmark value, defined as the median (or mean) value of D_n due to the 30 unscaled ground-motions. These comparisons are shown in figures 4 and 5 for elastic-perfectly-plastic systems with T_n=0.2, 0.5, 1, and 2.5 sec, and R=1, 2, 4, and 8 due to groups of 3, 4, 5, and 6 records called as G3, G4, G5 and G6, respectively. Seven sets of records were considered in each of these groups. Among these seven sets, the first five sets of records were selected randomly out of 30 records, and the two remaining sets of records were selected with the criteria explained previously; these are sets "Best1" and "Best2". For each T_n, R, and constitutive model combinations, a total of 30 sets of records are utilized. For the benchmark, the blue dot and the vertical line represent the median deformation value plus and minus one standard deviation (henceforth denoted as $\pm\sigma$), assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and maximum deformation value, respectively. Similar plots are presented in figures 6 and 7 for bilinear systems. Figures 4 and 5 permit the following observations: (1) Increasing the number of records from 3 to 6 has a minor effect in the accuracy of the procedure; overestimations range from 1 to 1500 percent and from 35 to 820 percent for groups G3 and G6, respectively. (2) The accuracy of the procedure decreases with increasing R value and decreasing period; the maximum error increases from 250 to 1,060 percent and from 620 to 1,500 percent if R changes from 1 to 8, and T_n changes from 2.5 to 0.2 sec, respectively. (3) The improvement gained by the use of sets "Best1" and "Best2" is marginal. For R equals 8, the errors range from 10 to 190 percent and from 0.2 to 1,130 percent for sets Best1 and Best2, respectively. For bilinear systems, the errors are slightly smaller than those for elastic-perfectly-plastic systems.

The benchmark results shown in figures 4 through 7 are based on the median deformation value; figure 8 compares the benchmark, calculated as the mean of 30 D_n values, and the ASCE/SEI 7 deformation values for elastic-perfectly-plastic and bilinear systems. Included also are the horizontal lines at 0.8 and 1.2 times the benchmark to indicate ± 20 percent error around the "true" value. It is apparent that the ASCE/SEI 7 scaling procedure is not accurate and overly conservative, especially for elastic-perfectly-plastic systems. Insignificant improvement is gained by the use of sets "Best1" and "Best2".

Figures 9 and 10 show intra- and inter-set dispersion values to assess, respectively, the efficiency and consistency of the ASCE/SEI 7 procedure. A lognormal distribution of D_n values was assumed. As shown in figure 9, the intra-set dispersion increases with increasing period; implying that the procedure becomes less efficient. Similarly, inter-set dispersion increases with increasing R (fig. 10), indicating that the procedure becomes less consistent. Note that the inter-set dispersion tends to decrease with increasing number of records per set. According to the results presented in figures 4 through 10, the accuracy, efficiency, and consistency in the estimation of inelastic deformations are not achieved in the ASCE/SEI 7 procedure if fewer than seven records are employed. The procedure was found to be unacceptably conservative and unstable.

Evaluation of ASCE/SEI 7 Scaling Procedure - Seven or More Ground-Motions

The accuracy of the ASCE/SEI 7 procedure was evaluated next by comparing the median (or mean) value of the inelastic deformation D_n due to seven sets of 7 to 10 scaled records against the benchmark value, defined as the median (or mean) value of D_n due to the 30 unscaled ground-motions.

Figures 11 and 12 show the range of inelastic deformation values D_n for elastic-perfectly-plastic systems due to groups of 7, 8, 9, and 10 records called G7, G8, G9, and G10, respectively. As explained previously, seven sets were considered in each of these groups (that is, a total of 28 sets plus sets Best1 and Best2 for each T_n, R and constitutive-model combinations). The dot and the vertical line represent the median deformation value $\pm\sigma$ assuming a lognormal distribution. Similar plots are presented in figures 13 and 14 for bilinear systems. Figures 15 and 16 compare the benchmark with the ASCE/SEI 7 deformation values for elastic-perfectly-plastic and bilinear systems for a range of R values. The ASCE/SEI 7 results in figure 15 are the median of 7, 8, 9, and 10 D_n values from scaled records, and the benchmark is defined as the median of 30 D_n values from unscaled records, whereas in figure 16, mean values are used for both the ASCE/SEI 7 and the benchmark results. Included also in these figures are the lines at 0.8 and 1.2 times the benchmark to represent ± 20 percent error around the "true" value. By comparing figure 8 with figure 16, it becomes obvious that the ASCE/SEI 7 scaling procedure utilizing seven or more randomly selected records provides a more accurate estimate of inelastic deformations. However, the overestimations in median values of inelastic deformation generally are larger than 20 percent, especially for R=4 and 8, as shown in figure 17. Figures 11, 12, and 15 permit the following observations: (1) increasing the number of records from 7 to 10 has a minor effect in the accuracy of the procedure; overestimations range from 0.5 to 140 percent and from 0.6 to 124 percent for groups G7 and G10, respectively. (2) The accuracy of the procedure decreases with increasing R value; the maximum error increases from 56 to 140 if the R value changes from 1 to 8. (3) The fundamental period T_n does not affect significantly the accuracy of the ASCE/SEI 7 procedure if the records are selected randomly. The maximum error is 140 and 134 percent for T_n=0.2 and 2.5 sec, respectively. Figures 13, 14, and 16 lead to similar conclusions.

For short periods and large R values, the mean of randomly selected sets is not similar to the mean of the benchmark data set as demonstrated by the analysis of variance (ANOVA) values in figure 18. The ANOVA test returns the p value under the null hypothesis that both ASCE/SEI 7 and benchmark results are drawn from populations with the same mean. If p is near zero, it questions the null hypothesis and suggests that the ASCE/SEI 7 mean is significantly different from the benchmark mean. This statistical test indicates that the random selection of records for the ASCE/SEI 7 procedure may lead to inconsistent results.

For systems with T_n≥0.5 sec or small R values, set "Best2" is more accurate than set "Best1", demonstrating that consideration of spectral shape and $A(T_n)$ in selecting and scaling ground-motions improves the D_n estimates significantly (Figs. 11-18). For T_n=2.5 sec, the error of the procedure ranges from 9 to 60 percent and from 3 to 30 percent for sets "Best1" and "Best2", respectively. For systems with very short periods ($T_n = 0.2$ sec) and large R values ($R = 4$ and 8), both sets "Best 1" and "Best 2" lead to inaccurate estimates of inelastic deformations (figs. 11-18); overestimations exceed 100 percent due to the high variability of spectral pseudo-accelerations and large discrepancies between elastic and inelastic spectra for periods in the acceleration sensitive region and large R values.

The intra- and inter-set dispersion values are shown next in figures 19 and 20, where a lognormal distribution of D_n values was assumed. The intra-set dispersion increases with increasing period, indicating larger variability of response values within a set. Similarly, the inter-set dispersion increases with increasing R values, implying that larger inelastic deformations would lead to increased set-to-set variability. As expected, the inter-set dispersion tends to decrease with increasing number of records per set. By comparing figures 10 and 20, it becomes evident that utilizing seven or more randomly selected records in the ASCE/SEI 7 reduces the inter-set dispersion significantly; the reduction is more pronounced for elastic-perfectly-plastic systems. The reduced inter-set variability indicates the consistency in the benchmark estimates of the ASCE/SEI 7 procedure using different sets. For systems with a fundamental period in the velocity or displacement sensitive region, accuracy, efficiency, and consistency are achieved only if records are selected on the basis of their spectral shape and $A(T_n)$ as opposed to random selection.

Modal-Pushover-Based Scaling Procedure - Alternative to the ASCE/SEI 7 Scaling Procedure

Because the ASCE/SEI 7 ground-motion scaling method does not consider explicitly the inelastic behavior of the structure, it may not be appropriate for structures with short periods or for structures located in near-field sites where the inelastic deformation can be significantly larger than the deformation of the corresponding linear system. For such cases, scaling methods that are based on the inelastic deformation spectrum, or methods that consider the response of the first-"mode" inelastic SDF system, are more appropriate (Luco and Cornell 2007, Tothong and Cornell 2008, PEER 2009). Kalkan and Chopra (2010a,b and 2011a,b) used these concepts to develop a modal pushover-based scaling (MPS) procedure for selecting and scaling earthquake ground-motion records in a form convenient for evaluating existing structures and proposed designs of new structures. This procedure explicitly considers structural strength, determined from the first-"mode" pushover curve, and determines a scaling factor for each record to match a target value of the deformation of the first-"mode" inelastic SDF system. If the MPS procedure were applied to the systems of this investigation, it would lead to null error in the estimation of inelastic deformations and null intra- and inter-set dispersions. Therefore, the MPS procedure for SDF systems would be absolutely accurate, efficient and consistent.

Conclusions

Based on elastic-perfectly-plastic and bilinear inelastic single-degree-of-freedom systems, the accuracy, efficiency, and consistency of the ASCE/SEI 7 ground-motion scaling procedure are examined by comparing the median and mean values of the inelastic deformation due to 480 sets of scaled records against benchmark values. The number of records in these sets varies from three to ten. The records in each set were selected either (i) randomly, (ii) considering their spectral shapes or (iii) considering the design spectral-acceleration value $A(T_n)$ in addition to their spectral shapes. This evaluation of the ASCE/SEI procedure has led to the following conclusions:

1. The ASCE/SEI 7 scaling procedure does not insure a unique scaling factor for each record; various combinations of scaling factors can be defined to insure that the mean spectrum of scaled records remains above the target spectrum over the specified period range. Utilizing a minimum scale factor closest to unity for each record may overcome this flaw in the ASCE/SEI 7 scaling procedure.
2. The ASCE/SEI 7 procedure is found to be conservative; it is neither efficient nor consistent if fewer than seven ground-motions are utilized. Only marginal improvements were gained by selecting and scaling records based on their spectral shape (as in sets Best1) and design spectral-acceleration value, $A(T_n)$ (as in sets Best2).
3. The ASCE/SEI 7 scaling procedure utilizing seven or more randomly selected records provides more accurate estimates of inelastic deformations. However, the overestimations in median values of inelastic deformation generally are larger than 20 percent. Increasing the number of records from 7 to 10 has a minor effect in the accuracy of the procedure. Thus, use of 7 records is found to be sufficient.
4. In general, the accuracy of the procedure decreases with increasing *R* value. The fundamental period, T_n, (that is, long or short periods) does not significantly affects its accuracy if the records are selected randomly.
5. For systems with $T_n \geq 0.5$ sec or small R values ($R < 4$), consideration of spectral

shape and $A(T_n)$ in selecting and scaling ground-motions improves the displacement response (D_n) estimates significantly. For systems with very short periods ($T_n = 0.2$ sec) and large R values ($R = 4$ and 8) however, both sets "Best 1" and "Best 2" lead to inaccurate estimates of inelastic deformations with overestimations exceeding 100 percent. This is due to the high variability of spectral pseudo-acceleration values, large discrepancies between elastic and inelastic spectra for periods in the acceleration-sensitive region and large R values (that is, increased inelastic response). For such cases, scaling methods that are based on the inelastic deformation spectrum, or that consider the response of the first-"mode" inelastic SDF system, are more appropriate.

This study has focused on the statistical examination of the required number of records for the ASCE/SEI ground-motion scaling method, which has been limited to elastic-perfectly-plastic and bilinear inelastic single-degree-of-freedom systems.

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Notation

The following symbols are used in this report:

$A(T)$	Pseudo-spectral-acceleration at period *T*
$\mathbf{A}$	Vector of pseudo-spectral-acceleration values
$\hat{A}(T)$	Target value of pseudo-spectral-acceleration at period *T*
$\hat{\mathbf{A}}$	Vector of target pseudo-spectral-acceleration values
$\hat{\mathbf{A}}_{\text{scaled}}$	Mean scaled spectrum of *m* records
$\varepsilon_{\text{ASCE}}$	Maximum normalized difference between target and mean scaled spectrum
m	Number of ground-motion records
M_w	Moment magnitude
R	Yield-strength reduction factor
R_{JB}	Joyner-Boore distance-perpendicular distance to surface projection of fault plane
SF	Ground motion scaling factor
T_n	Period of single-degree-of-freedom system; or elastic first-“mode” vibration period of structure
V_{S30}	Average shear-wave velocity within 30 m depth from surface
σ	Standard deviation

Table 1. Selected near-fault ground-motion records. [NEHRP, National Earthquake Hazard Reduction Program; AS, aftershock]

Record sequence number	Earthquake name	Year	Station Name	Earthquake magnitude (M_w)	Joyner-Boore distance (km)	NEHRP site class	Highest usable period (sec.)
1	San Fernando, Calif.	1971	LA - Hollywood Stor FF	6.6	22.8	D	4
2	San Fernando, Calif.	1971	Santa Felita Dam (Outlet)	6.6	24.7	C	8
3	Imperial Valley (AS), Calif.	1979	Calipatria Fire Station	6.5	23.2	D	8
4	Imperial Valley (AS), Calif.	1979	Delta	6.5	22.0	D	16
5	Imperial Valley (AS), Calif.	1979	El Centro Array #1	6.5	19.8	D	8
6	Imperial Valley (AS), Calif.	1979	El Centro Array #13	6.5	22.0	D	4
7	Imperial Valley (AS), Calif.	1979	Superstition Mtn Camera	6.5	24.6	C	8
8	Irpinia, Italy	1980	Brienza	6.9	22.5	C	4
9	Superstition Hills (AS), Calif.	1987	Wildlife Liquef. Array	6.5	23.9	D	8
10	Loma Prieta, Calif.	1989	Agnews State Hospital	6.9	24.3	D	4
11	Loma Prieta, Calif.	1989	Anderson Dam (Downstream)	6.9	19.9	C	4
12	Loma Prieta, Calif.	1989	Anderson Dam (L Abut)	6.9	19.9	C	8
13	Loma Prieta, Calif.	1989	Coyote Lake Dam (Downst)	6.9	20.4	D	8
14	Loma Prieta, Calif.	1989	Coyote Lake Dam (SW Abut)	6.9	20.0	C	8
15	Loma Prieta, Calif.	1989	Gilroy Array #7	6.9	22.4	D	4
16	Loma Prieta, Calif.	1989	Hollister - SAGO Vault	6.9	29.5	C	8
17	Northridge, Calif.	1994	Castaic - Old Ridge Route	6.7	20.1	C	8
18	Northridge, Calif.	1994	Glendale - Las Palmas	6.7	21.6	C	6
19	Northridge, Calif.	1994	LA - Baldwin Hills	6.7	23.5	D	6
20	Northridge, Calif.	1994	LA - Centinela St	6.7	20.4	D	4
21	Northridge, Calif.	1994	LA - Cypress Ave	6.7	29.0	C	4
22	Northridge, Calif.	1994	LA - Fletcher Dr	6.7	25.7	C	5
23	Northridge, Calif.	1994	LA - N Westmoreland	6.7	23.4	D	4
24	Northridge, Calif.	1994	LA - Pico & Sentous	6.7	27.8	D	5
25	Kobe, Japan	1995	Abeno	6.9	24.9	D	16
26	Kobe, Japan	1995	Kakogawa	6.9	22.5	D	8
27	Kobe, Japan	1995	Morigawachi	6.9	24.8	D	10
28	Kobe, Japan	1995	OSAJ	6.9	21.4	D	16
29	Kobe, Japan	1995	Sakai	6.9	28.1	D	8
30	Kobe, Japan	1995	Yae	6.9	27.8	D	16

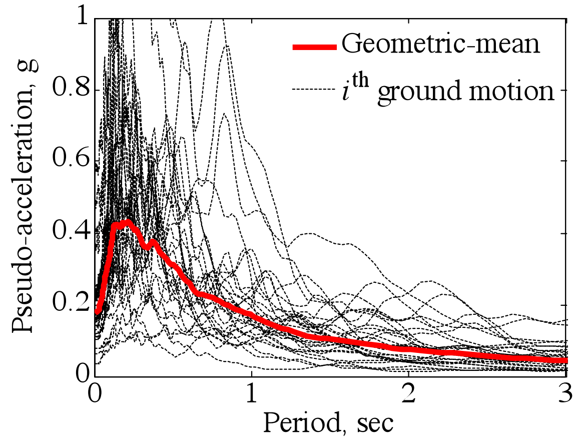


Figure 1. Response spectra of thirty near-fault ground-motions and their geometric-mean (that is, median) used as the target (that is, "design") spectrum for evaluation of the ASCE/SEI 7 ground-motion scaling procedure. Damping ratio 5-percent.

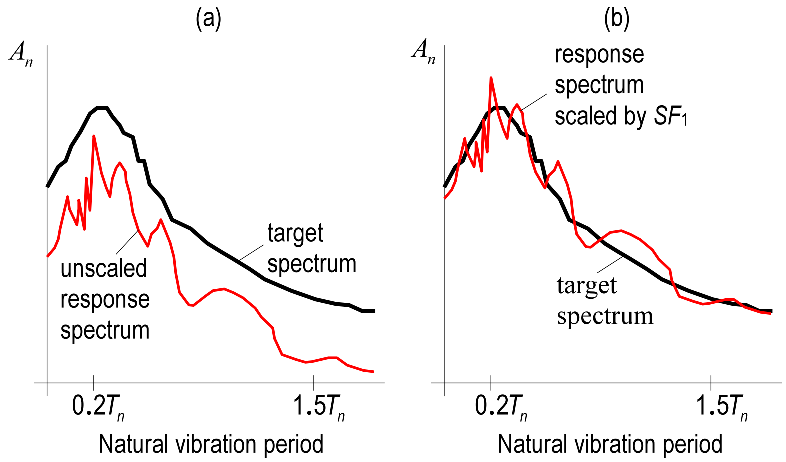


Figure 2. Schematic illustration of Step 3 of the evaluation methodology.

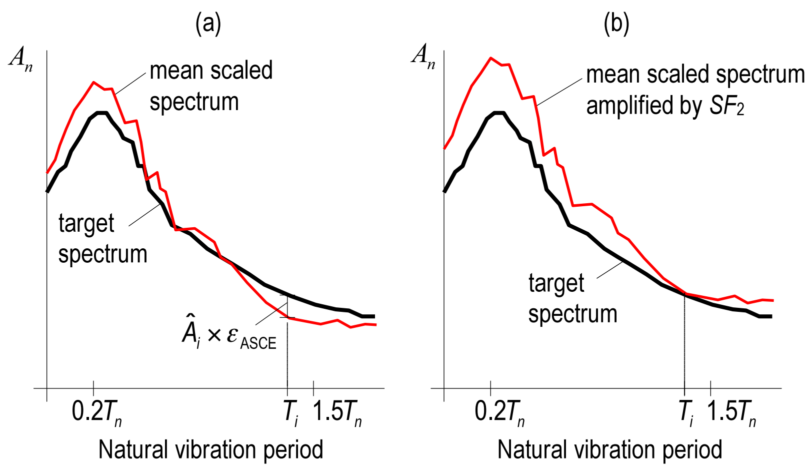


Figure 3. Schematic illustration of Step 6 of the evaluation methodology.

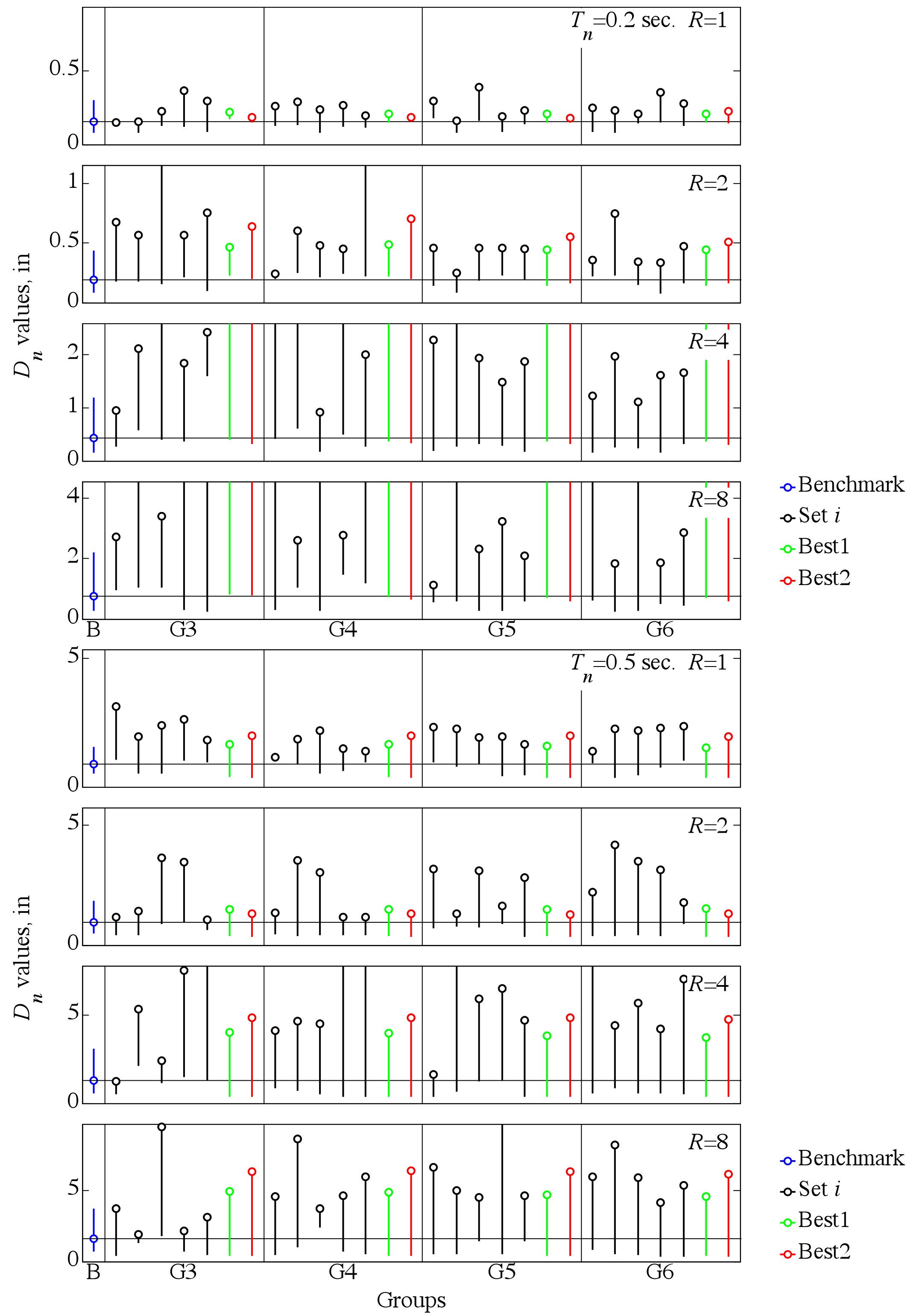


Figure 4. Range of inelastic deformation values for elastic-perfectly-plastic systems with T_n=0.2 sec (top four panels) and T_n=0.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 3, 4, 5, and 6 records denoted respectively as G3, G4, G5, and G6. The blue dot and the vertical line represent the benchmark (denoted as B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and maximum deformation value, respectively.

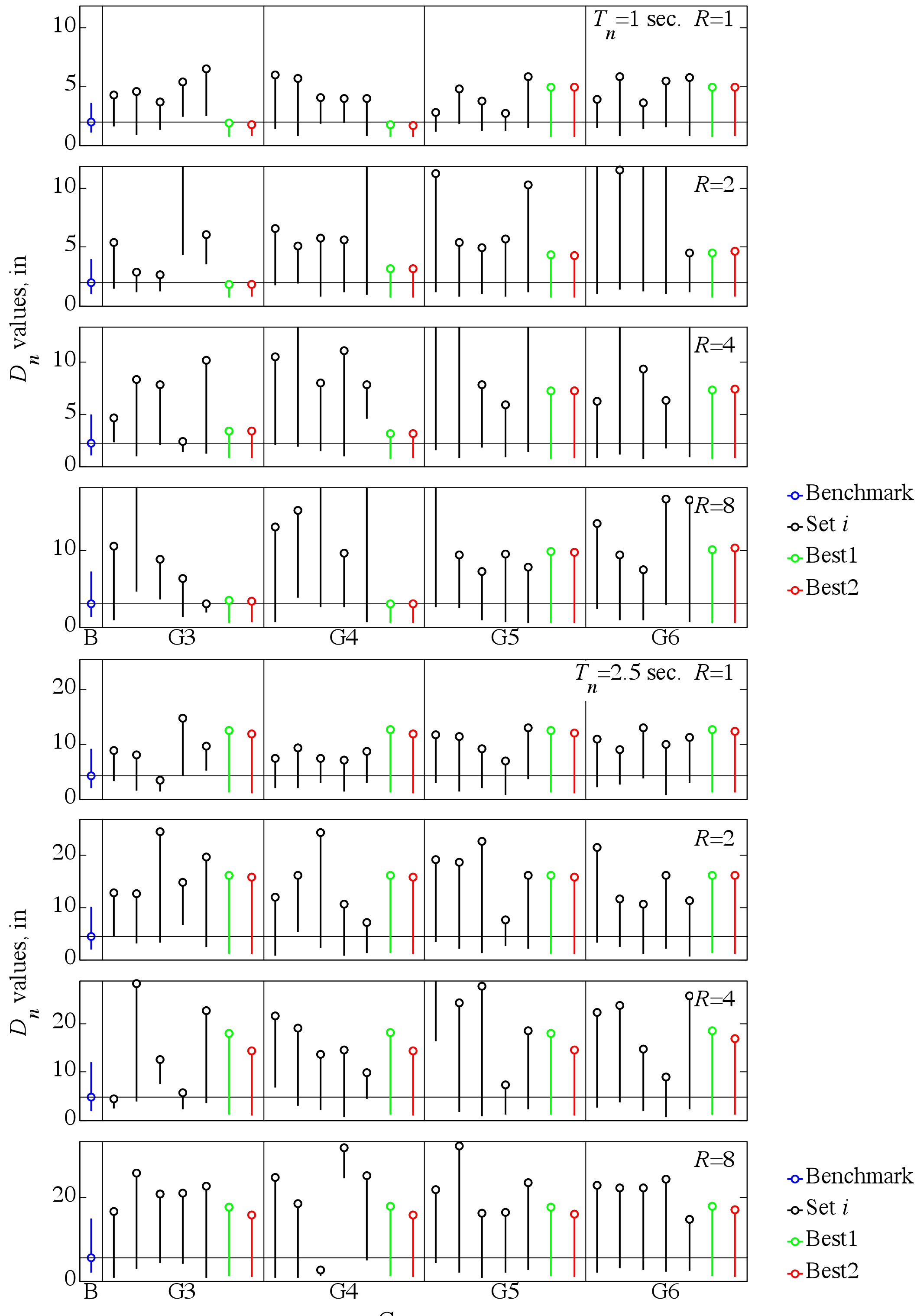


Figure 5. Range of inelastic deformation values for elastic-perfectly-plastic systems with T_n =1 sec (top four panels) and T_n=2.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 3, 4, 5, and 6 records denoted respectively as G3, G4, G5, and G6. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and maximum deformation value.

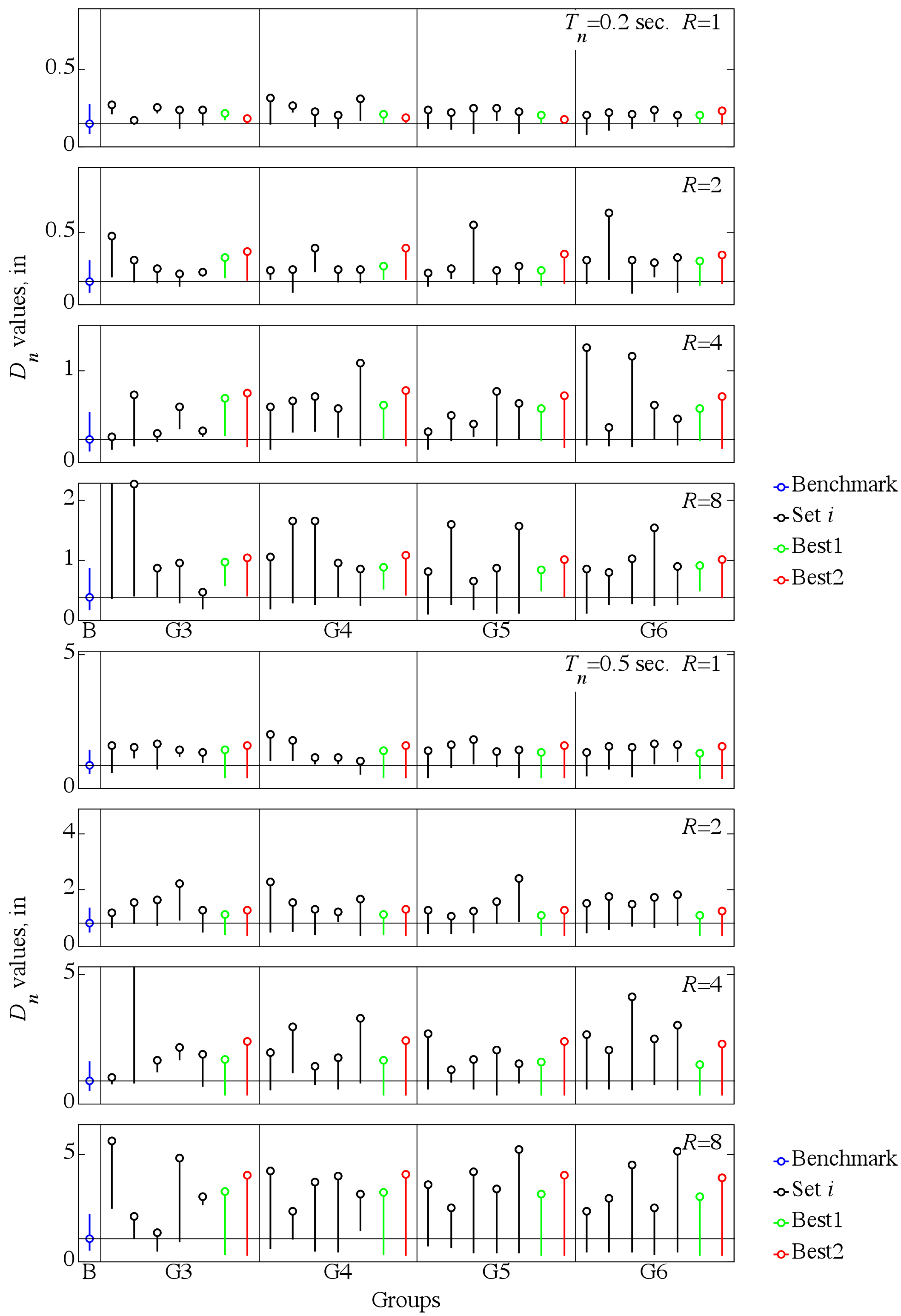


Figure 6. Range of inelastic deformation values for bilinear systems with T_n =0.2 sec (top four panels) and T_n=0.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 3, 4, 5, and 6 records denoted respectively as G3, G4, G5, and G6. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and maximum deformation value, respectively.

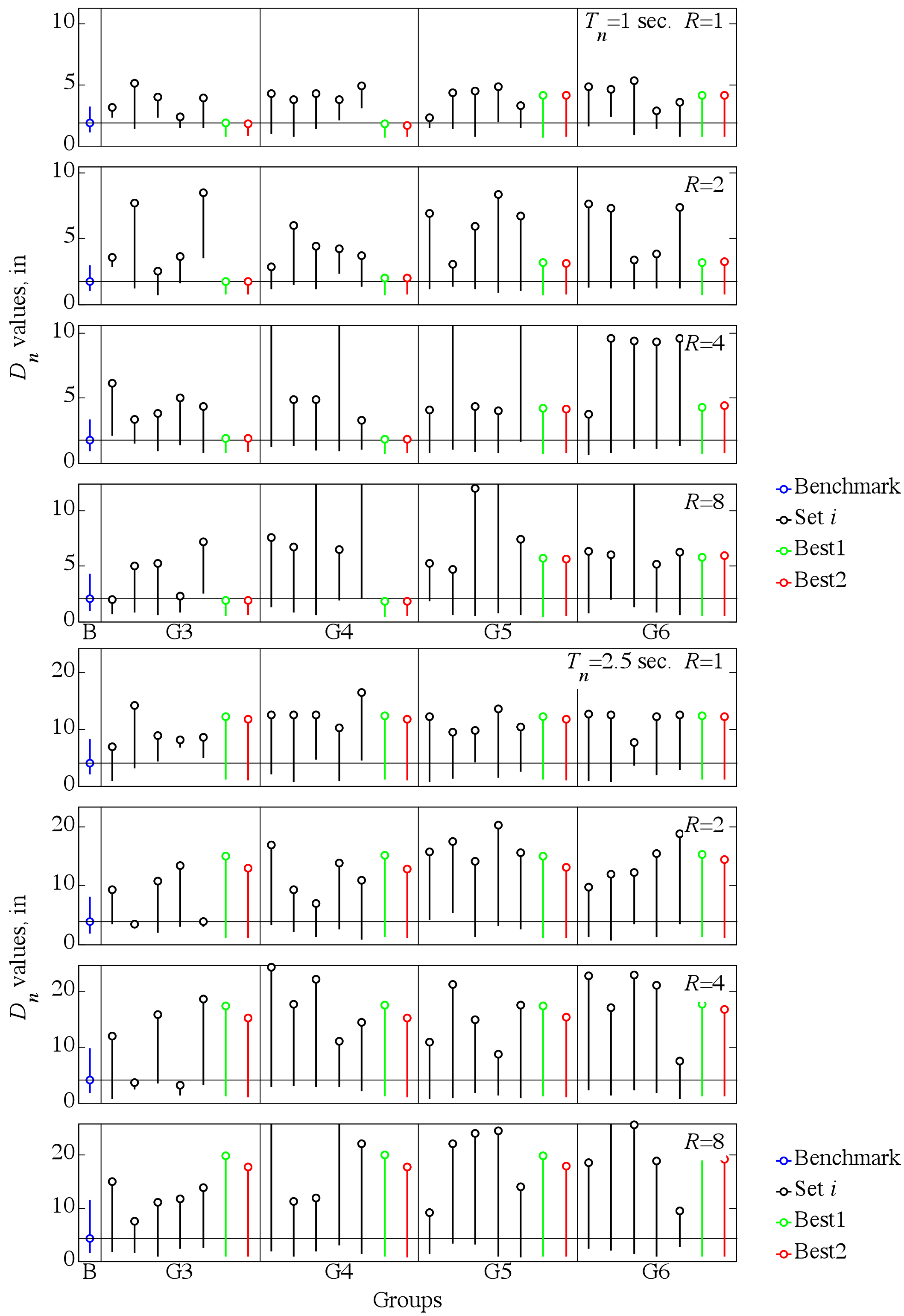


Figure 7. Range of inelastic deformation values for bilinear systems with T_n =1 sec (top four panels) and T_n =2.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 3, 4, 5, and 6 ground-motion records denoted respectively as G3, G4, G5, and G6. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and maximum deformation value, respectively.

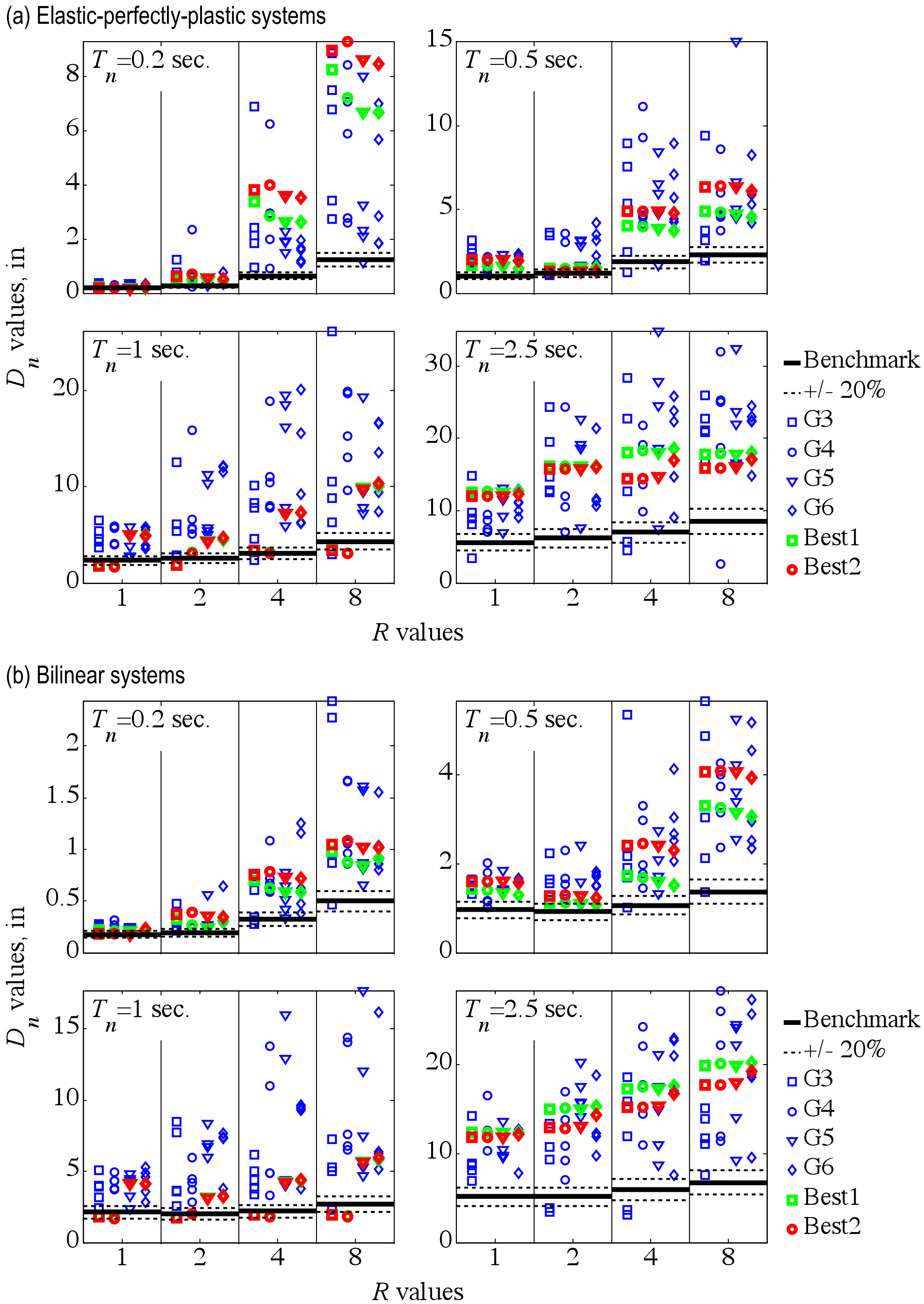


Figure 8. Comparison of benchmark and ASCE/SEI 7 deformation values for (a) elastic-perfectly-plastic, and (b) bilinear systems. The benchmark engineering demand parameters (EDPs) correspond to the mean of 30 deformation values. The deformation values for each set scaled by the ASCE/SEI 7 procedure are obtained as the maximum deformation values of 3, 4, 5 and 6 records in each of seven sets. Included also are sets Best1 and Best2.

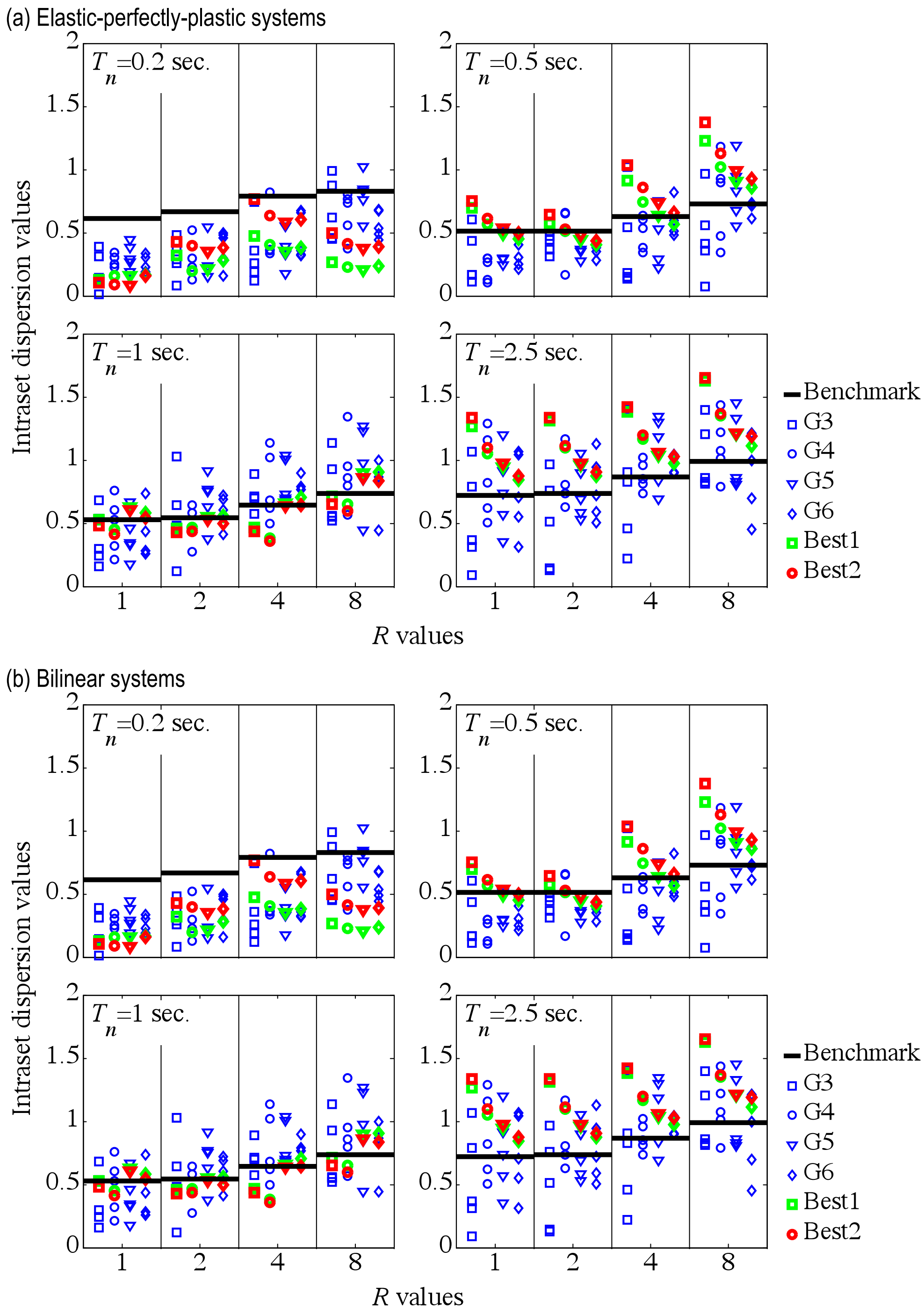


Figure 9. Comparison of benchmark and ASCE/SEI 7 intra-set (that is, within set) dispersion values for (a) elastic-perfectly-plastic, and (b) bilinear systems. G3, G4, G5, and G6 contain seven sets of 3, 4, 5 and 6 ground-motion records, respectively. Lognormal distribution is assumed.

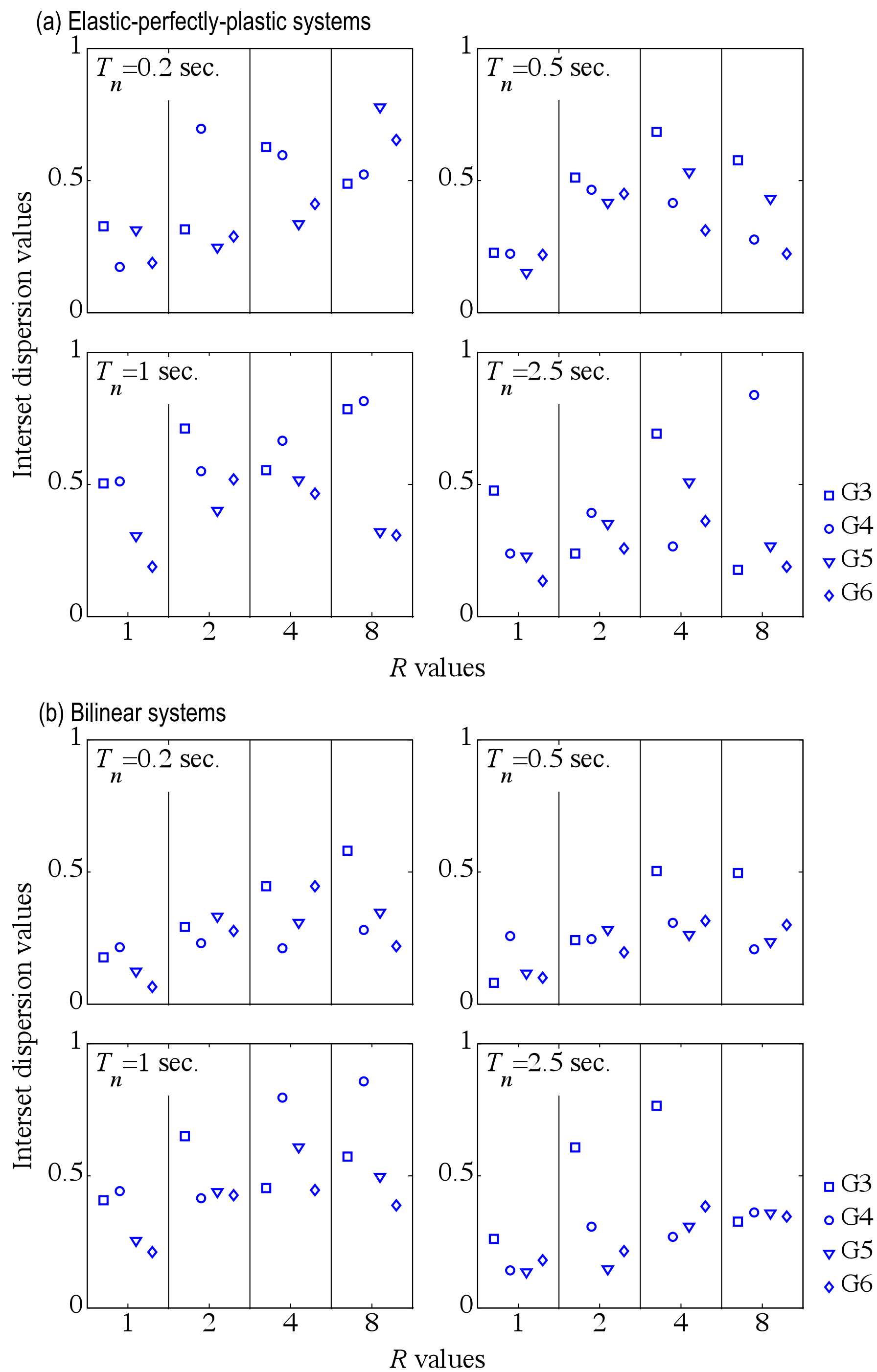


Figure 10. ASCE/SEI 7 inter-set (that is, set-to-set) dispersion values for (a) elastic-perfectly-plastic, and (b) bilinear systems. G3, G4, G5, and G6 contain seven sets of 3, 4, 5 and 6 ground-motion records, respectively. Lognormal distribution is assumed.

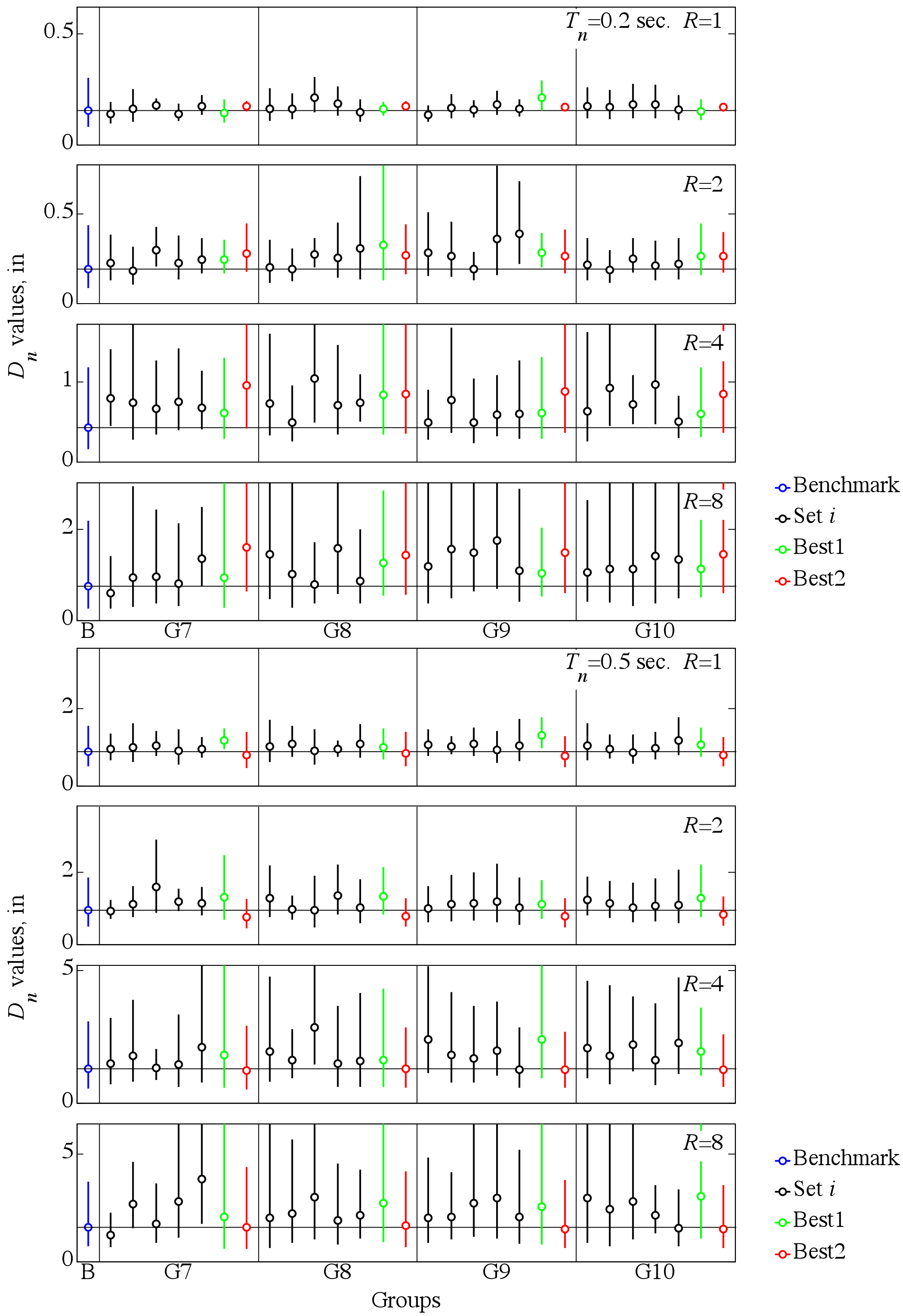


Figure 11. Range of inelastic deformation values for elastic-perfectly-plastic systems with T_n=0.2 (top four panels) and 0.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 7, 8, 9, and 10 ground-motion records denoted respectively as G7, G8, G9, and G10. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and median deformation value, respectively.

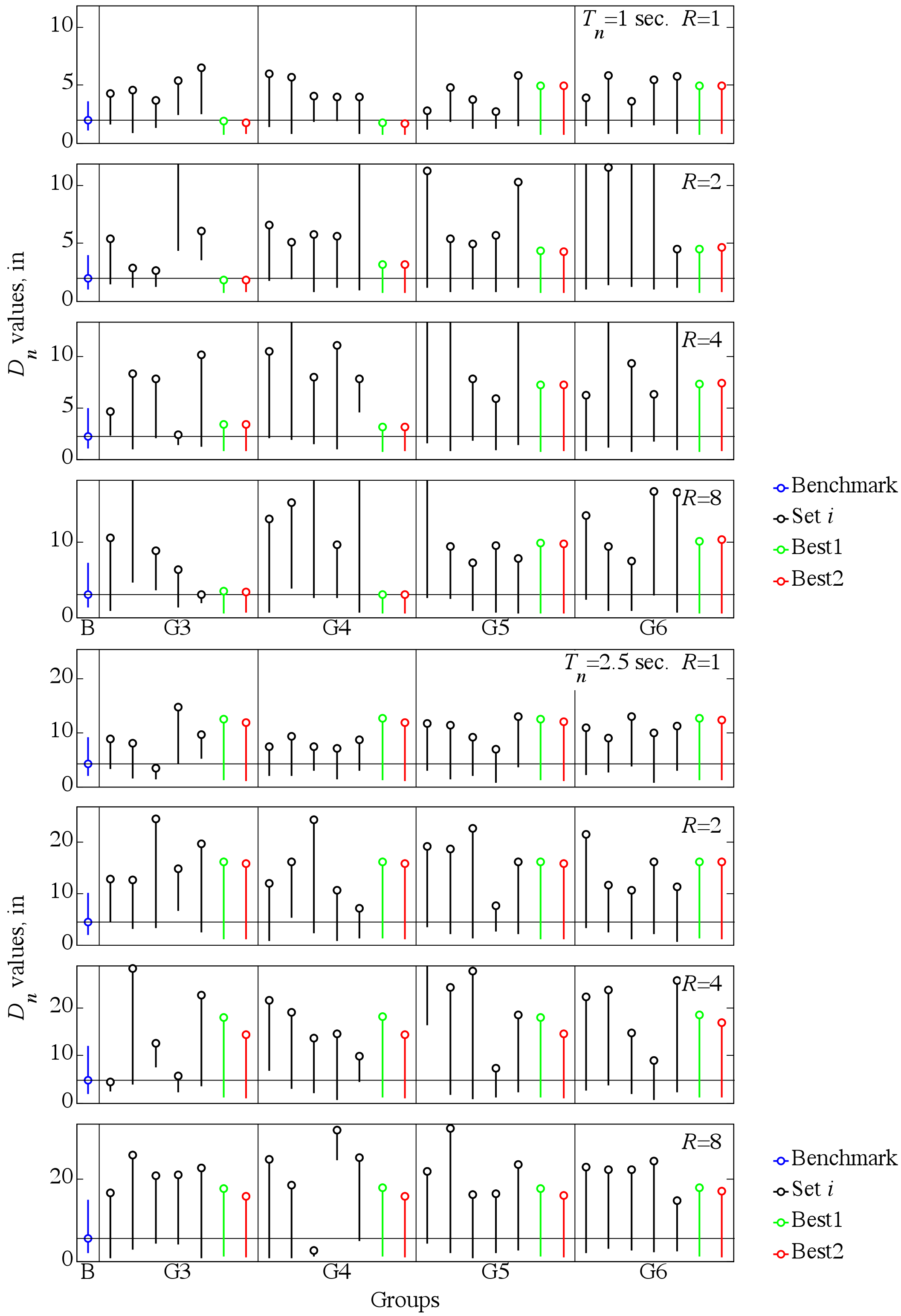


Figure 12. Range of inelastic deformation values for elastic-perfectly-plastic systems with T_n=1 (top four panels) and 2.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 7, 8, 9, and 10 ground-motion records denoted respectively as G7, G8, G9, and G10. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and median deformation value, respectively.

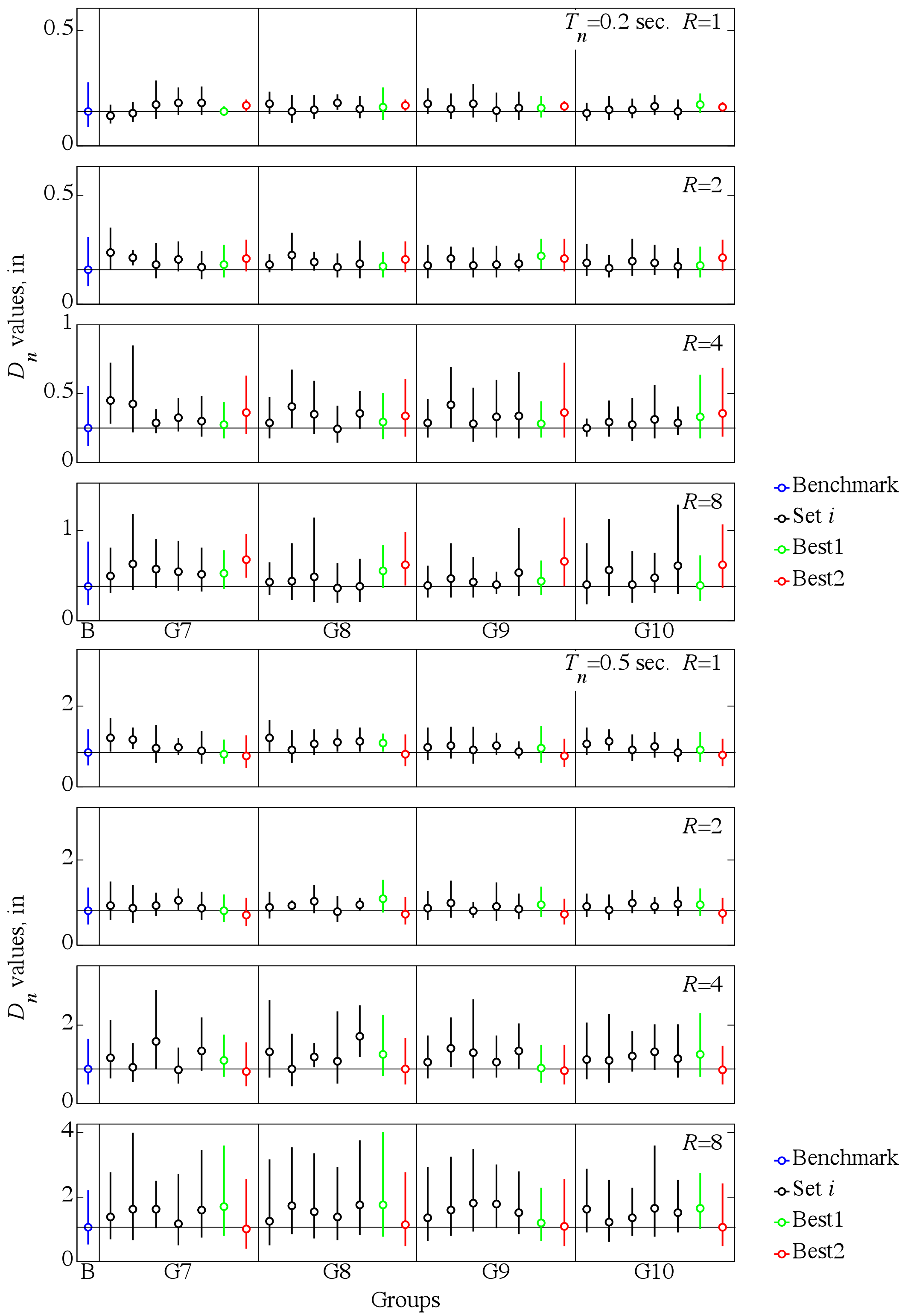


Figure 13. Range of inelastic deformation values for bilinear systems with T_n=0.2 (top four panels) and 0.5 s (bottom four panels), and R=1, 2, 4, and 8 for sets of 7, 8, 9, and 10 ground-motion records denoted respectively as G7, G8, G9, and G10. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and median deformation value, respectively.

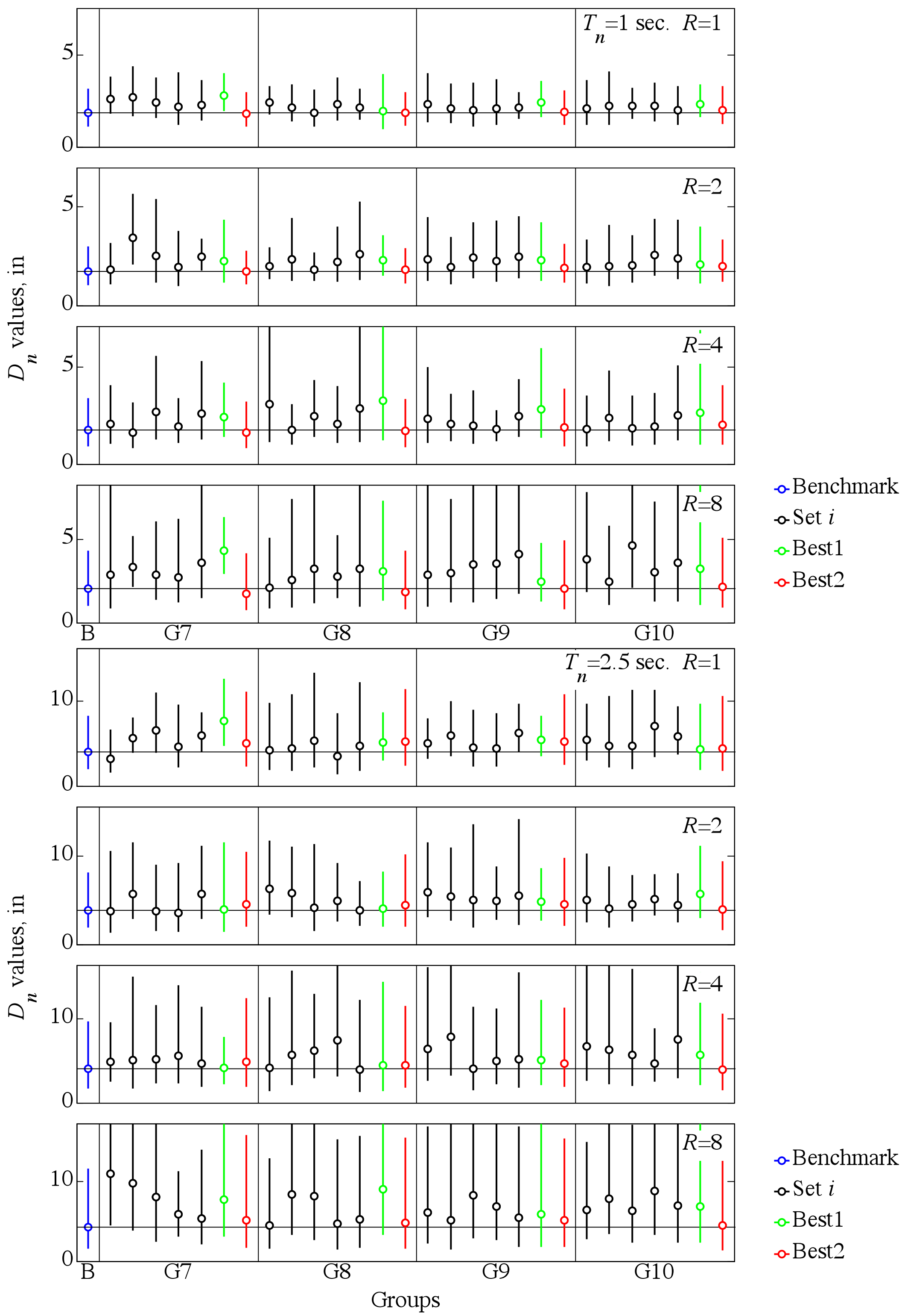


Figure 14. Range of inelastic deformation values for bilinear systems with T_n=1 (top four panels) and 2.5 sec (bottom four panels), and R=1, 2, 4, and 8 for sets of 7, 8, 9, and 10 ground-motion records denoted respectively as G7, G8, G9, and G10. The blue dot and the vertical line represent the benchmark (B) median deformation value $\pm\sigma$ assuming a lognormal distribution. For each set, the vertical line and the dot represent the range of the data set and median deformation value, respectively.

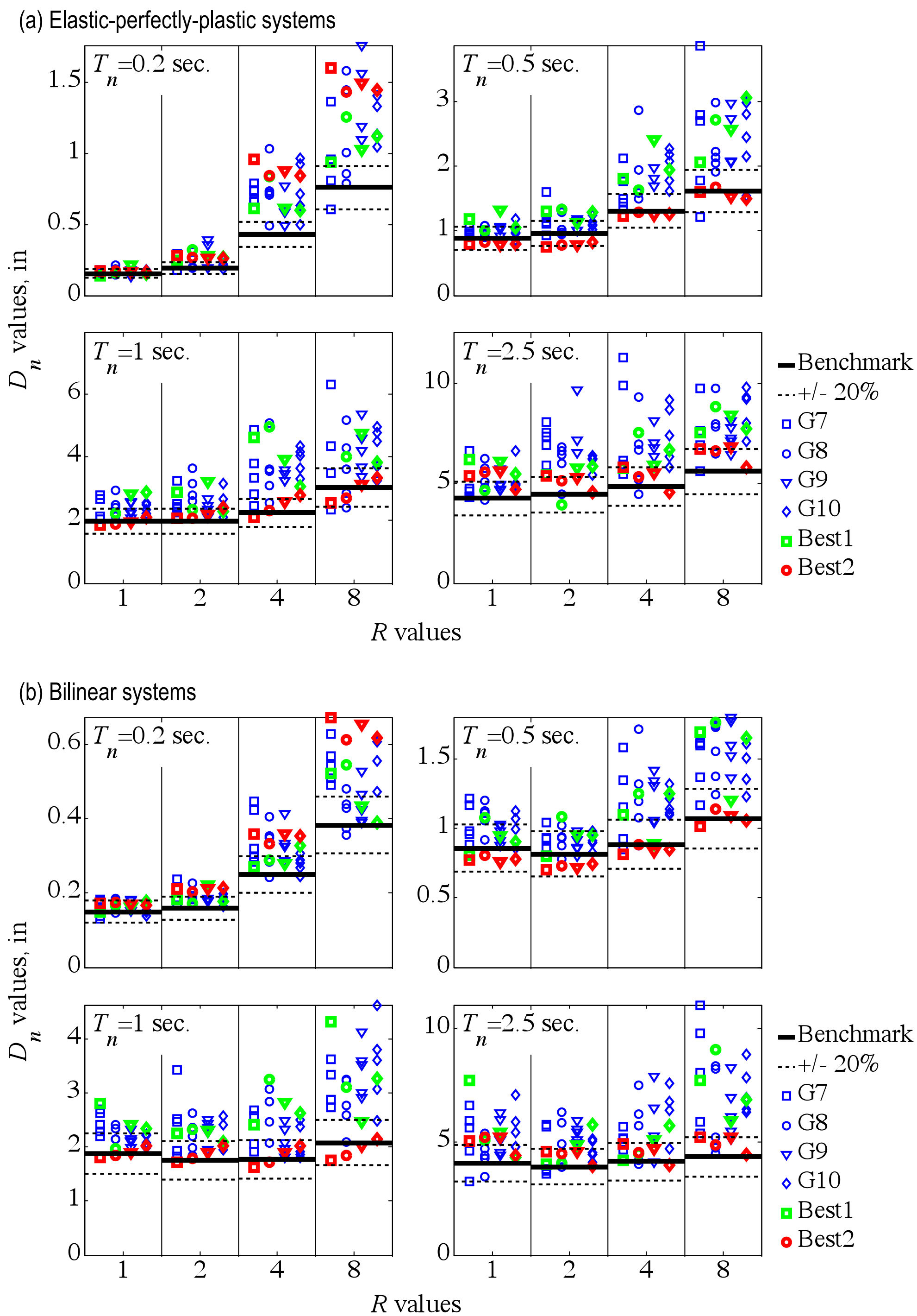


Figure 15. Benchmark and ASCE/SEI 7 deformation values for (a) elastic-perfectly-plastic, and (b) bilinear systems. The benchmark EDPs correspond to the median of 30 deformation values. The deformation values for each set scaled by the ASCE/SEI 7 procedure are obtained as the <u>median</u> of 7, 8, 9, and 10 deformation values. Included also are sets Best1 and Best2.

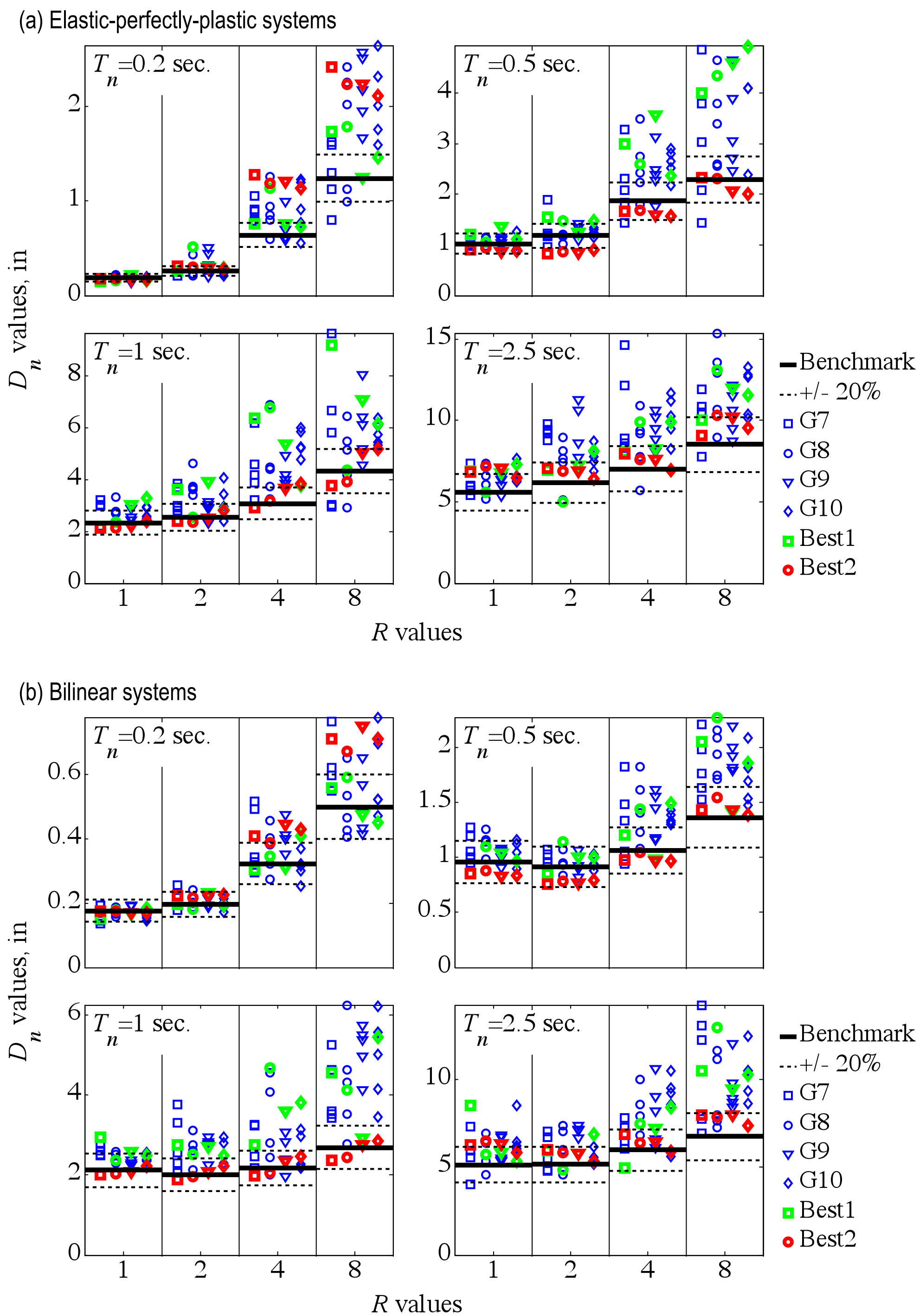
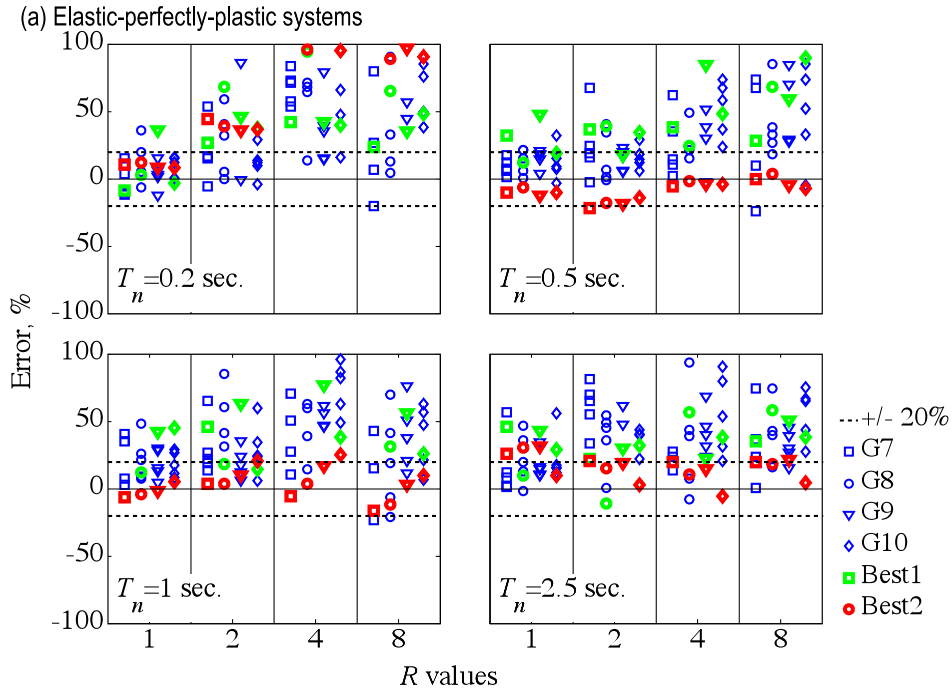


Figure 16. Benchmark and ASCE/SEI 7 deformation values for (a) elastic-perfectly-plastic, and (b) bilinear systems. The benchmark EDPs correspond to the mean of 30 deformation values. The deformation values for each set scaled by the ASCE/SEI 7 procedure are obtained as the <u>mean</u> of 7, 8, 9, and 10 deformation values. Included also are sets Best1 and Best2.



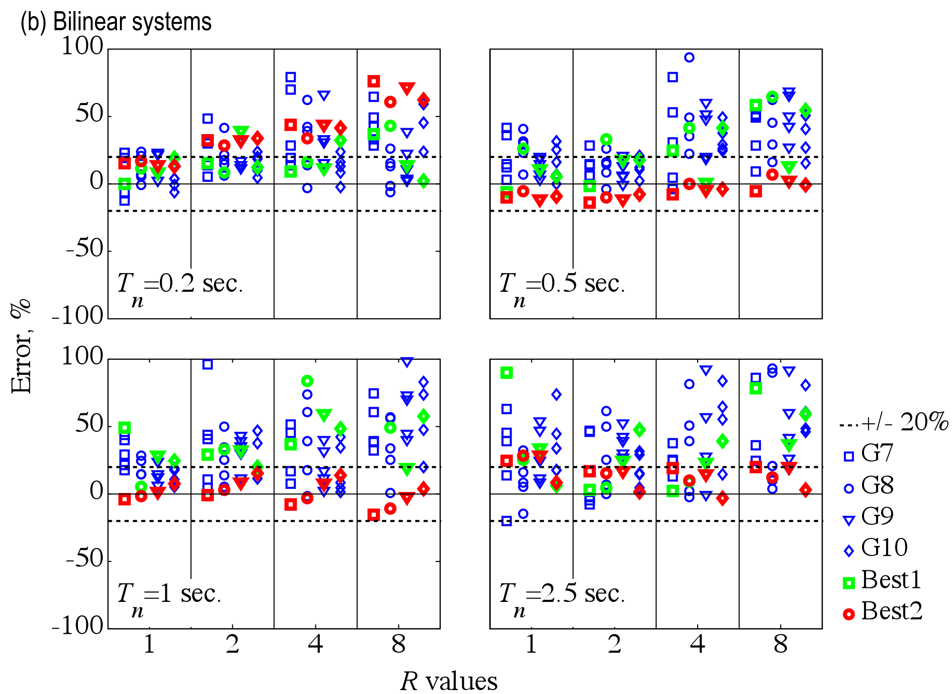


Figure 17. Error in the estimation of median deformation values for (a) elastic-perfectly-plastic and (b) bilinear systems. The benchmark EDPs correspond to the <u>median</u> of 30 deformation values. The deformation values for each set scaled by the ASCE/SEI 7 procedure are obtained as the <u>median</u> of 7, 8, 9, and 10 deformation values. Included also are sets Best1 and Best2.

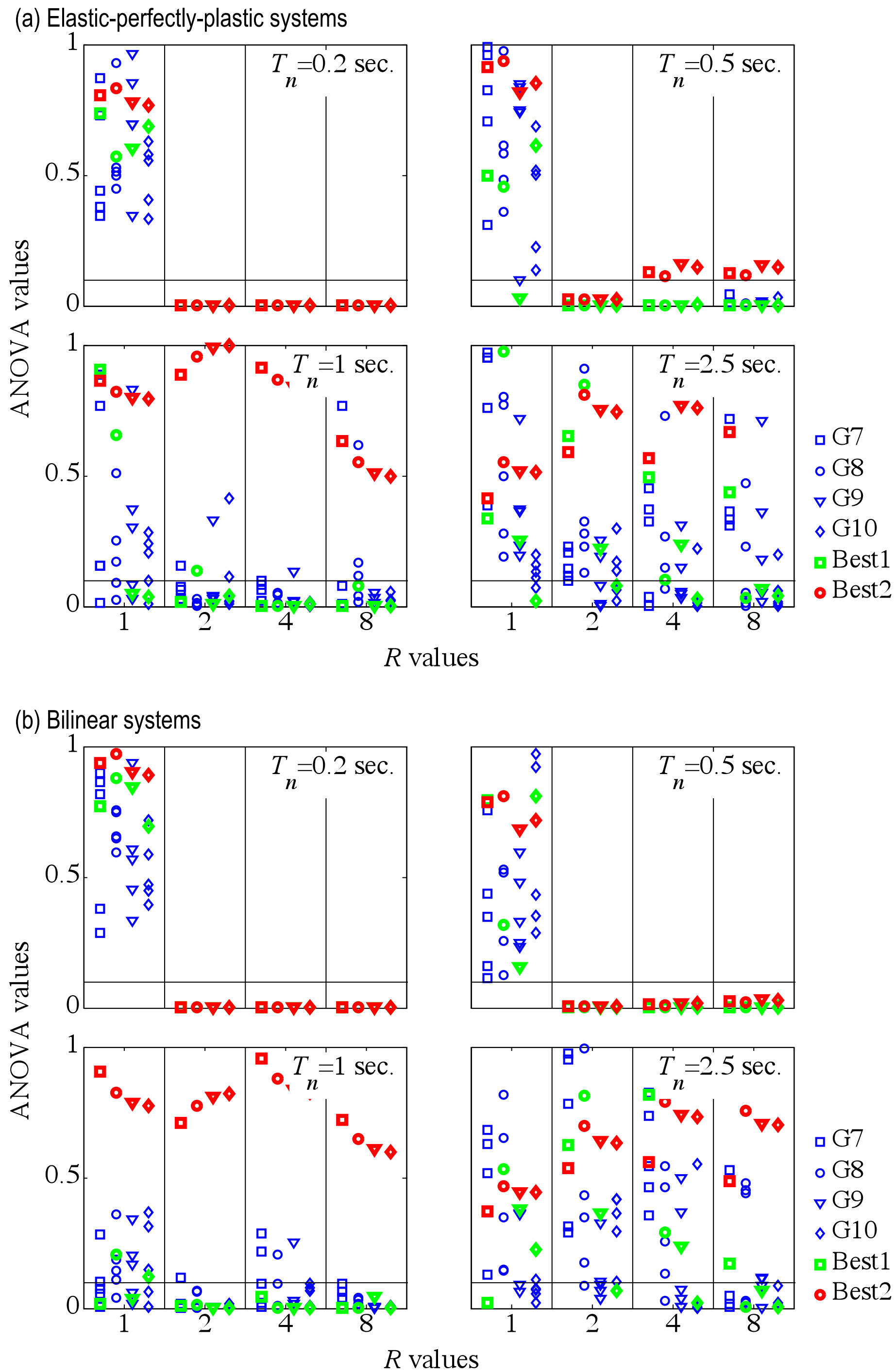


Figure 18. ANOVA values for (a) elastic-perfectly-plastic, and (b) bilinear systems. The ANOVA test compares deformation values from each set against the benchmark deformation values.

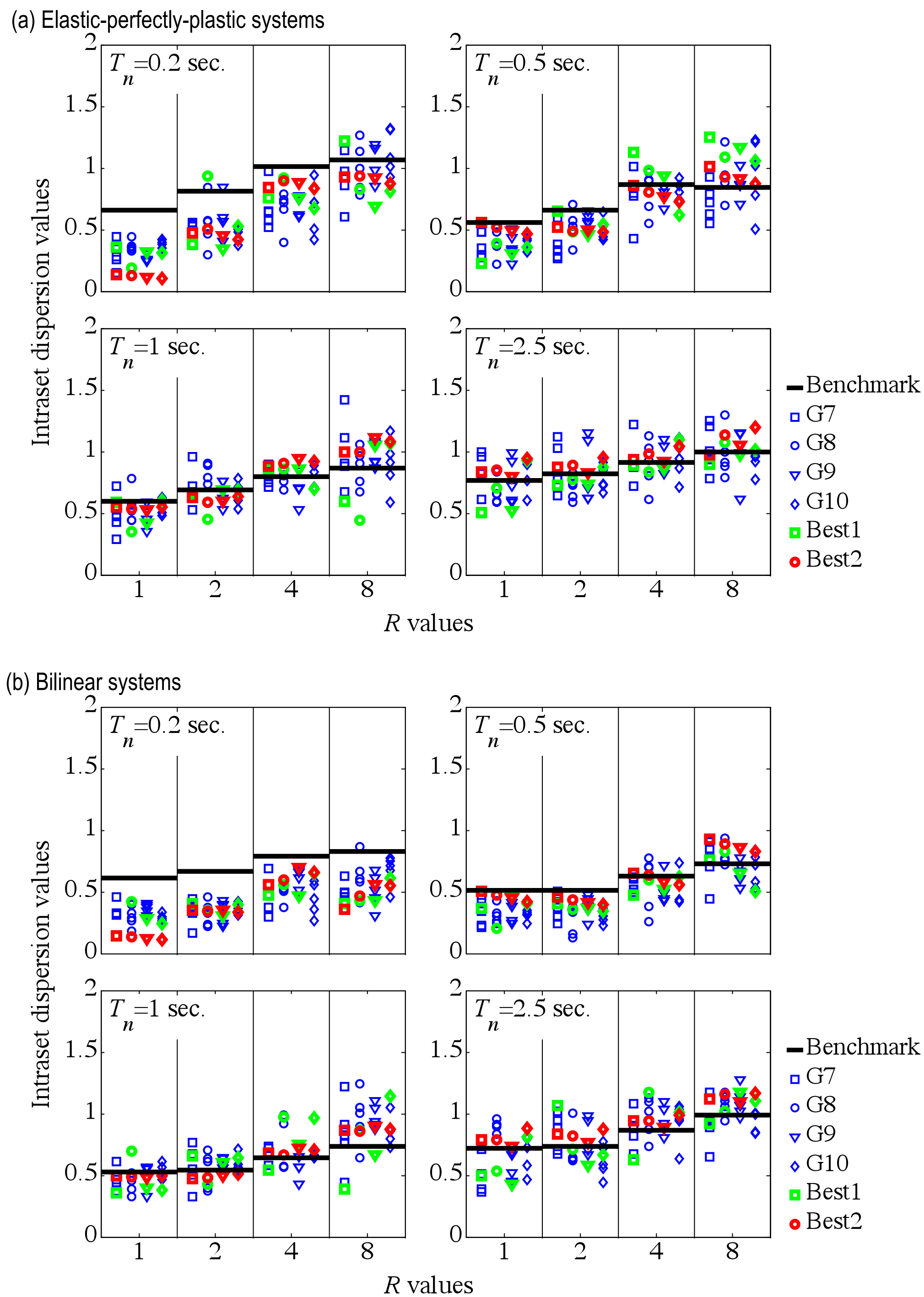
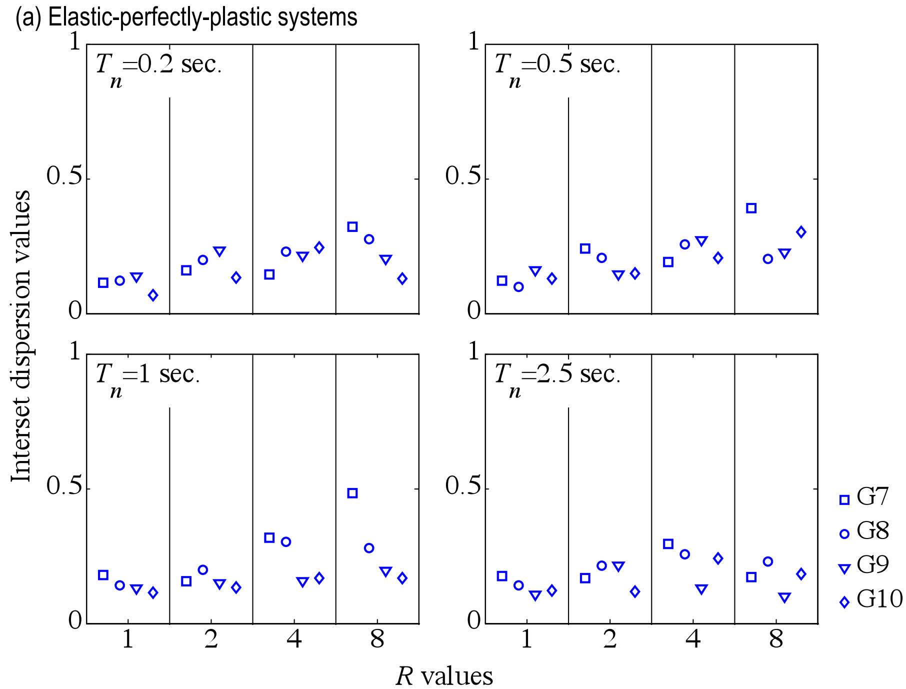


Figure 19. Benchmark and ASCE/SEI 7 intra-set dispersion values for (a) elastic-perfectly-plastic, and (b) bilinear systems. Lognormal distribution is assumed.



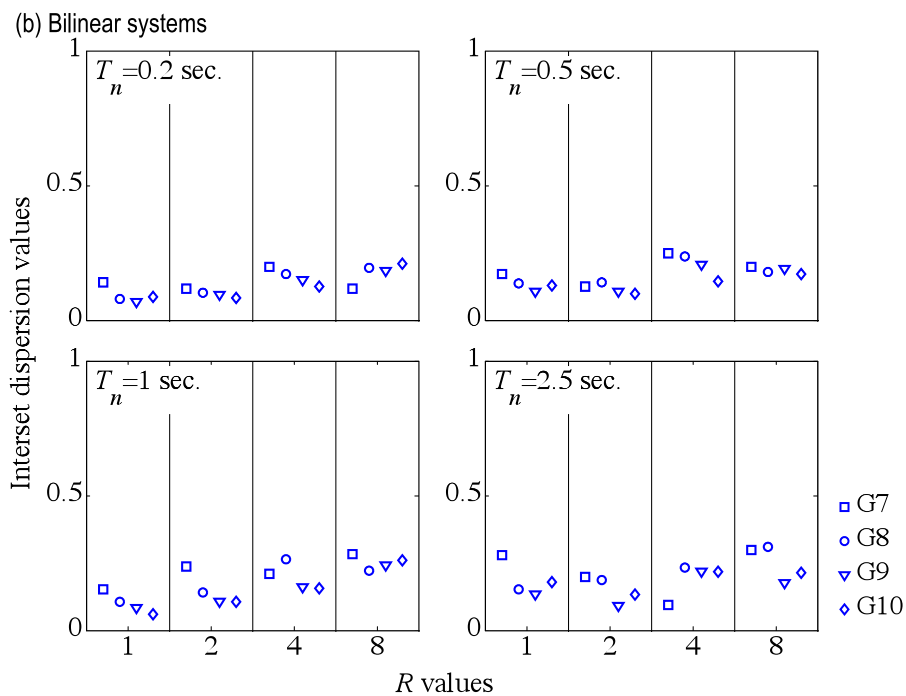


Figure 20. ASCE/SEI 7 inter-set dispersion values for (a) elastic-perfectly-plastic, and (b) bilinear systems. Lognormal distribution is assumed.