

COMPARISON BETWEEN NZS 1170.5 SEISMIC DESIGN SPECTRA AND HYSTERESIS-DAMPED SPECTRA

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ABSTRACT

This study aims to provide a comparison and identify the key distinctions between the New Zealand Standard – Earthquake Actions (NZS 1170.5: 2004) seismic design spectra and the hysteresis-damped seismic demand spectra specified by either the New Zealand Society for Earthquake Engineering (NZSEE) “Assessment and Improvement of the Structural Performance of Buildings in Earthquakes” (AISPBE) Guidelines, or the “Displacement-Based Seismic Design of Structures” (DBSDS) textbook by Priestley et al. (2007). The damping provided by the draft document, “The Seismic Assessment of Existing Buildings” (TSAEB), was also briefly discussed. The seismic design spectrum was calculated for various levels of ductility using all three methods and compared against each other. This was performed for structural elastic periods from 0.1 to 4.5 seconds. For a given set of requirements based on the NZS 1170.5 parameters, a representative acceleration-displacement hysteresis loop has been generated. The equivalent viscous damping was then calculated based on the area under this hysteresis using the recommendations of either the AISPBE or through the damping equations based on the DBSDS. The final damped spectra were then compared with each other and against the NZS 1170.5 design spectrum. Results indicate good correlation between the NZS 1170.5 design spectra and the damped design spectra at low levels of ductility but show significant disparities at higher levels of ductility.

INTRODUCTION

The New Zealand Society for Earthquake Engineering (NZSEE) has published a document entitled “Assessment and Improvement of the Structural Performance of Buildings in Earthquakes” (AISPBE) to serve as a set of guidelines for the seismic assessment of New Zealand buildings. The document provides the customary force-based approach for comparing the calculated capacity of an existing structure with the New Zealand Standard – Earthquake Actions (NZS 1170.5: 2004) requirements. The AISPBE also provides an alternative displacement-based approach, which references the Applied Technology Council Report ATC-40, “Seismic Evaluation and Retrofit of Concrete Buildings” 1996, and the journal paper by Pekcan, Mander and Chen, “Fundamental Considerations for the Design of Nonlinear Viscous Dampers” 1999, for calculation of hysteretic damping. The author observed large disparities in the outputs between the force-based and displacement-based methods for some structure types and decided to conduct a series of calculations to quantify these discrepancies. The textbook “Displacement-Based Seismic Design of Structures” (DBSDS) by Priestley, Calvi and Kowalski (2007) also presented a series of equations for analysis of structural hysteretic damping. This has also been considered for comparison to broaden this study further.

BACKGROUND TO THE STUDY

This study was initiated to quantify the discrepancies observed by the author between the results of force-based against displacement-based seismic assessments of structures following the procedures presented in the NZSEE-AISPBE document. This study is based mainly on calculations of the New Zealand seismic demand as defined by the two main references, namely NZS 1170.5 which is the current Standard for the design of new structures, and NZSEE-AISPBE, which

is the widely-accepted industry guideline for the assessment of existing structures. The textbook DBSDS has also been considered in this study, as the displacement-based methodology proposed in that book is gaining popularity in New Zealand. The draft document entitled, “The Seismic Assessment of Existing Buildings” (TSAEB), which is intended to replace AISPBE when finalized, provides updated hysteretic damping values which have also been briefly discussed in this study. These references are discussed below.

NZS 1170.5: 2004 – New Zealand Standard – Earthquake Actions

NZS 1170.5 specifies a set of equations and spectra that serve as the current basis for quantifying seismic demand of structures in New Zealand. It defines several 5% damped spectra that represent the spectral shape factors, $C_h(T)$, for discrete structure periods, T , for five different types of site subsoils (see Figure 1). The spectral shape factors are also defined differently for the equivalent static method (ESM) and the modal response spectrum (MRS) or numerical integration time history (NITH) analysis methods. These spectral shape curves are then modified by the hazard factor, return period factor, and near-fault factor to calculate the elastic site hazard spectrum, $C(T)$, which is specific to a structure. The final design spectrum is then calculated from this elastic spectrum together with the ductility factor, μ , and the structural performance factor, S_p . These factors directly scale the design acceleration up and down the acceleration period graph.

$$C_d(T) = \frac{C(T) S_p}{k_\mu} \quad (1a)$$

For equal-displacement approach:

$$k_\mu = \mu \quad \text{for } T \geq 0.7s \quad (1b)$$

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For equal-energy approach:

$$k_{\mu} = \frac{(\mu-1)}{0.7}T + 1 \quad \text{for } T < 0.7\text{s, soil type A-D} \quad (1c)$$

$$k_{\mu} = (\mu - 1.5)T + 1.5 \quad \text{for } T < 0.7\text{s, soil type E} \quad (1d)$$

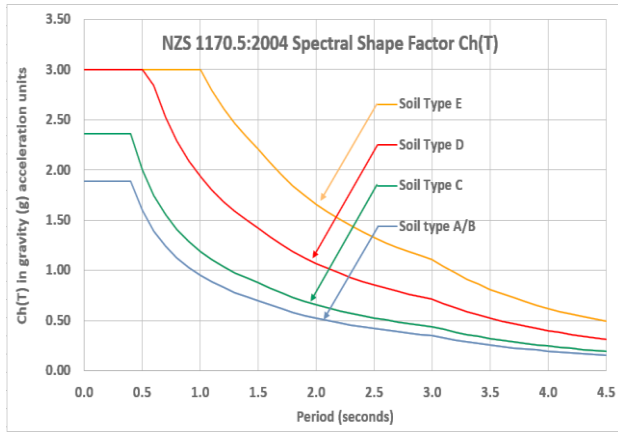


Figure 1: NZS 1170.5: 2004 Spectra shape factor, $C_h(T)$.

The Standard adopts an “equal-displacement” and an “equal-energy” approach in calculating the design spectrum. This is dependent on the fundamental period or elastic period, which is based on the 1st mode natural frequency of the structure prior to occurrence of plastic deformations. This approach can be visualized by converting the acceleration-period graph into an acceleration-displacement graph (see Figures 2a and 2b). It should be noted that the Standard does not explicitly promote the calculation of a displacement spectrum from the acceleration spectrum. This is achieved through first principles by adopting the simple harmonic motion relationship between period (T), acceleration (S_a), and displacement (S_d) as noted in Equations 2a to 2c.

$$S_d = S_a / \omega^2 \quad (2a)$$

$$\omega = 2\pi / T \quad (2b)$$

$$T = 2\pi \sqrt{S_d / S_a} \quad (2c)$$

The “equal-displacement” approach is applicable for periods equal to or greater than 0.7 seconds. The approach equates the design displacement, Δ_d , as equal to the elastic displacement. It calculates the design acceleration coefficient, $C_d(T)$, by directly dividing the elastic acceleration coefficient, $C(T)$, by the ductility factor, μ . An idealized bilinear elasto-plastic curve representing this approach can thus be plotted in an acceleration-displacement graph as shown in Figure 2a.

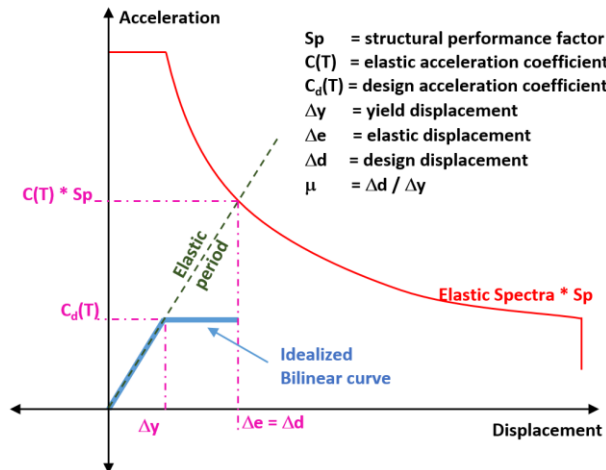


Figure 2a: Equal displacement approach.

The “equal-energy” approach is applicable for elastic periods less than 0.7 seconds. The approach, in theory, equates the area under the elastic force-displacement response with the area under the inelastic response. However, the Standard does not fully match the area and has a ratio of inelastic response over elastic response less than unity. The NZS 1170.5 Commentary discusses this in further detail. For purposes of this analysis, the design acceleration is taken by dividing the elastic acceleration by the k_{μ} factor (see Equations 1c and 1d); the yield displacement is calculated from the elastic period (as per Equation 2c) and design acceleration, and the design displacement is taken as the yield displacement multiplied by the ductility factor.

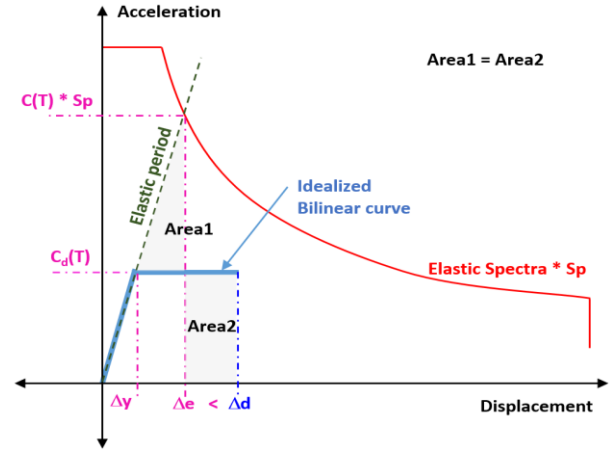


Figure 2b: Equal energy approach.

NZSEE-AISPBE

The New Zealand Society for Earthquake Engineering (NZSEE) “Assessment and Improvement of the Structural Performance of Buildings in Earthquakes” (AISPBE) Guidelines provide a set of procedures for conducting seismic assessments on existing buildings. It provides a force-based and displacement-based method. Both methods use the NZS 1170.5 Standard for defining the elastic seismic actions. The difference between the force-based and displacement-based methods transpires based on how the ductility relates to the reduction of the elastic demand spectra. The force-based method follows the NZS 1170.5 standard discussed above which divides the elastic spectrum depending on the ductility while the displacement-based method reduces the elastic spectrum through equivalent viscous damping. The damping, however, is still a function of the ductility. AISPBE has referenced Pekcan et al. (1999) for calculation of the equivalent viscous damping ξ_e expressed as a fraction of critical damping (see Equation 3).

$$\xi_e = \xi_o + \xi_{hys} + \xi_d = \xi_o + \frac{2}{\pi} \eta \frac{(1-\alpha_s)(1-1/\mu)}{(1-\alpha_s + \mu\alpha_s)} + \xi_d \quad (3)$$

Where, ξ_o = inherent viscous damping, taken as 5% for this study

ξ_{hys} = hysteretic damping

ξ_d = added damping due to supplemental dampers, taken as zero for this study

μ = displacement ductility, ranging from 1.0 to 6.0

α_s = post-yield to initial yield stiffness ratio, taken as zero for this study

η = efficiency factor

The efficiency factor is a function of the ratio between an approximate area of the actual hysteresis curve over a perfect bilinear hysteresis curve (see Figure 3). This is dependent on the structure type, material, and ductility of the system. AISPBE provides the empirical values as shown in Table 1.

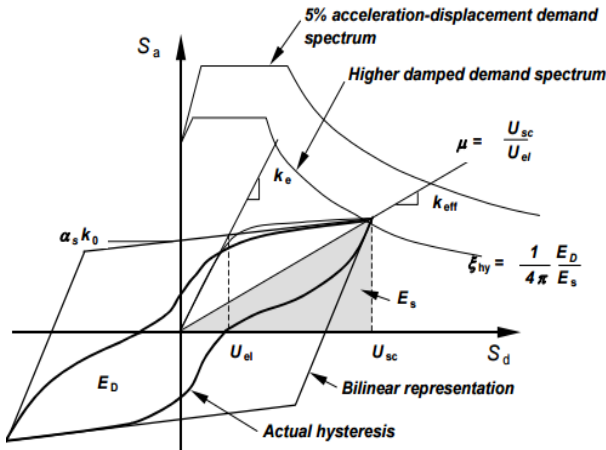


Figure 3: AISPBE - Bilinear curve and hysteretic damping.

Table 1: AISPBE - Typical damping values.

Material	Structural Type	μ	η	ξ_e (for $\alpha_s = 0$)
Concrete	Ductile	6	0.35	0.24
	Limited Ductile	3	0.3	0.18
	Limited Ductile	2	0.25	0.13
	Nominally Ductile	1.25	0.2	0.08
Timber	Limited Ductile	3	0.15	0.11
Steel	Ductile	6	0.65	0.39
	Limited Ductile	3	0.4	0.22
All	Rocking Walls	3	0.15	0.11

The efficiency factor, and thus the equivalent viscous damping, can vary significantly, depending upon the material, as seen in Table 1. This contrasts with the NZS 1170.5 where the demand reduction remains the same irrespective of the material.

The scaling factor to be applied to the elastic spectrum to calculate the damped spectra is calculated from the commonly used equation below, where the equivalent viscous damping ξ_e is a percentage (%) of critical damping.

$$K_\xi = \left(\frac{7}{2 + \xi_e} \right)^{0.5} \quad (4)$$

DBSDS – Damped Spectra

A series of simplified equations have been provided in the “Displacement-Based Seismic Design of Structures” (DBSDS) textbook by Priestley et al. (2007). This reference relates ductility to structural hysteretic damping. The inherent damping is also taken as 5%. The equations for equivalent viscous damping, expressed as a fraction of critical damping, adopted in this study are as follows:

$$\text{RC wall buildings / bridges: } \xi_e = 0.05 + 0.444 [(\mu - 1) / \mu\pi] \quad (5)$$

$$\text{RC frame buildings: } \xi_e = 0.05 + 0.565 [(\mu - 1) / \mu\pi] \quad (6)$$

$$\text{Steel frame buildings: } \xi_e = 0.05 + 0.577 [(\mu - 1) / \mu\pi] \quad (7)$$

The calculated damping for typical ductilities are shown in Table 2. The DBSDS is observed to have lower damping compared to AISPBE considering $\alpha_s = 0$. The scaling factor used to calculate the damped spectra is the same as Equation 4.

TSAEB – Damped Spectra

At the time of writing this paper, a draft document, “The Seismic Assessment of Existing Buildings” (TSAEB), has been made available for engineering briefings. This document is intended to replace the NZSEE-AISPBE once finalised. It

has retained both the force-based and displacement-based approach and has provided an updated set of hysteretic damping values for a wider range of material and structure types. It is noted that the TSAEB ξ_{hys} damping values provided for H and M-H levels (see Table 3) are identical to the DBSDS damping for frame and wall buildings respectively. Two other levels (M and L) provide lower damping values. The TSAEB has lower damping values than the AISPBE, which equate to an increase in seismic demands for a displacement-based approach once implemented.

Table 2: DBSDS – Typical damping values.

Structure / Material	μ	ξ_0	ξ_{hys}	ξ_e
RC wall buildings / bridges	6	0.05	0.118	0.168
	3	0.05	0.094	0.144
	2	0.05	0.071	0.121
	1.25	0.05	0.028	0.078
RC frame buildings	6	0.05	0.150	0.200
	3	0.05	0.120	0.170
	2	0.05	0.090	0.140
	1.25	0.05	0.036	0.086
Steel frame buildings	6	0.05	0.153	0.203
	3	0.05	0.122	0.172
	2	0.05	0.092	0.142
	1.25	0.05	0.037	0.087

Table 3: TSAEB – Typical damping values.

Assessed level of hysteretic energy dissipation available	μ	ξ_{hys}	Applicable structural systems / mechanisms
H (high)	6	0.15	- Concrete frame (deformed bars) - Steel frame with rigid connections
	3	0.12	
	2	0.10	
	1.25	0.03	
	≤ 1	0.00	
M-H (medium to high)	6	0.12	- Concrete wall - Lightweight timber frame - Shallow footing rocking systems - Steel EBFs
	3	0.10	
	2	0.07	
	1.25	0.03	
	≤ 1	0.00	
M (medium)	6	0.10	- Steel frame with flexible connections - Steel CBFs - Concrete frame (plain bars) - URM system
	3	0.08	
	2	0.06	
	1.25	0.02	
	≤ 1	0.00	
L (low)	6	0.05	- Hybrid prestressed concrete frame - Rocking system
	3	0.04	
	2	0.03	
	1.25	0.02	
	≤ 1	0.00	

ANALYSIS METHODOLOGY

In order to present a proper comparison, the damped design spectra should be directly related to the NZS 1170.5 design spectra. This is performed by representing ductile structures that have been designed to NZS 1170.5 design loadings as single-degree-of-freedom (SDOF) systems which are then idealized as bilinear curves on an acceleration-displacement graph. Each bilinear curve would have an elastic component from origin to a yield acceleration and yield displacement, then a plastic component which is assumed to have zero post-elastic slope with the acceleration as constant and only the displacement increasing. The ultimate displacement is taken as the yield displacement multiplied by the ductility (see Figure 2). The relationship between the elastic period, acceleration and yield displacement is derived through the simple harmonic motion relationship as noted in Equation 2a.

A representative hysteresis shape and thus equivalent viscous damping can then be interpolated from the NZS 1170.5 idealized bilinear curve (see Figure 4). The damped spectra

can then be calculated by multiplying the elastic spectra with the reduction factor K_{ξ} (see Equation 4). The effective period represents the decrease in stiffness as the structure undergoes plastic deformation. This is calculated based on Equation 2 above using the idealized elasto-plastic design displacement, Δ_d , and design acceleration, $C_d(T)$. The intersection of the effective period with the damped spectrum defines the design acceleration and displacement response of the damped system. These can then be compared with the NZS 1170.5 idealized bilinear design acceleration and displacement. This process is repeated across the period range of 0.4 to 4.5 seconds and ranging from ductility 1.25 to 6.0 for both NZSEE and DBSDS damping approaches.

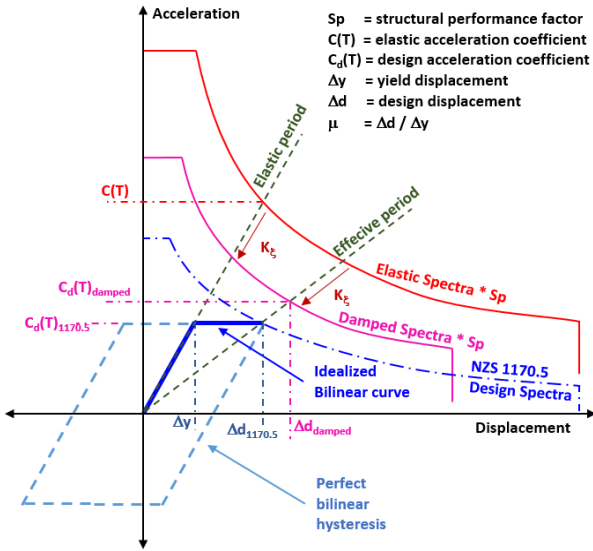


Figure 4: Damped spectra graphical representation.

The seismic parameters adopted in this study are as follows:

- Site subsoil class = Type D
- Hazard Factor, Z = 0.4
- Risk Factor, R = 1.0
- Near-fault Factor, N(T,D) = 1.0
- Structural Performance Factor, $S_p = 1.3 - 0.3\mu$ (for $\mu \leq 2$)
 $= 0.7$ (for $\mu > 2$)

A Type D site subsoil class is selected for this study since the spectral shape factors for the ESM and the MRS or NITH methods are identical for this subsoil class.

The Z, R and N(T,D) factors define the elastic spectra demand but do not influence the comparison between the NZS 1170.5 design spectra and the damped design spectra. These values can change but the ratio between the different design spectra will remain the same.

The Structural Performance Factor, S_p , is a reduction coefficient to allow for effects that are not explicitly represented by the other design spectra factors (e.g. higher material strength, strain hardening, redundancy, damping from non-structural elements and foundations, maximum acceleration occurring only once during duration of shaking, etc.). It can be applied for both the force-based and displacement-based method as specified in the AISPBE. There is no mention of this or any similar factor in the DBSDS Textbook. For the purpose of this study, it is universally applied to all the spectra, namely the NZS 1170.5, damped AISPBE, TSAEB, and DBSDS spectra. This ensures consistency of results among all methods.

Material strength reduction factors are universally applied as unity for all methods to minimize inconsistency of results.

ANALYSIS RESULTS

The calculated seismic demand spectra for the three methods, NZS 1170.5 spectra, AISPBE damped spectra, and DBSDS damped spectra, have been compared and discussed below. The demand spectra from NZS 1170.5 and the hysteretic-damped spectra are plotted in three different formats, namely, acceleration-period, displacement-period and acceleration-displacement graphs. Tables of outputs have also been presented.

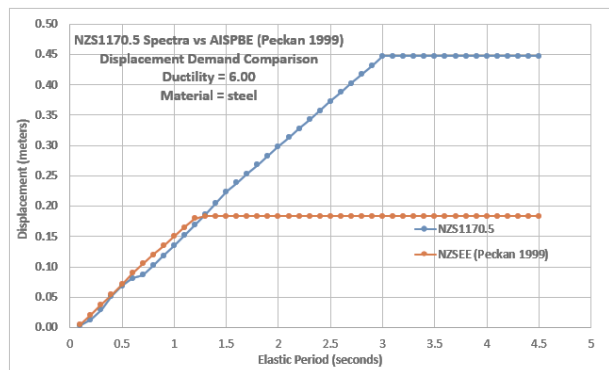
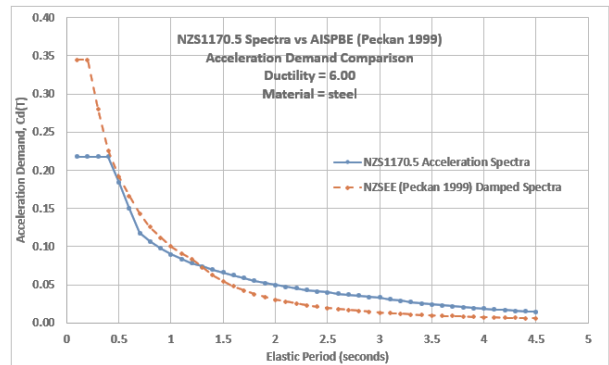
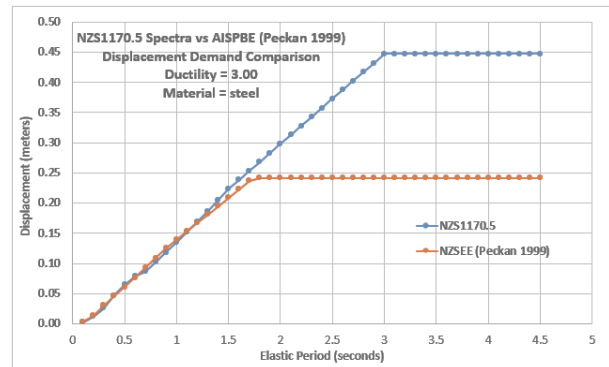
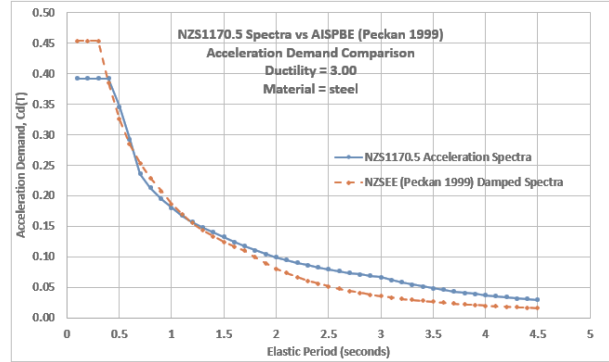


Figure 5a: NZS 1170.5 and AISPBE (steel) spectra demand comparison.

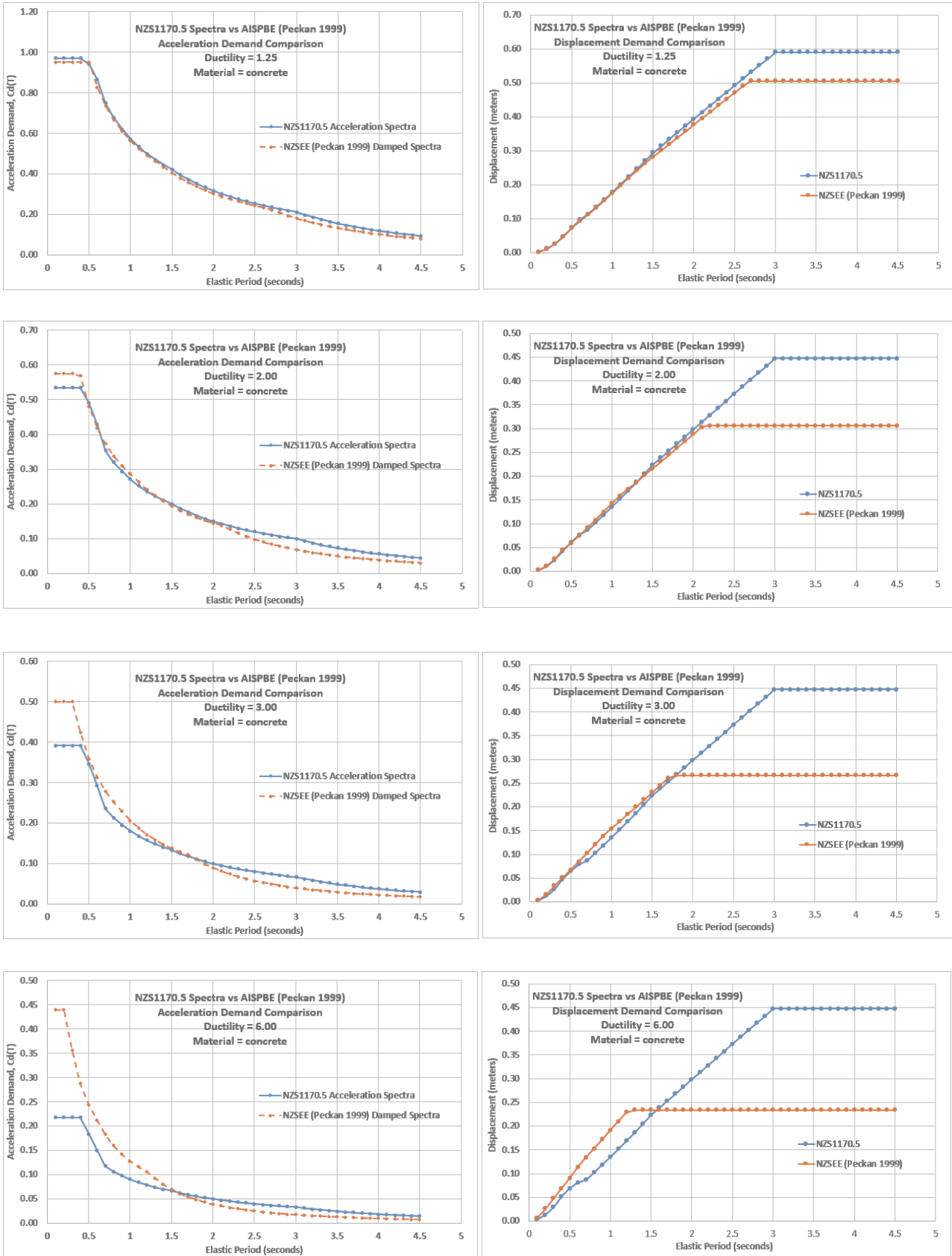


Figure 5b: NZS 1170.5 and AISPBE (concrete) spectra demand comparison.

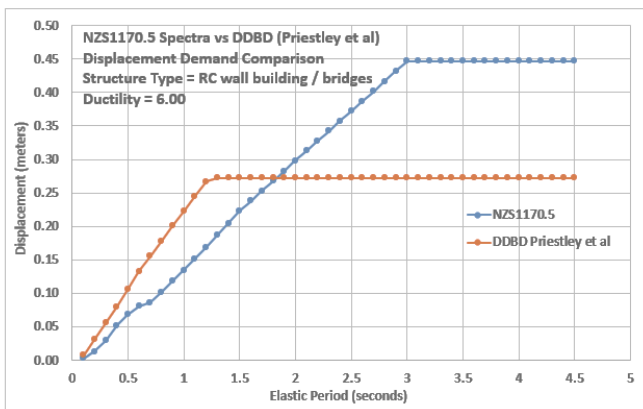
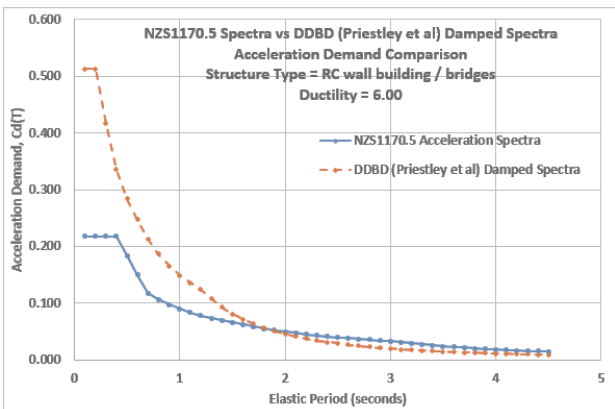
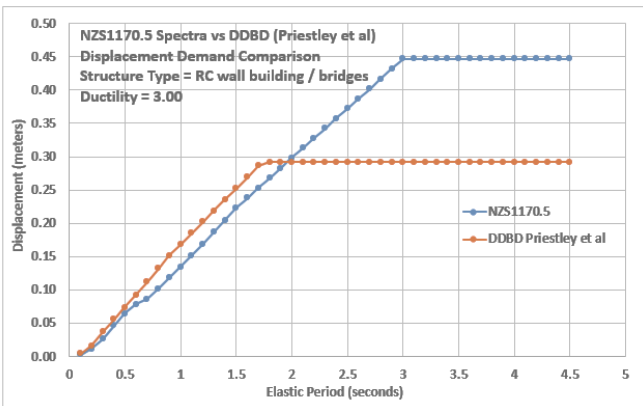
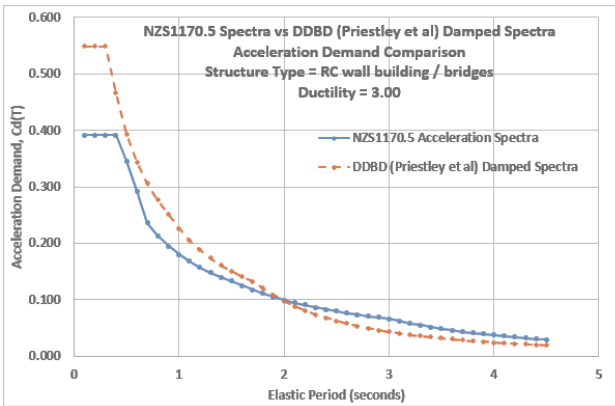
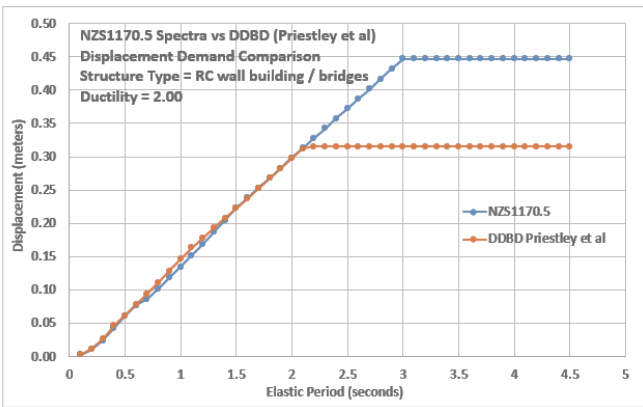
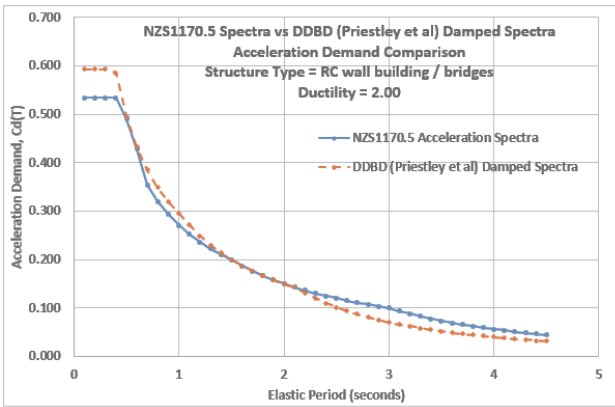
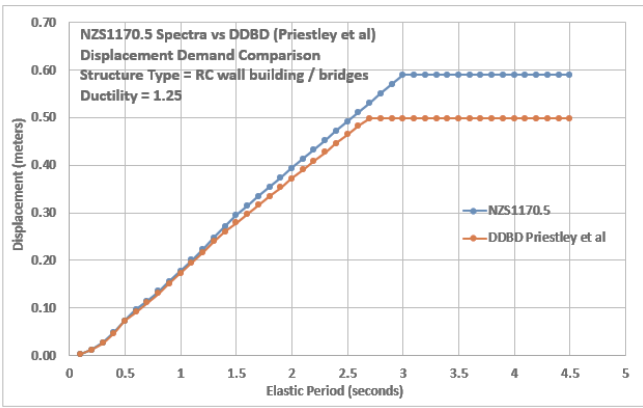
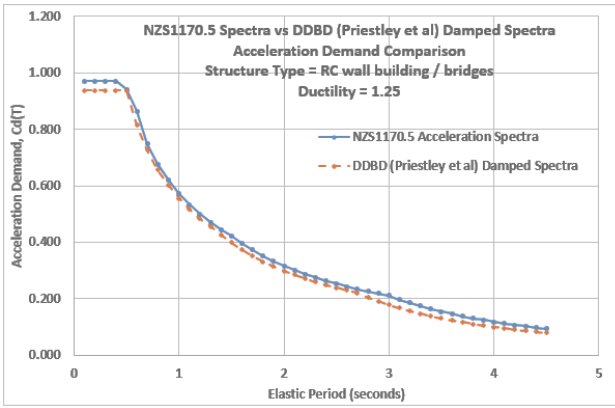


Figure 5c: NZS 1170.5 and DBSDS (RC wall building/bridges) spectra demand comparison.

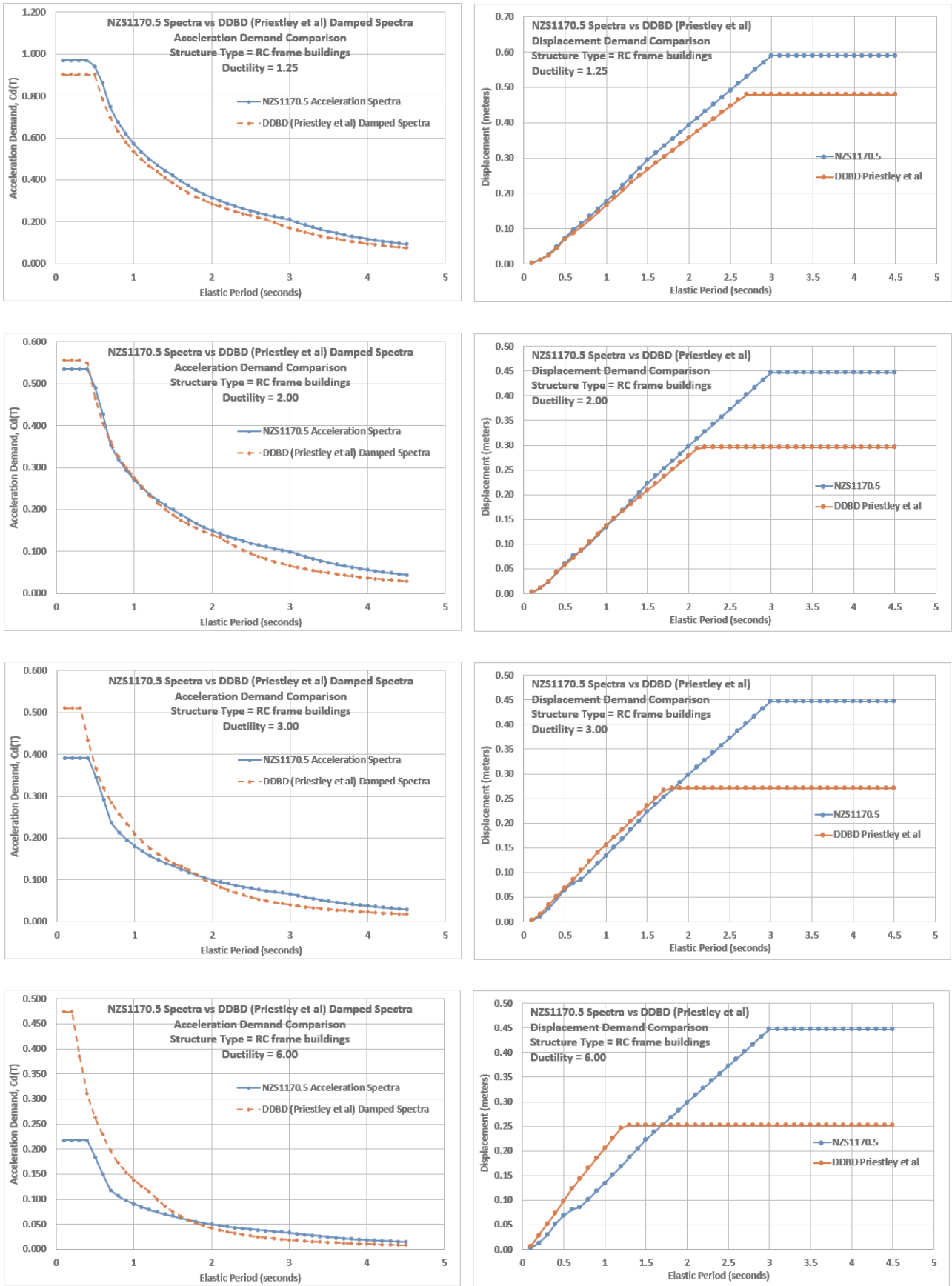


Figure 5d: NZS 1170.5 and DBSDS (RC frame buildings) spectra demand comparison.

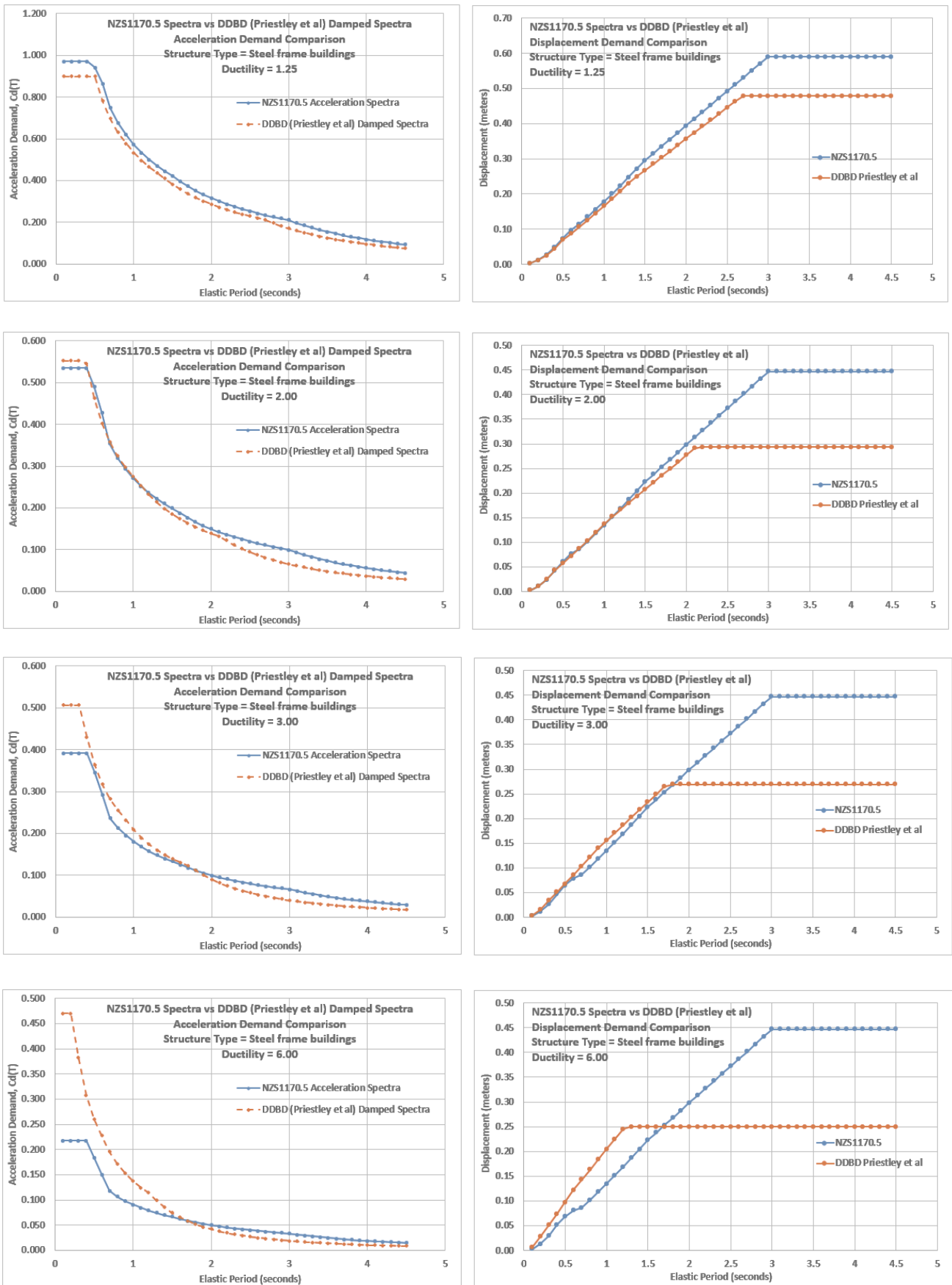


Figure 5e: NZS 1170.5 and DBSDS (steel frame buildings) spectra demand comparison.

Table 4a: Acceleration demand comparison for steel buildings ($\mu = 6.0$).

Elastic T	NZS 1170.5 ($\mu=6$)		Effective T $\mu=6$	AISPBE (2) - Steel		1170.5 / AISPBE (2)	DBSDS (3) - Steel Frame		1170.5 / DBSDS (3)
	$C_d(T)1$	$\Delta_d(T)1$		$C_d(T) (2)$	$\Delta_d(T) (2)$		$C_d(T) (3)$	$\Delta_d(T) (3)$	
0	0.218		0.000						
0.1	0.218	0.003	0.245	0.345	0.005	0.63	0.471	0.007	0.46
0.2	0.218	0.013	0.490	0.345	0.021	0.63	0.471	0.028	0.46
0.3	0.218	0.029	0.735	0.280	0.038	0.78	0.382	0.051	0.57
0.4	0.218	0.052	0.980	0.226	0.054	0.96	0.308	0.073	0.71
0.5	0.184	0.068	1.225	0.191	0.071	0.96	0.261	0.097	0.71
0.6	0.150	0.081	1.470	0.167	0.089	0.90	0.227	0.122	0.66
0.7	0.118	0.086	1.715	0.144	0.105	0.82	0.196	0.143	0.60
0.8	0.107	0.102	1.960	0.126	0.120	0.85	0.171	0.163	0.62
0.9	0.098	0.118	2.205	0.112	0.135	0.87	0.152	0.184	0.64
1	0.090	0.135	2.449	0.100	0.150	0.90	0.137	0.204	0.66
1.5	0.067	0.223	3.674	0.055	0.183	1.22	0.075	0.250	0.89
2	0.050	0.298	4.899	0.031	0.183	1.62	0.042	0.250	1.19
2.5	0.040	0.372	6.124	0.020	0.183	2.03	0.027	0.250	1.49
3	0.033	0.447	7.348	0.014	0.183	2.43	0.019	0.250	1.79
3.5	0.024	0.447	8.573	0.010	0.183	2.43	0.014	0.250	1.79
4	0.019	0.447	9.798	0.008	0.183	2.43	0.010	0.250	1.79
4.5	0.015	0.447	11.023	0.006	0.183	2.43	0.008	0.250	1.79

Table 4b: Acceleration demand comparison for RC buildings ($\mu = 6.0$).

Elastic T	NZS 1170.5 ($\mu=6$)		Effective T $\mu=6$	AISPBE (2) - RC		1170.5 / AISPBE (2)	DBSDS (3) - RC Frame		1170.5 / DBSDS (3)	DBSDS (4) - RC wall		1170.5 / DBSDS (4)
	$C_d(T)1$	$\Delta_d(T)1$		$C_d(T) (2)$	$\Delta_d(T) (2)$		$C_d(T) (3)$	$\Delta_d(T) (3)$		$C_d(T) (4)$	$\Delta_d(T) (4)$	
0	0.218		0.000									
0.1	0.218	0.003	0.245	0.440	0.007	0.50	0.474	0.007	0.46	0.513	0.008	0.42
0.2	0.218	0.013	0.490	0.440	0.026	0.50	0.474	0.028	0.46	0.513	0.031	0.42
0.3	0.218	0.029	0.735	0.357	0.048	0.61	0.385	0.052	0.57	0.417	0.056	0.52
0.4	0.218	0.052	0.980	0.288	0.069	0.76	0.310	0.074	0.70	0.336	0.080	0.65
0.5	0.184	0.068	1.225	0.243	0.091	0.75	0.262	0.098	0.70	0.284	0.106	0.65
0.6	0.150	0.081	1.470	0.212	0.114	0.71	0.229	0.123	0.66	0.248	0.133	0.61
0.7	0.118	0.086	1.715	0.183	0.134	0.65	0.197	0.144	0.60	0.213	0.156	0.55
0.8	0.107	0.102	1.960	0.160	0.153	0.67	0.173	0.165	0.62	0.187	0.178	0.57
0.9	0.098	0.118	2.205	0.142	0.172	0.69	0.153	0.185	0.64	0.166	0.200	0.59
1	0.090	0.135	2.449	0.128	0.191	0.71	0.138	0.206	0.65	0.149	0.223	0.60
1.5	0.067	0.223	3.674	0.070	0.234	0.96	0.075	0.252	0.89	0.081	0.273	0.82
2	0.050	0.298	4.899	0.039	0.234	1.27	0.042	0.252	1.18	0.046	0.273	1.09
2.5	0.040	0.372	6.124	0.025	0.234	1.59	0.027	0.252	1.48	0.029	0.273	1.36
3	0.033	0.447	7.348	0.017	0.234	1.91	0.019	0.252	1.77	0.020	0.273	1.64
3.5	0.024	0.447	8.573	0.013	0.234	1.91	0.014	0.252	1.77	0.015	0.273	1.64
4	0.019	0.447	9.798	0.010	0.234	1.91	0.011	0.252	1.77	0.011	0.273	1.64
4.5	0.015	0.447	11.023	0.008	0.234	1.91	0.008	0.252	1.77	0.009	0.273	1.64

Comparison of Acceleration Demand

The NZS 1170.5 acceleration demand reduction is directly proportional to the ductility as shown in Equation 1 above. The damped spectrum, however, shows less demand reduction as the ductility increases. The disparity between the NZS 1170.5 and the damped acceleration spectra thus becomes larger with increasing ductility. The damped spectra demands (AISPBE and DBSDS) are found to be significantly larger than the NZS 1170.5 demands, especially at high ductilities and low periods. For periods beyond the elastic corner period, the NZS 1170.5 spectra become slightly larger than the damped spectra. See Figures 5a to 5e and Tables 4a and 4b for comparison of acceleration-period graphs.

Comparison of Displacement Demand

The NZS 1170.5 method, for periods greater than 0.7 seconds, assumes that the design displacement is equal to the elastic displacement demand no matter what the ductility. For periods less than 0.7 seconds, the design displacement is slightly larger than the elastic displacement (see Figures 2a and 2b). The damped spectra show an increase in displacement demand as ductility increases for periods up to the corner period, then

becomes constant past the corner period (see Figures 5a to 5e and Tables 4a and 4b).

The corner period is at 3.0 seconds as defined by the NZS 1170.5 spectral shape factor, $C_h(T)$. For NZS 1170.5, this will remain constant as the analysis adopts only the elastic period. However, damped spectra require that the effective period is utilized in calculating the acceleration and displacement demands. The effective period, however, increases significantly from the elastic period with increasing ductility. This results in a much lower elastic equivalent corner period for structures with high ductility. The effective period can be 3.0 seconds for a significantly lower initial elastic period (see Figures 6a and 6b). The extreme case would be at ductility 6.0 where the elastic corner period would be at 1.22 seconds for an equivalent effective corner period of 3.0 seconds.

The corner period defines where the displacement demand becomes constant. Thus, for the damped spectra the displacement plateaus earlier than does the NZS 1170.5 spectra. It has been found that the damped spectra have a higher displacement demand for elastic periods less than the corner period but become lower for periods greater than the corner period.

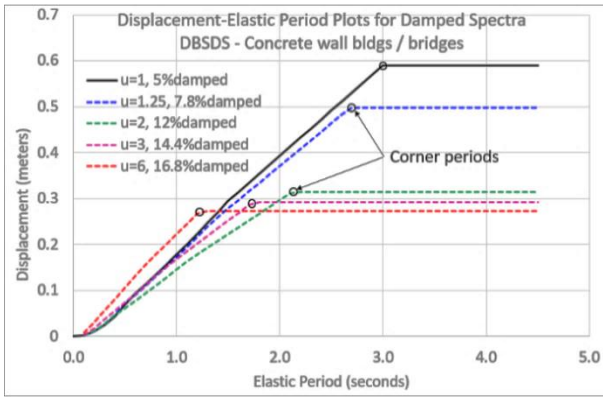


Figure 6a: Displacement vs. elastic period graph.

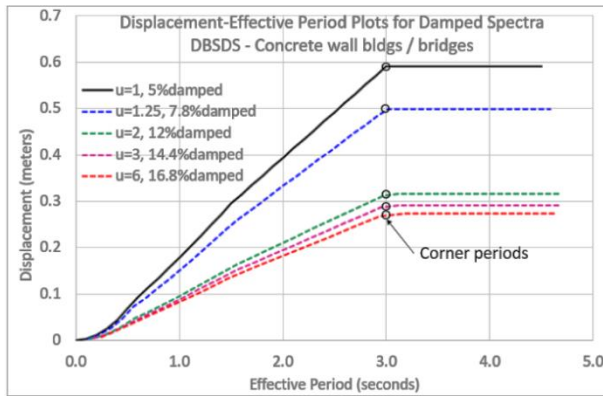


Figure 6b: Displacement vs. effective period graph.

Acceleration-Displacement Graph Comparison

This comparison can also be visualised through an acceleration-displacement graph (see Figure 7 as an example). As presented in the graph, the NZS 1170.5 acceleration demand decreases as the period increases, but the displacement demand continues to increase even beyond the corner period. The damped spectra acceleration also decreases and displacement increases as the period increases, albeit at a different rate. However, beyond the corner period, the acceleration decreases significantly while the displacement remains constant. It should be noted that the NZS 1170.5 equations change the spectra shape while the damped spectra retain the spectra shape.

Comparison between NZS 1170.5 and Damped Spectra

An attempt had been made by the author to quantify the disparity between the NZS 1170.5 spectra demand with the various damped spectra demand defined by the NZSEE-AISPBE guidelines and the DBSDS textbook. Tables 5a and 5b provide the approximate ratios of the NZS 1170.5 spectra demand over the specified damped spectra demand. The outputs have been further grouped into period ranges below and above the elastic corner period up to an effective period of 4.5 seconds. Note that the ratio is the same for either acceleration demand or displacement demand.

Tables 5a, for elastic periods less than the elastic corner period, indicates that the ratio of the NZS 1170.5 demand over the damped spectra demand ranges from 0.4 (for ductility 6.0) to 1.1 (for ductility 1.25). Table 5b, for elastic periods greater than the corner period, indicates that the damped spectra have lower demand than the NZS 1170.5 spectra for ductility 3 or lower with ratios of up to 1.9. However, for ductility up to 6.0, it is shown that the damped spectra can produce higher demands and thus ratios as low as 0.65.

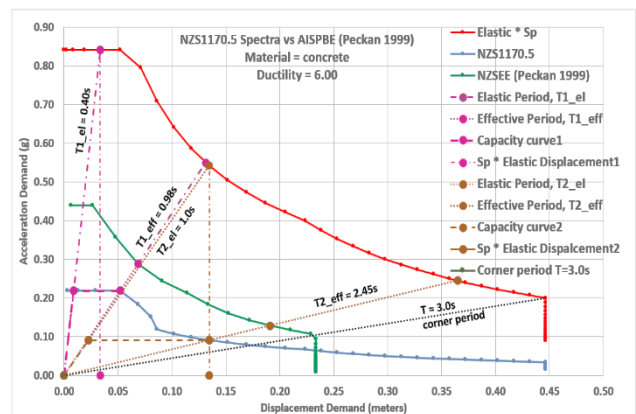
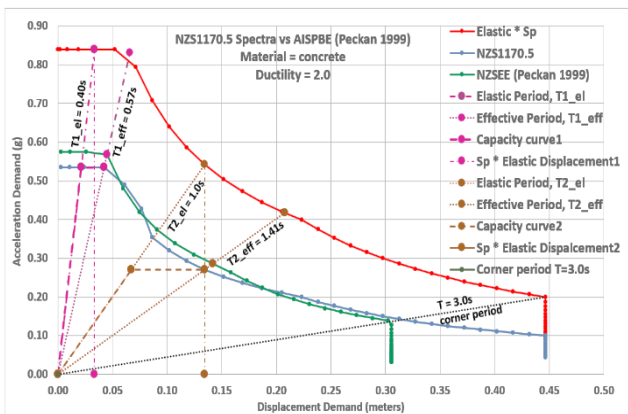
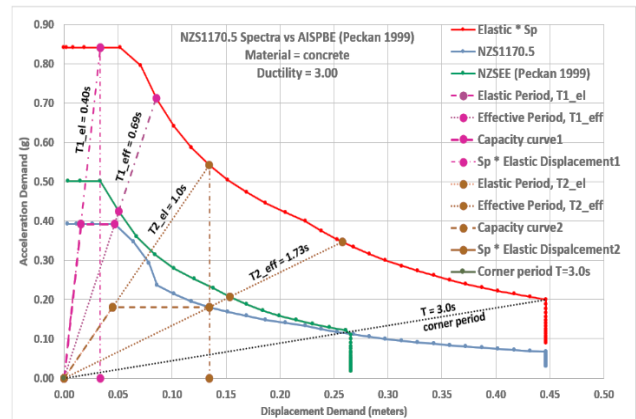
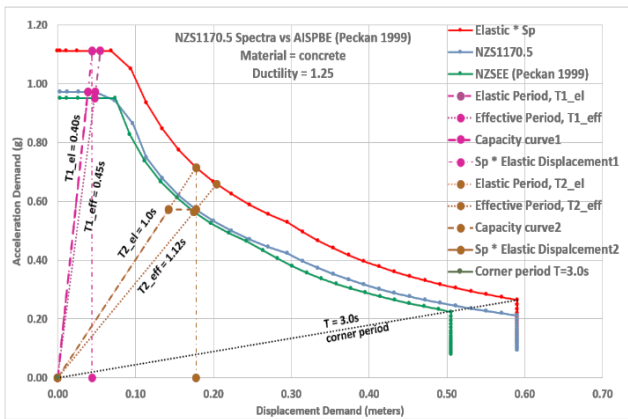


Figure 7: Acceleration vs. displacement plots.

Table 5a: Ratio of NZS 1170.5 demand over damped spectra demand for periods less than elastic corner period.

Ductility	$\mu = 1.25$	$\mu = 2.00$	$\mu = 3.00$	$\mu = 6.00$
Corner period (elastic)	$T_c = 2.68$ s	$T_c = 2.12$ s	$T_c = 1.73$ s	$T_c = 1.22$ s
AISPBE RC Bldgs	1.0 - 1.05	0.9 - 1.0	0.8 - 1.0	0.5 - 0.75
AISPBE Steel Bldgs	-	-	0.85 - 1.1	0.6 - 0.95
DBSDS RC Frame Bldgs	1.0 - 1.1	0.95 - 1.1	0.8 - 1.0	0.5 - 0.7
DBSDS RC Wall Bldgs	1.0 - 1.1	0.9 - 1.0	0.7 - 0.9	0.4 - 0.65
DBSDS Steel Bldgs	1.0 - 1.1	1.0 - 1.1	0.8 - 1.0	0.5 - 0.7

Table 5b: Ratio of NZS 1170.5 demand over damped spectra demand for periods greater than elastic corner period.

Ductility	$\mu = 1.25$	$\mu = 2.00$	$\mu = 3.00$	$\mu = 6.00$
Corner period (elastic)	$T_c = 2.68$ s	$T_c = 2.12$ s	$T_c = 1.73$ s	$T_c = 1.22$ s
AISPBE RC Bldgs	1.05 - 1.2	1.0 - 1.5	1.0 - 1.7	0.75 - 1.9
AISPBE Steel Bldgs	-	-	1.1 - 1.85	0.95 - 2.4
DBSDS RC Frame Bldgs	1.1 - 1.2	1.1 - 1.5	1.0 - 1.65	0.7 - 1.8
DBSDS RC Wall Bldgs	1.1 - 1.2	1.0 - 1.4	0.9 - 1.5	0.65 - 1.6
DBSDS Steel Bldgs	1.1 - 1.2	1.1 - 1.5	1.0 - 1.65	0.7 - 1.8

Comparison between Damped Spectra

The AISPBE equivalent viscous damping equation (see Equation 3) can be simplified further assuming that ξ_d and α_s are equal to zero and ξ_o is 5% (see Equation 8).

$$\xi_e = 0.05 + \frac{2}{\pi} \eta \left(\frac{\mu-1}{\mu} \right) \quad (8)$$

This is identical to the DBSDS Equations 5 to 7 shown above, with the difference mainly being the efficiency factor adopted. Note that this factor is based on the ratio of the area of an assumed hysteresis shape for a specific material over the area of a perfectly bilinear hysteresis. A comparison of the efficiency factors is shown in Table 6. It is noted that the AISPBE shows good correlation with the DBSDS damping equations for concrete type structures, but large disparity for steel structures. The DBSDS equations show significantly higher demand spectra compared to AISPBE spectra (see Table 6 and Figures 8a and 8b).

The TSAEB damping provided for H and M-H levels are identical to the DBSDS damping for frame and wall buildings respectively. The other levels M and L represent less ductile structures with lower damping. TSAEB also has significantly lower damping than the AISPBE. This equates to a higher demand spectra for a displacement-based approach compared to a force-based approach.

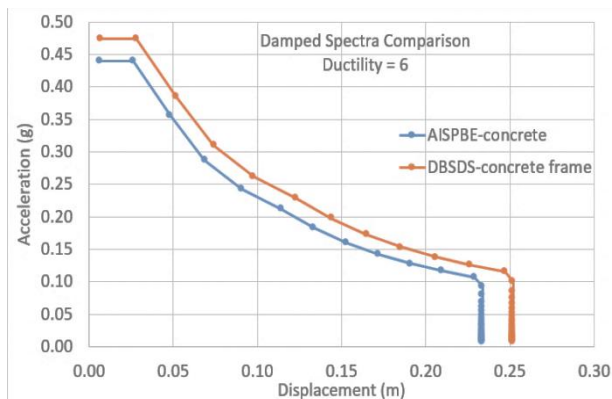


Figure 8a: Damped spectra comparison for concrete.

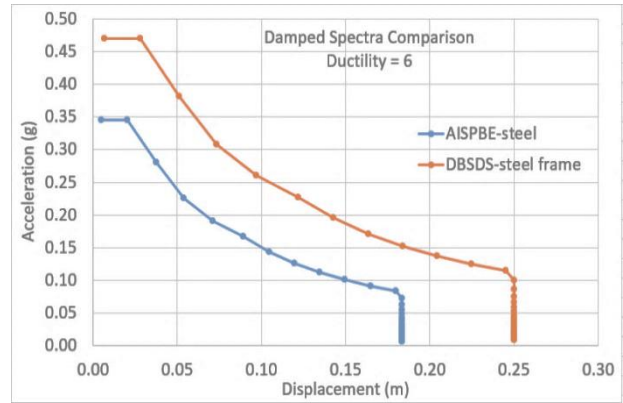


Figure 8b: Damped spectra comparison for steel.

Table 6: Damping efficiency factors comparison.

Material	AISPBE (2η)	DBSDS
Concrete	0.4 – 0.7	0.444 – 0.565
Steel	0.8 – 1.3	0.577

CONCLUSIONS

In order to compare the NZS 1170.5 seismic design spectra with the hysteretic-damped spectra specified in the NZSEE-AISPBE guidelines, DBSDS textbook and TSAEB draft guidelines, this study adopted the following simplified step-by-step procedure.

- Calculate the yield displacement, Δ_y , from the NZS 1170.5 acceleration, $C_d(T)_{1170.5}$, and the elastic period using the simple harmonic motion relationships shown in Equations 2a to 2c.
- Calculate the design displacement, $\Delta_{d1170.5}$, by multiplying this yield displacement by the ductility.
- Calculate the effective period from $C_d(T)$ and the design displacement $\Delta_{d1170.5}$ using the simple harmonic motion relationships (i.e. Equations 2a to 2c).
- Plot $C_d(T)$, Δ_y , and Δ_d as an idealized bilinear curve on an acceleration-displacement graph as shown in Figures 2 to 4. This represents the backbone of a hysteresis shape as shown in Figure 3.
- Calculate damping based on this hysteresis shape using the AISPBE, DBSDS or TSAEB methodologies.
- Plot the damped spectra in the acceleration-displacement graph together with the idealized bilinear curve (Figure 4).
- Project the effective period to intersect with the damped spectra to quantify the acceleration $C_d(T)_{damped}$ and displacement $\Delta_{d,damped}$ demands (see Figure 4).
- Repeat this for a wide range of period and ductility values.
- Establish a direct comparison between the NZS 1170.5 acceleration and the displacement demand ($C_d(T)_{1170.5}$, $\Delta_{d1170.5}$) as well as the damped spectra ($C_d(T)_{damped}$, $\Delta_{d,damped}$).

The results of this comparison show disparity between the NZS 1170.5 design spectra and the hysteretic-damped spectra defined by either NZSEE-AISPBE, DBSDS or TSAEB. This disparity becomes significantly larger with increasing ductility. The following are the main differences found between the NZS 1170.5 design spectra, and the AISPBE, DBSDS and TSAEB damped spectra:

- The disparity between the acceleration and displacement demand of the NZS 1170.5 design spectra compared with either the AISPBE or DBSDS design spectra increases

significantly the higher the ductility of the system. The damped spectra demand is generally higher than the NZS 1170.5 demand if the structure's elastic period is below the elastic corner period, but is generally lower if the structure's elastic period is above the elastic corner period.

2. The effective period increases as the ductility increases. This results in the elastic corner period of a displacement-period plot becoming lower with increasing ductility, and thus plateauing earlier compared to lower ductility spectra. Flexible high ductility structures can potentially have a lower demand if the damped spectrum is adopted.
3. This study also shows a disparity between the NZSEE-AISPBE and DBSDS damped spectra. The main difference is in the 'efficiency factor' which is an empirical value for both methods. The disparity is small for concrete structures but can be substantial for steel structures. This disparity becomes significantly large with increasing ductility. The AISPBE produces lower loadings compared to DBSDS for both concrete and steel.
4. The damping provided by the draft document TSAEB was also reviewed and was shown to be identical to DBSDS but with a wider range of material and structure types considered. The TSAEB has lesser damping, and thus larger loadings, compared to AISPBE.

The calculation of seismic demand is all based on theoretical representation of the physical phenomena of earthquake induced motions, and the methods discussed here provide differing ways of interpreting this demand. The disparity observed here is due to the difference on how the demand is calculated. The two methods for calculating seismic loadings proposed by the AISPBE and TSAEB, where one adopts the NZS 1170.5 equal-energy/equal-displacement approach and the other damped spectra, can potentially produce two different seismic ratings, especially for structures with high ductility. From previous experience as a practitioner, this has often led to uncertainty as to what the seismic rating of the building actually is, or if the structure is earthquake-prone and will require retrofit or not. This can also be a point of contention between various parties, e.g. between assessor and peer reviewer. This inconsistency of outputs also raises the question of which method provides better representation of a structure's ductile behaviour subject to a real earthquake event. If the damped spectrum methods, being more contemporary, provide more realistic representation, then the current NZS 1170.5 approach could potentially be under-designing structures.

It is recommended that further scrutiny regarding the NZS 1170.5 equal-energy/equal-displacement approach and the hysteresis-damping approach be carried out. Further study on hysteresis-shapes and efficiency factors is also advocated. The utilization of either the force-based or the displacement-based method set in the NZSEE-ASIPBE and TSAEB could be limited to a specific range of period, ductility, material and structure type to minimize the conflicting outputs. Additional modification factors for either the NZS 1170.5 ductility factor μ or the damped spectra efficiency factor η specific to a material and structure type could also resolve these discrepancies. Specific guidelines and detailed explanations would provide clarity and could also provide resolution regarding the discrepancies between the two methods.

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