0444

COMPARATIVE PERFORMANCE EVALUATION OF DISPLACEMENT BASED DESIGN PROCEDURES FOR NEAR FIELD EARTHQUAKES

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SUMMARY

The ductile behaviour of structures is essential for earthquake resistant design. This implies the importance of controlled deformation, which underlies performance-based seismic design. The study presented here compares two iterative seismic design procedures suitable to the philosophy of performance-based seismic engineering. They are representative of displacement-based design, the most challenging issue in performance-based engineering. The first method is the Capacity Spectrum Method (CSM), proposed recently for seismic performance evaluation of reinforced concrete buildings in the United States. It predicts the performance of structures considering the global demand from ground motions. The second method is analogous to CSM but predicts the structural performance considering the local deformation demand of earthquakes. It is called the Drift Capacity Spectrum Method (DCSM). When near field earthquakes (NFEQs) must be taken into consideration, DCSM is probably more refined than CSM as NFEQs increase the local deformations considerably. These methods are evaluated for two frame type buildings under six different ground excitations. The selected suite of ground motions is from firm soil sites. Among them, four represent near source and the remaining two represent far field earthquakes. The results indicate that both methods underestimate the performance of model structures considerably. The relative errors with respect to non-linear time history analysis show that, CSM gives an (unsafe) error of 7.5-50 per cent while DSCM errors, again on the unsafe side, reach 82 per cent. It is believed that such large magnitude errors arise because of the unrealistic representation of excitation demands and equivalent damping values in the non-linear range. Therefore, further improvement of these methods is necessary before being used in performance based engineering.

INTRODUCTION

Traditional seismic design methods are generally adapted from techniques assumed to be adequate for gravity load design (design approaches that emphasize strength instead of deformation). The design is based on an instantaneous snapshot of a dynamic event (elastic spectrum analysis) in which response at the time of maximum base shear is considered to be adequate. The member sizes are calculated via the distribution of this maximum base shear (elastic strength demand) along the height of the structure. During this process, the structural periods are calculated using gross-section properties assuming that elastic (shorter) period will usually result in higher design forces. In brief, traditional methods do not explicitly consider the duration effects of ground motions and hysteretic behaviour of structural members, which in turn affect the overall force and deformation patterns on the structure. As yet, well developed seismic design codes accomplish the above effects implicitly by checking deformation limits (even extending to inelastic range) after sizing the structural members from the calculated elastic forces [UBC, 1997]. However, there is a lack of consensus among different seismic codes about these empirical formulations for converting the calculated elastic displacements to inelastic ones [Priestley, 1997]. The above discrepancies of traditional seismic design methods are well known. However the lack of alternative design approaches has made them essential for daily design practice.

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Seismic response demands ductile building behaviour focusing the seismic design on displacements rather than forces. The ductile behaviour demand is more apparent in near field earthquakes (NFEQs) that contain long period impulsive wave components that appear as more pronounced in velocity and displacement time histories. Actually, these long period components increase the displacement demand in structures. The 1994 Northridge earthquake is a near source ground motion that called attention to the importance of displacement demand in structures. The structural response records of this earthquake indicate the inadequacy of drift limitations imposed by traditional design methods [Huang and Shakal, 1996]. After this dramatic example of NFEQ, many earthquake engineering professionals have put efforts to grapple with finding alternative design procedures for future seismic design codes. Among these, the performance-based seismic design is one of the most prominent. Performance-based design can simply be achieved with a demand/capacity based design process to fulfil all performance objectives in a structurally and economically effective manner [Krawinkler, 1996]. Though the objective seems difficult to acquire, considerable research has been done to clarify the obscure concepts of this design philosophy. Among preliminary efforts is Capacity Spectrum Method (CSM) [ATC-40, 1996]. The method has been known since 1970 but the most mature form for evaluating and upgrading reinforced concrete structures has been published recently [Freeman, 1998]. CSM matches the displacement-strength capacity of a structure with the demand imposed by the ground motion. The capacity is expressed by pushover curves. The ground motion demand is in the form of well-known response spectrum. The consequential result of CSM is the estimated overall structural performance (i.e., roof displacement and base shear) for that particular ground motion. An analogous method to CSM has been recently proposed [Iwan and Huang, 1998]. This method is called the Drift Capacity Spectrum Method (DCSM). It is similar to CSM except that regarding the inadequacy of response spectrum in emphasizing the local deformation demand it suggests another tool for ground motion demand. The tool that replaces response spectrum is called as “drift spectrum”. This is calculated by applying wave propagation theory to elastic shear beam model and it is stated to capture the local deformations within a structure [Iwan, 1997]. The increased local deformation demand is the inherent result of NFEQs due to their long period velocity pulses. Therefore, this alternative method seems to be more powerful in estimating the performance of structures subjected to NFEQs. The drift spectrum is well defined for base level drift demand, generally the most critical level for regular frame type buildings. DCSM defines the strength-displacement capacity of a structure as shear-drift relationship calculated from simple pushover analysis. As stated earlier, the ground motion demand is defined by the drift spectrum. Successively, the outcome of DCSM is the drift demand and story shear for that particular excitation.

The research presented here seeks to compare the performance of CSM and DCSM for NFEQs. For this purpose, two moment resisting reinforced concrete frames are used together with a suite of ground motions. The chosen earthquakes are firm soil records, and contain both near and far field excitations for comparison. The following sections describe shortly the basic formulations and theoretical background of CSM and DCSM. Then the case study and its results are discussed. In the last section, the conclusions derived from the case study results are presented.

CAPACITY SPECTRUM METHOD (CSM)

The Capacity Spectrum Method integrates the global force-displacement capacity of the structure with the earthquake demand. The procedure compares the capacity and demand by defining a “performance point” that represents the condition for which the capacity is equal to the demand imposed by the ground motion. In other words, the performance point is a location on the capacity curve where the displacement ductility demand of the excitation is equal to the displacement ductility capacity of the structure. The procedure approximates this point iteratively. The graphical illustration of the method is shown in Figure 1.

The global force-displacement capacity is calculated from pushover analysis, generally assuming that the first mode response is dominant. This curve is then converted to pseudo acceleration (PSA) versus spectral displacement (S_d) coordinates in order to make a comparison with the ground demand. The conversion formulations can be derived by the modal analysis techniques [ATC-40, 1996]. The important fact about the conversion is to be aware of the changes in modal mass and participation factors in the inelastic deformation stage. As the system responds in the inelastic range, the increase of period may change the modal shapes, affecting the above variables that are essential for conversion. An equivocal conversion will not reflect the real behaviour of the structure. The earthquake demand is defined by response spectrum in PSA versus S_d format. In order to account for inelastic behaviour, the linear elastic response spectrum is reduced by using effective viscous damping (βeff) concept. This concept establishes a relation between the structural damping and displacement ductility ratio (μ). The consequential implementation is the spectral reduction factors to obtain constant ductility spectrum curves (i.e., inelastic response spectra). It should be noted that βeff is defined by the hysteretic damping and the inherent viscosity of structures.

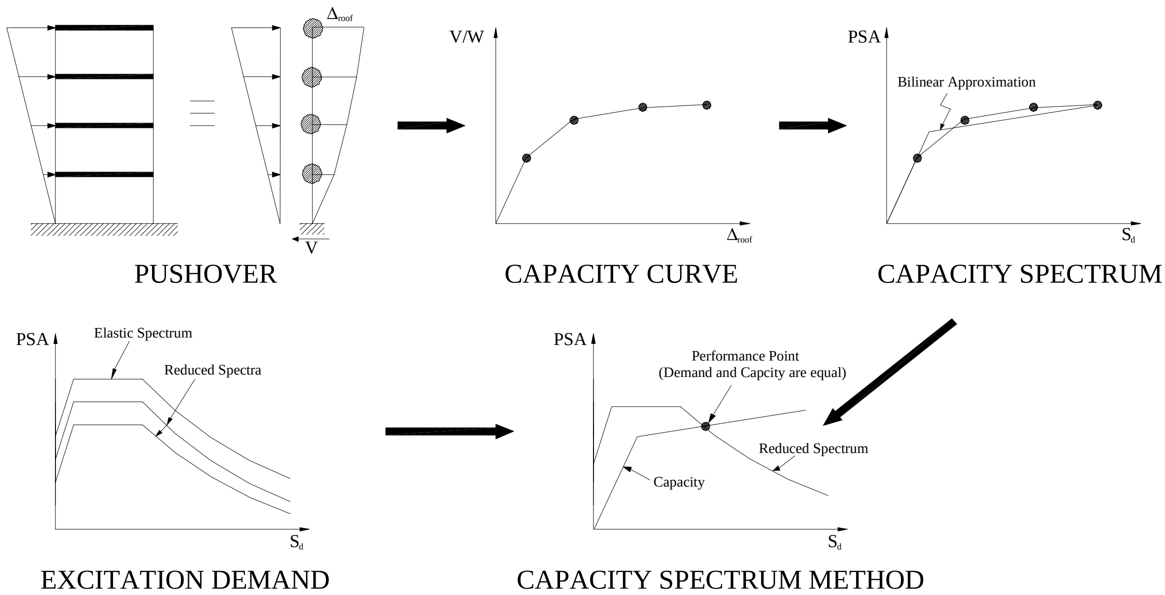

Figure 1. Graphical illustration of CSM

DRIFT CAPACITY SPECTRUM METHOD (DCSM)

The Drift Capacity Spectrum Method (DCSM) has been proposed as an alternative to CSM. In fact it is very similar to CSM in many ways. The major difference is the replacement of response spectrum in CSM by a new tool called the “drift spectrum”. This spectrum is based on the maximum shear deformation in a shear beam due to a travelling wave. The maximum shear deformation is analogous to inter-story drift ratio in building systems. The explicit formulation of drift spectrum for basement level is given below [Iwan, 1997].

$$D(T,\beta) = \left|\gamma\right|_{max} = \max_{\forall t} \frac{1}{c}\left| v(t) + \frac{2\pi\beta}{T} z(t) + 2\sum_{n=1}^{N\le 2t/T} (-1)^n \, e^{-n\pi\beta}\left[v(t - n\frac{T}{2}) + \frac{2\pi\beta}{T} z(t - n\frac{T}{2})\right]\right| \qquad [1]$$

where,

$D(T,\beta)$	= maximum first story drift ratio (maximum shear strain, γ_{max}),
c	= shear wave speed,
T	= period,
β	= damping ratio,
$v(t)$	= ground velocity time history,
$z(t)$	= ground displacement time history.

The plot of Eq.[1] as a function of period for different damping values yields the drift spectrum. The drift spectrum cast in the form of force-displacement demand spectrum can be done by using simple elastic theory formulations. This new version of drift spectrum is called Shear-Drift Demand Spectrum (SDDS) [Iwan and Huang, 1998]. The derivation of SDDS is given in Appendix A.

The proponents of DCSM emphasize the capability of drift spectrum in capturing local deformation demands that are inherently overlooked by response spectrum. The response spectrum only gives a global demand view of an excitation. This is important for NFEQs since they increase the local deformation demand considerably owing to their impulsive, long period velocity.

In analogy to CSM, DCSM relates story shear-interstory drift (capacity) with the drift demand of ground excitation. The story shear-drift is determined by global pushover analysis. In general the interstory drift is maximum at the base of frame systems. Therefore, when base level of the structure is considered, the story shear turns out to be the base shear and the interstory drift at the ground story. The transition of elastic SDDS to inelastic range can be done in a similar fashion to CSM. Considering that the hysteretic behaviour of ground story is similar to the overall structural behaviour, effective damping concept is adapted for SDDS. This approximation is assumed to hold also for the model buildings used in this study. The capacity curve of total drift ratio versus base shear almost envelopes the first story drift ratio to base shear curve in all cases. The above approximation is utilized to calculate the effective damping for obtaining the reduced elastic SDDS (constant ductility inelastic SDDS). It should be noted that effective damping concept for inelastic range transition of SDDS is not favoured. Instead an equivalent linear system yielding the same drift would be preferable. This can be done by applying Eq.[1] directly to inelastic range using a hysteresis model. However, this is not very easy due to the nature of the nature of drift spectrum formulation, and is inconvenient for practical applications.

The Drift Capacity Spectrum Method seems more refined than CSM in two aspects. First, it treats local deformations that are important for NFEQs. Second, the comparison of capacity and demand is done in the same format. Consecutively, there is no need for a coordinate system conversion by making approximations as in the case of CSM. On the other hand, the method is as yet not fully tested, and the results of its application to practical cases are not fully explored.

CASE STUDY

Two hypothetical moment resisting frames are designed using the provisions of Uniform Building Code [UBC, 1997]. The fundamental period of the first model (M1T2) is 0.65 whereas the second model (M1T3), the fundamental period is 0.84. Both buildings are assumed to be located in Zone 4, 10 km away from a known seismic source. The soil is firm soil. The seismic source chosen can produce earthquakes with moment magnitudes equal or greater than 6.5 [UBC, 1997].

The non-linear dynamic and static pushover analysis have been performed by IDARC40 [Valles et al., 1996]. The hysteresis model for non-linear analysis is chosen as three parameter Park Model that incorporates stiffness degradation, strength deterioration and slip [Valles et al., 1996]. During the analysis stage, the behaviour of this hysteresis model is defined by nominal stiffness and strength deterioration. The slip effect is ignored in the hysteresis model assuming that the bonding between concrete and steel is well developed. These definitions are ideal for a newly constructed structure.

Six ground excitations are applied to the buildings. The excitations are firm soil records and have a 10 per cent probability of exceedence in 50 years. They are generated from past earthquakes by considering several variables such as magnitude and distance that directly affect the general behaviour of ground motions. The simulations are done by defining the earthquake source as a shear dislocation. The shear dislocation radiation pattern and its tendency to become suppressed at periods shorter than 0.5 are accurately presented. This is important especially for the realistic representation of NFEQs in which the large pulse of motion "fling" oriented perpendicular to the fault strike is due to rupture directivity and radiation pattern effects [Somerville et al., 1998]. The ground motion components are strike normal and parallel that are claimed to be important for structures subjected to NFEQs. It should be noted that, the selected excitations are representative of performance oriented design since the implementation of performance based-design requires well-specified input ground motions. Information about these earthquakes is given in Table1, where LA11, LA12, LA15 and LA16 constitute the near source ground motions selected for this study. The records SE07 and SE08 represent far field excitations. Maximum velocity of each excitation is given so as to indicate the damage potential, especially prevalent in NFEQs. The last column of Table 1, labelled as Zone, describes the active earthquake region of U.S. for that particular simulation.

The calculated capacities from CSM and DCSM are presented in Table 2. These calculations are done using the βeff - μ relations presented in a previous study [Freeman, 1998]. In this study, the relation between βeff and μ is established considering the building behaviour as stated in ATC-40. In Table 2, the errors shown are relative to "true" top displacement and ground story drift calculated from non-linear time history analysis for CSM and DCSM, respectively. The negative error indicates that the estimation is on the unsafe side (i.e., the results from non-linear time history analysis are greater). The approximate βeff is the damping value at which the capacity of the model and the excitation demand are equal.

Table 1. Ground motion records used

Record Name	Description	M(1)	ED(2)	Duration (sec)	PGV(3)	Zone
LA11(N4)	Loma Prieta, 1989, Gilroy	7.0	12	40	79	4
LA12(P5)	Loma Prieta, 1989, Gilroy	7.0	12	40	56	4
SE07(N4)	West Washington Seattle Army Building, 1949	6.5	80	67	36	3
SE08(P5)	West Washington Seattle Army Building, 1949	6.5	80	67	40	3
LA15(N4)	Northridge 1994, Rinaldi R.S.	6.7	7.5	15	98	4
LA16(N5)	Northridge 1994, Rinaldi R.S.	6.7	7.5	15	101	4

(1) Moment magnitude
(2) Epicentral distance in km.
(3) Peak ground velocity in cm/sec
(4) Fault normal component
(5) Fault parallel component

Table 2. The summary of CSM and DCSM performance

		CSM		DCSM		
Record	**Model**	**Relative Error (%)**	**β_{eff} (%)**	**Relative Error (%)**	**β_{eff} (%)**	**Location of First Mode Elastic Periods in Spectrum**
LA11	M1T2	19.50	29.0	-54.1	25.8	Velocity constant
LA12		-23.4	25.0	-28.6	17.5	Velocity constant
SE07		-34.8	26.0	-51.0	19.4	Can not be defined
SE08		-44.7	27.2	-67.5	19.8	Can not be defined
LA15		-35.7	40.0	-70.8	31.3	Velocity constant
LA16		-49.0	40.0	-80.0	31.2	Acceleration constant
LA11	M1T3	-11.9	29.0	-72.5	22.3	Velocity constant
LA12		-7.5	16.9	-19.2	16.7	Velocity constant
SE07		-31.2	22.9	-62.0	15.5	Can not be defined
SE08		-39.9	23.1	-69.1	15.2	Can not be defined
LA15		-45.2	40.0	-75.9	25.7	Velocity constant
LA16		-49.1	40.0	-82.0	24.3	Velocity constant

For each ground motion, the spectral regions are defined by linear curve fitting. The definition of spectral regions is important for the evaluation of results as the peak linear and non-linear deformations are approximately equal in the velocity and displacement sensitive part of the spectrum. These are shown in Figure 2 and used together with Table 2 to explain the observations made in the case study. It should be noted that for far field earthquakes, the spectral regions are not defined due to their steep Pseudo Velocity Spectra (PSV). These sharp PSVs make the curve fitting impossible to find a constant velocity region. The following observations are derived from the case study:

(1) Effective damping concept for inelastic demand representation of DCSM does not work for all ground motion types. The errors are very high reaching to 82 per cent on the unsafe side. In most cases the elastic fundamental period of the models lies in the velocity constant region, the average relative error for NFEQ group is -60.4 per cent. This average is calculated as -62.4 per cent in far field ground motions.

(2) In CSM, the computed results confirm the conclusion above. A detailed summary of the observations and their explanations considering the limitations of this study are given below:

(3) Generally, when the effective period (T_{eff}) of the structure translates from one spectral region to other, the relative error increases. This observation is clear for NFEQs for which the spectral regions are well defined. Both models in LA16 record and M1T3 in LA15 record exhibit large magnitude errors due to this fact. In far field excitations, the spectral region translation for both models is inherent owing to the undefined velocity constant plateau. Therefore, considering the limitations in this study, the large magnitude errors of CSM for

the chosen far field earthquakes are also attributed to the spectral transition of the models. Excessive damping values different from the customary value of 5 per cent cause changes in the shape of the response spectrum. This changes the definition of the spectral regions, masking other features of the ground motions.

(4) The relative error is considerably small when the T_{eff} changes are small and remain in the boundaries of velocity constant region (M1T3, record LA12). However, the error increases when T_{eff} variation is large even if this change occurs in the velocity constant region (M1T2, LA12 and LA15 records). A significant Teff change in a structure suggests increased damage. The under-estimated structural performance by CSM for these cases indicates the misrepresentation of hysteretic behaviour, via effective damping concept.

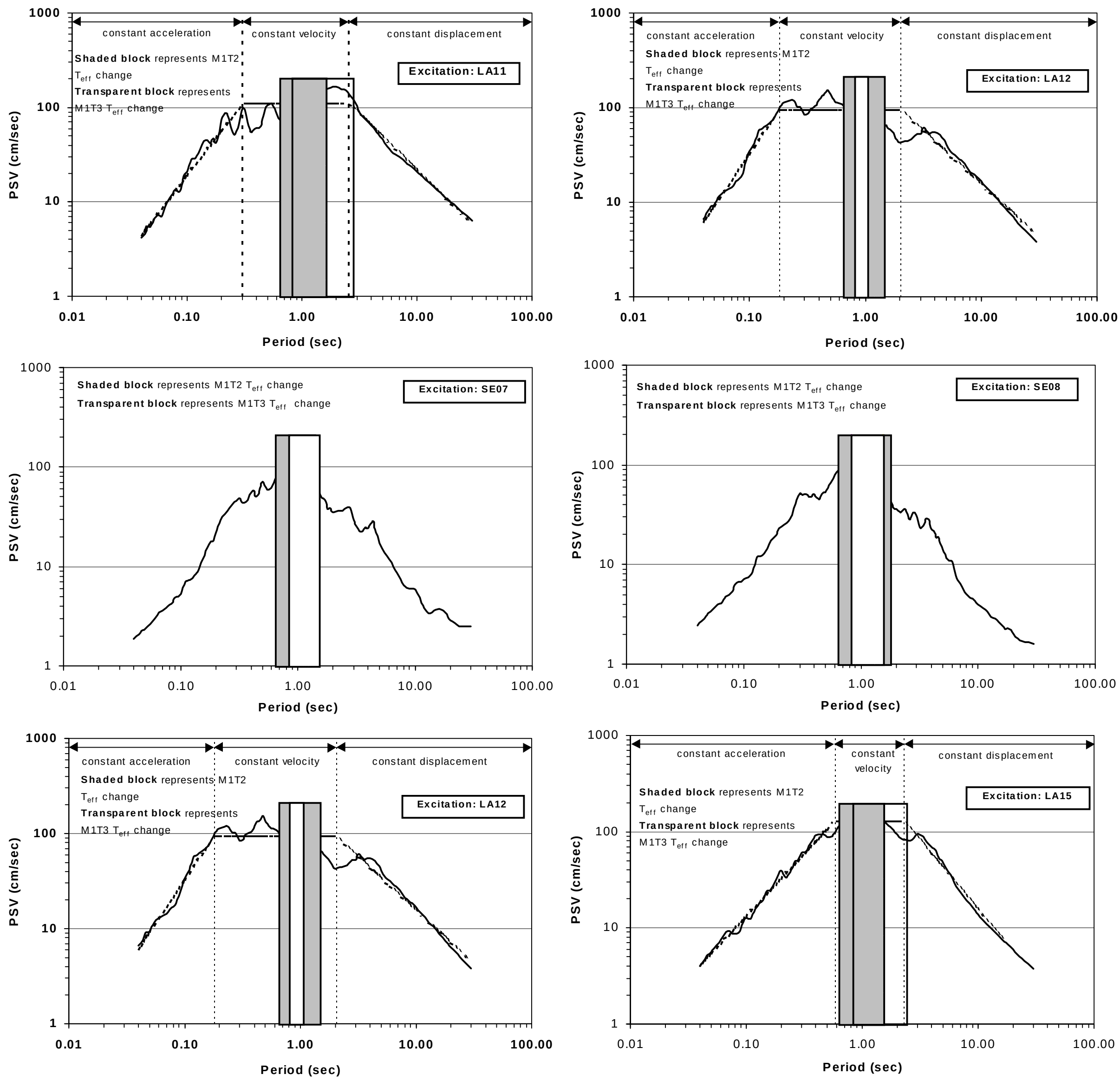

Figure 2. Spectral regions of ground motions and change of T_{eff} in the models (5 per cent damped PSV)

The above observations indicate that the weakness of CSM and DCSM is the unrealistic representation of inelastic ground motion demand by effective damping concept. Large magnitude unsafe errors mean that the β_{eff} values calculated in this study are equivocally larger than they should be. Therefore, other well-established damping-ductility relations must be examined. Relations exist where approximations for damping as a function of ductility may allow a closer match within the limited findings of this study [Gülkan and Sözen, 1974].

CONCLUSIONS

Two performance based design methods are compared for various earthquakes. The main difference between the two is the representation of ground motion demand. CSM adapts response spectrum while DCSM considers SDDS for defining ground motion demand. The later, theoretically, seems more appropriate for NFEQs as it captures local deformations. Both methods use the capacity curves calculated from static pushover analysis. The methods are very well oriented to performance-based engineering.

The results from non-linear time history analysis indicate that both methods underestimate the performance of the models considerably. The poor correlation of structural performance becomes unacceptable in DCSM, which is developed regarding the inherent characteristics of near source ground motions. The main reason for this can be attributed to the failure of methods in mimicking the inelastic ground motion demand. Though proponents of DCSM advise the use of hyteresis models for non-linear behaviour, the application is not practical due to the nature of drift spectrum formulation. The effective damping concept also does not seem to hold for CSM. The fundamental periods of the models fall in the velocity constant region for most of the NFEQs used in the study. In this region the peak non-linear deformations are approximately equal to linear ones. However, even for this spectral region CSM fares poorly in the prediction of structural behaviour. As a result, these indications point the need of re-evaluation for CSM and DCSM in their future role as performance-based design tools.

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APPENDIX A

The drift spectrum cast in the form of SDDS can be derived by using simple elastic theory equations. The maximum shear force due to maximum shear strain is

$$F_{max} = \gamma_{max}\ G\ A \qquad [A1]$$

In Eq.[A1], G is shear modulus and A is cross-sectional area of the shear beam. The shear wave velocity, c, is expressed as:

$$c = \sqrt{\frac{G}{\rho}} \qquad [A2]$$

The variable ρ in Eq.[A2] is mass per volume. Using Eq.[A2] and the definition of mass density, Eq.[A1] can be re-written as:

$$F_{max} = \gamma_{max}\ \frac{m}{H}\ c^2 \qquad [A3]$$

In the above equation, m represents mass and H defines height of the shear beam. The shear velocity, height and fundamental period (T) of shear frame buildings can be related by:

$$c = \frac{4H}{T} \qquad T = C\ H^{(3/4)} \qquad [A4]$$

Note that, the second formula of Eq.[A4] is empirical and suggested in many seismic design codes. The capital letter C is a constant that depends the material type (i.e. steel or reinforced concrete). Using relations in Eq.[A4] and defining the total weight of the shear beam (W) as the product of beam mass and gravitational acceleration (g), Eq.[A3] can be further reduced:

$$\frac{F_{max}}{W} = \frac{16}{g\ C^{4/3}}\ \gamma_{max}\ T^{-2/3} \qquad [A5]$$

Eq.[A5] is the recast form of drift spectrum in normalized force (Fmax/W) and interstory drift ratio (γ_{max}) terms. Of course Eq.[A5] would look different if the expression for T is different in Eq.[A4].