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# Displacement Focused Seismic Design Methods - A Comparative Study

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**ABSTRACT:** Two methods of seismic design, namely Direct Displacement Based Design and Displacement Focused Force Based Design, are reviewed together with the Capacity Spectrum Method for the analysis for existing structures. Modifications to these three approaches are proposed to enable them to more accurately predict the influence of different hysteretic behaviour on response. To assess the relative accuracy of these methods a range of single degree of freedom structures were proportioned by each of the methods for different hysteretic behaviour. The responses of these proportioned structures to four different earthquake records were then determined. A comparison of the maximum displacement recorded in each time history analysis, shows that there is little to pick between the three design approaches in terms of accuracy.

## 1 INTRODUCTION

During the last decade the concept of “performance based design” has received considerable attention. The objective is to ensure that under design level earthquakes predetermined damage levels are not exceeded. As damage is principally a function of material strain levels, and these can be related to displacements, performance based design methods generally focus on displacements.

The currently widely accepted method of seismic design, namely force based design, has been criticised for having displacements checked only at the end of the design process with no apparent focus on these values. With the displacement focused method a structure can be proportioned (tuned) to sustain a predetermined displacement level under design earthquake ground motion.

A number of different displacement focused design methods have been proposed. In this paper three of these are considered, namely-

- Direct displacement based design, which was proposed by Priestley and his co-workers [Kowalsky et al. 1994]
- Capacity spectrum method, one of the non-linear static procedures described in [ATC40]. This is based on a method initially proposed by Freeman et al. [1975].
- Displacement focused force based design, which is a modification of forced based design [Judi et al. 2001a].

These methods are described and several series of single degree of freedom structures are designed using methods based on these approaches. The maximum displacements obtained in time history analyses with a number of different earthquake records are compared with the design values. While this paper deals only with single degree of freedom structures, techniques have been proposed which enable the approaches to be extended to multi-degree of freedom structures [ATC 40 1996, Loeding et al. 1998].

## 2 SEISMIC DESIGN METHODS

### 2.1 *General*

In a major earthquake, structures that have been designed to behave in a ductile manner, referred here as “design structures”, respond non-linearly due to yielding, cracking and crushing of material, and different forms of damping. However, in all the seismic design methods the design actions are assessed from elastically responding models, of which there are two forms. In this paper the term “associated elastic model” is given to the form used in the direct displacement based and capacity spectrum design methods, while the term “analytical elastic model” describes the form used in the force based and displacement focused force based methods.

With the “associated elastic model” the elastic member properties are based on the secant stiffness between the origin and the design maximum displacement, see Figure 1. To allow for the energy dissipated in an earthquake, the model is given an increased level of viscous damping. However, with the “analytical elastic model” the member properties are based on the stiffness values appropriate for load cycles sustained prior to yield or significant non-linear behaviour of material. For reinforced concrete an equivalent elastic stiffness is chosen to allow for non-linearity due to tension stiffening and axial load effects, as illustrated in Figure 1. The viscous damping associated with this model represents the energy dissipation of the design structure in its pre-yielding load cycles and the nonlinear behaviour of the structure is described by the level of “ductility” sustained.

In all the design methods it is assumed that the maximum acceptable design displacement, $\Delta_d$, is determined on the basis of either, material strains, as these give a measure of structural damage, or acceptable inter-storey drift limits, as these give a measure of non-structural damage. As currently presented the influence of P-delta effects on the deformation of structures is ignored in the direct displacement based design and the capacity spectrum methods. For the sake of comparison of the three methods in this paper it is also neglected in the displacement focused force based design approach. However, it should be noted that P-delta effects can have a major influence on structures where low lateral strengths are permitted for ductile structures, as is the case for structures designed to meet the minimum requirements of the New Zealand Loadings Standard [NZS4203-1992].

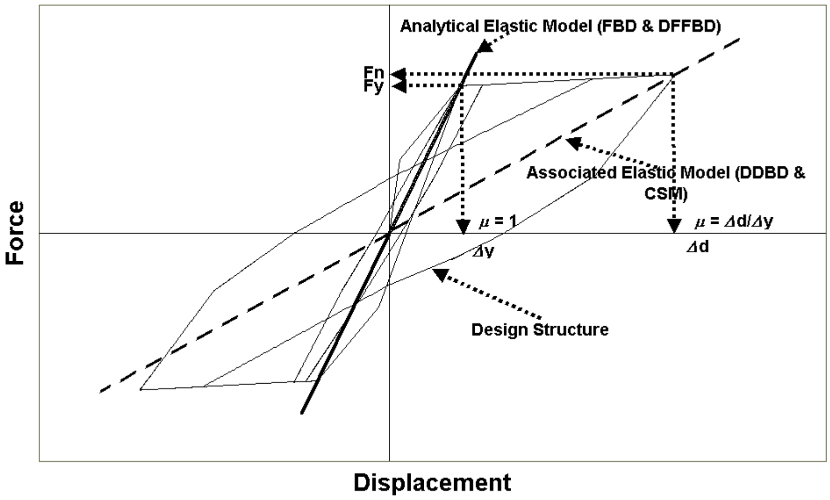

Figure 2-1 Relationship between load – deflection response of design structure and elastic models used in analyses

### 2.2 *Direct Displacement Based Design*

The direct displacement based design method was set up for the design of new structures. The following steps are involved with this method as originally proposed.

1. From the design displacement, $D_d$, and an assessment of the ductility one displacement, $D_y$, a first estimate is made of the displacement ductility, μ, which is equal to $D_d/D_y$.
2. The viscous damping level of the associated elastic model is determined from the hysteretic form and ductility, using relationships such as those given in [Priestley et al. 2000]. The values vary with ductility and they are calculated using the "equivalent damping" concept. With this the viscous damping levels are found by equating the energy dissipated by the associated elastic model to that dissipated by the design structure when they are both subjected to a load cycle with peak displacements of ± the design displacement, $D_d$.
3. From the design displacement, $D_d$, and damping level, $x$, the period of the associated elastic model can be read off from displacement versus period response spectra as shown in Figure 2. In this figure the elastic displacement spectra are overlaid on the elastic acceleration spectra in one plot.
4. Using the period from the previous step the base-shear can be assessed from acceleration versus period response spectra for different damping levels. With this value and knowledge of the strain-hardening characteristics, the required yield strength of the design structure can be assessed, as illustrated in Figure 2.
5. From the required strength and details of the members the initial stiffness can be assessed, and hence the ductility one displacement, $D_y$, can be found.
6. The ductility one displacement found in step 5 is compared with the assessed value in step 1. If there is a significant discrepancy between these two values a new estimate of $D_y$ is made and steps 1 to 6 are repeated until convergence is obtained.

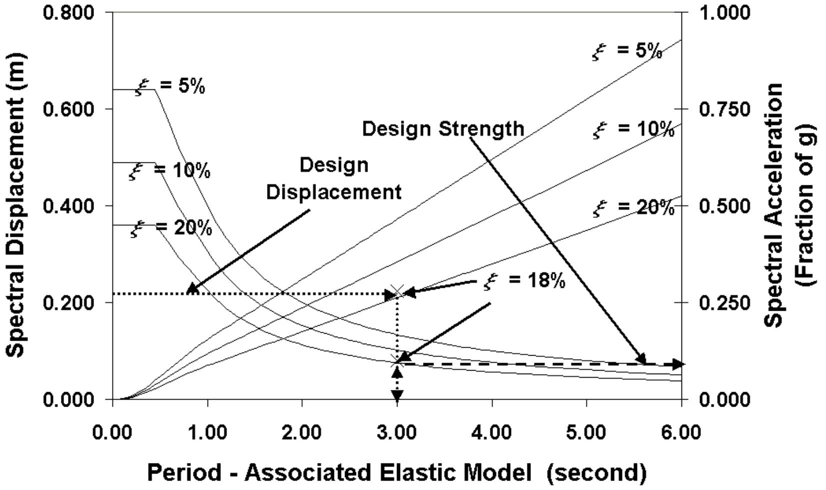

Figure 2-2 Direct Displacement Based Design

## 2.3 *Capacity Spectrum Non-linear Static Procedure*

The capacity spectrum non-linear static procedure method described in ATC40, which as outlined below, is intended for the analysis of existing structures. As the details of the structure are known its initial stiffness can be found. The process is illustrated in Figure 3. The following steps are required.

1. Spectral acceleration versus spectral displacement response spectra, for varying levels of viscous damping, are developed for associated elastic models.
2. A model of the design structure is subjected to a push over analysis to give a lateral force divided by mass versus displacement trace and this is superimposed on the response spectra.
3. From the analytical lateral force divided by mass versus displacement trace for the structure

the ductility one displacement, $D_y$, can be determined. This is used to define the displacement ductility values at different positions along the displacement trace.

4. Positions along this trace are assigned effective damping values. These depend on the ductility at the point being considered and the characteristics of the hysteretic response.
5. The predicted maximum displacement corresponds to a balance point where the effective damping value on the lateral force versus displacement trace intersects the design response spectrum for the associated elastic model with the same damping value.

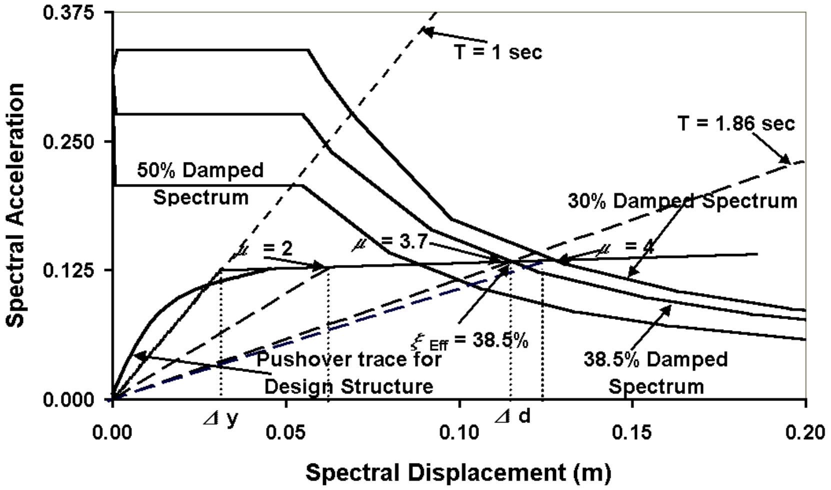

Figure 3 Capacity Spectrum Nonlinear Static Procedure

The effective damping values for the points on the lateral force displacement curve are calculated for different hysteretic relationships by taking the equivalent damping value found assuming a bi-linear response and multiplying by a factor, $k$. This factor has a maximum value of 1 and smaller values are used where the hysteretic forms show significant stiffness degradation, as less energy is dissipated. The $k$ factor acts as a calibration factor to improve the accuracy of the method.

As shown in the next section the direct displacement based design method and the capacity spectrum non-linear static procedure are in essence different versions of the same concepts.

### 2.4 *Modification of Direct Displacement Based Design and Capacity Spectrum Methods*

The direct displacement based design method can be modified to eliminate the need to determine the period of the associated elastic model. From Figure 3 it can be seen that the period of an associated elastic model is only required as a link between the displacement and acceleration response spectra. This link is unnecessary if spectral displacement versus spectral acceleration response relationships were drawn directly. With this modification it can be seen that the capacity spectrum and direct displacement based design methods are identical in concept. There are a number of minor differences between the two approaches as outlined below.

- Different rules are used to develop the spectral acceleration versus spectral displacement relationships with different levels of viscous damping. However, the corresponding values are in close agreement.
- With the Capacity Spectrum method the calibration factor, $k$, is applied to the equivalent damping coefficients found for bi-linear hysteretic response. With direct displacement based design the equivalent damping values are taken from a series of relationships determined for different hysteretic forms.

In a detailed study of the direct displacement based design method it was found that equivalent damping overestimates the damping values of the associated elastic models when the hysteretic forms exhibited limited stiffness degradation. This leads to an under-estimate of the required strength for this range of structures. Replacing "equivalent" damping by "substitute" damping, which is described in the next paragraph, was found to eliminate the need for the calibration factor, *k*, in the capacity spectrum method. This change also led to improved accuracy of prediction of the direct displacement design method [Judi et al. 2000, 2001b] over a wide range of hysteretic forms.

Substitute damping is defined as the level of viscous damping of an associated elastic model, which causes it to dissipate the same energy as the design structure when subjected to the full earthquake ground motion. In theory substitute damping values depend on the ground motion. However, analyses of a wide range of structures with different hysteretic responses to different ground motions have shown that the influence of the earthquake record is small. For practical purposes substitute-damping values can be determined on the basis of the ductility level, fundamental period of structure and hysteretic form. Expressions have been developed for these values [Judi et al. 2002b].

### 2.5 *Displacement Focused Force Based Design*

Force based design is widely used for seismic resistant structures and as such it is embedded in many seismic codes of practice. With a few modifications it can be changed into a displacement focused force-based design. A major advantage of this method is its similarity to existing practice.

The following steps are involved in displacement focused force based design.

1. An analytical elastic model of the structure is developed using estimated member sizes and details. From this model the fundamental period, T, is found.
2. From the design displacement versus period response spectrum the period $T_d$, which corresponds to the design displacement, $D_d$, is read off. If T is equal to or less than $T_d$ then the displacement of the structure will be less than the design value. If it is larger than this value the members need to be stiffened. If T is appreciably less than $T_d$ then a more efficient structure may be obtained by reducing the member sizes so that the period more closely approaches the critical value, $T_d$.
3. With the period T calculated, the required strength could be selected from the set of design (acceleration) spectra for the different ductility levels.

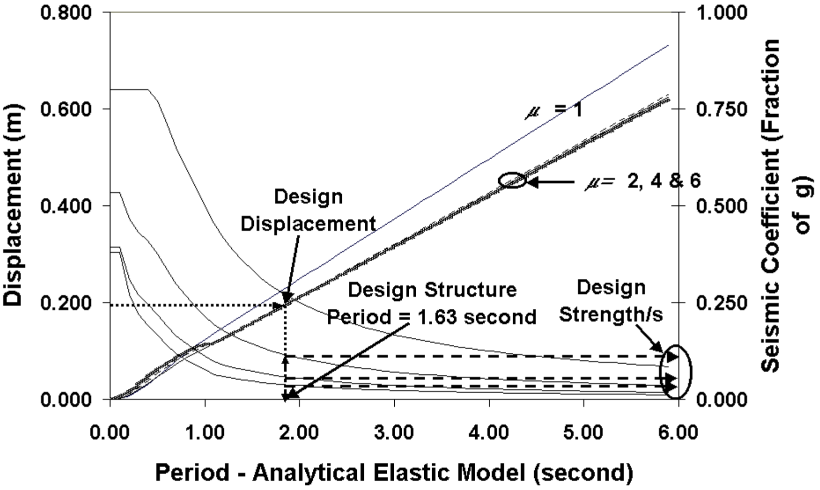

Figure 4 Displacement Focused Force Based Design

4. The process described above is illustrated in Figure 4. In this figure, the construction of the spectra is based upon the NZS4203:92 intermediate soil ductility one basic seismic hazard acceleration coefficient. The ductility 2, 4 and 6 acceleration spectra have been developed using the scale factors determined from the analysis of 16 earthquakes as described by Judi et al. [2002a]. The displacement spectra have been constructed from these using a simple bilinear envelope form. One point should be noted where this process is used with reinforced

concrete. Many codes of practice recommend that second moment of area values are taken as some fraction of the value based on the gross section. These recommendations vary significantly, for example Eurocode 8 [1994] recommends that the gross section properties are used for beams while in the NZ Structural Concrete Standard the corresponding recommendation for rectangular beams is to take 40% of the gross value. Neither recommendation recognises the influence of reinforcement content on stiffness. To allow for this factor the stiffness values used in step 1 should be based on assessed reinforcement proportions and these should be checked against those required for strength in step 3. If necessary the steps 1 to 3 should be repeated until convergence is obtained.

As with direct displacement based design the period of the elastic model can be used to link the displacement period and acceleration period response spectra. Hence one step may be removed from the design process by working directly with acceleration spectra, in a manner which is similar to the Capacity Spectrum method.

## 3 DESIGNS AND TIME HISTORY ANALYSES

As noted in section 2 the accuracy of both the "Direct Displacement Based Design" method and the "Capacity Spectrum Method" is improved if the viscous damping values for the associated elastic models are based on substitute damping rather than equivalent damping [Judi et al 2000, 2002]. Relationships that link substitute damping values with ductility, period of structure and the hysteretic form have been developed from analyses with a range of earthquake ground motions [Judi et al 2002].

To compare the three methods of design/analysis, a range of structures were designed using Displacement Focused Force Based Design, and a modified form of Direct Displacement Based Design. The modification involved using substitute damping instead of equivalent damping. In addition a range of structures were analysed using the Capacity Spectrum Method, which also was modified in that substitute damping was used instead of equivalent damping for an elastic- plastic hysteretic response and the calibration factor, *k*. The designs/analyses were repeated for three different hysteretic models, namely-

Elastic plastic response,

Column model, which was based on load deflection response observed in tests It exhibits stiffness degradation of both loading and un-loading curves [Fenwick et al. 1994],

Masonry model, which was also based on test results, and which exhibits greater stiffness degradation of the loading curves than the column model. It was developed using the approach proposed by Fenwick et al. [1994].

**Table 1 Details of Designs/Analyses of Structures**

| **Method of design** | **Number of structures** | | | **Period range (seconds)** | **Ductility range or values** |
|---|---|---|---|---|---|
| | **Hysteretic model** | | | | |
| | **Bilinear** | **Column** | **Masonry** | | |
| **Direct displacement based design** | 90 | 90 | 87 | 0.3 – 4.75 | 1.25- 6 |
| **Capacity spectrum method** | 87 | 86 | 85 | 0.3 – 4.75 | 1.25- 6 |
| **Displacement focused force based design** | 54 | 54 | 54 | 0.3 – 4.75 | 2, 4, & 6 |

In all cases zero strain hardening was assumed with a base level 5% viscous damping. The required strengths were found from the design spectrum for intermediate soils in the New Zealand Loadings Standard [NZS4203-1992]. Details of the designs/analyses are summarised in Table 1. Each designed/analysed structure was subjected to four earthquake records, which were scaled so that the peak response of a 5% damped elastic oscillator, with a period equal to that of the design structure, was equal to that implied by the design spectrum. The four earthquake records that were used were-

- Loma Prieta Earthquake 1989, Hollister, South St. and Pine Dr., Channel 1-90$^o$
- Landers earthquake, 1992, Joshua Tree Fire Station, Channel 3-0$^o$
- Northridge Earthquake 1994, Moorpark, Channel 1-90$^o$
- Northridge Earthquake 1994, Century City, LACC North, Channel 3-360$^o$.

In all cases the ratio of the peak displacement found in the time history analysis to the design displacement was calculated.

## 4 RESULTS OF ANALYSES

Each of the design structures noted in Table 1 was subjected to the four earthquakes ground motions, normalised as detailed in section 3. The ratios of the resulting time history displacements to the design displacements were calculated and averaged for the four ground motions. To study the effects of periods and ductility on the results, they were grouped into three period ranges, namely, 0.4 to 1.0s, 1.0 to3.0s and 3.0 to 5.0s. The averages were also regrouped into three ductility, $\mu$, subsets of $\mu<2$, $2<\mu<4$ and $4<\mu<6$. These groups are shown in Tables 2 and 3.

**Table 2 Results variation with periods**

| | | **Bilinear** | | **Column** | | **Masonry** | |
|---|---|---|---|---|---|---|---|
| | | **AVG** | **CoV** | **AVG** | **CoV** | **AVG** | **CoV** |
| **DDBD** | **0.4-1.0** | 0.983 | 0.126 | 0.988 | 0.094 | 1.153 | 0.106 |
| | **1.0-3.0** | 1.137 | 0.084 | 0.957 | 0.016 | 1.098 | 0.055 |
| | **3.0-5.0** | 1.023 | 0.051 | 0.886 | 0.055 | 0.972 | 0.062 |
| **CSM** | **0.4-1.0** | 0.800 | 0.136 | 0.831 | 0.090 | 0.961 | 0.075 |
| | **1.0-3.0** | 1.070 | 0.095 | 0.841 | 0.013 | 0.912 | 0.035 |
| | **3.0-5.0** | 0.985 | 0.027 | 0.796 | 0.053 | 0.825 | 0.054 |
| **DFFBD** | **0.4-1.0** | 1.127 | 0.097 | 1.065 | 0.126 | 1.128 | 0.154 |
| | **1.0-3.0** | 1.198 | 0.054 | 1.073 | 0.036 | 1.209 | 0.071 |
| | **3.0-5.0** | 1.030 | 0.047 | 0.964 | 0.083 | 1.038 | 0.101 |

Several observations can be made of the results of the analyses.

- The three methods are comparable in their effectiveness in predicting structural displacements with the three hysteretic models.
- The time history results showed a lot of scatter, which is in part due to the normalisation method, which was used for the four ground motions.

**Table 3 Results variation with ductility**

| | | **Bilinear** | | **Column** | | **Masonry** | |
|---|---|---|---|---|---|---|---|
| | | **Avg** | **Cov** | **Avg** | **CoV** | **AVG** | **CoV** |
| **DDBD** | $m\leq 2$ | 0.896 | 0.171 | 0.967 | 0.126 | 1.003 | 0.146 |
| | $2<m\leq 4$ | 0.956 | 0.197 | 0.907 | 0.117 | 1.077 | 0.144 |
| | $4<m\leq 6$ | 1.164 | 0.173 | 0.965 | 0.177 | 1.194 | 0.226 |
| **CSM** | $m\leq 2$ | 0.890 | 0.166 | 0.881 | 0.094 | 0.991 | 0.122 |
| | $2<m\leq 4$ | 0.865 | 0.186 | 0.768 | 0.096 | 0.859 | 0.123 |
| | $4<m\leq 6$ | 0.975 | 0.165 | 0.745 | 0.132 | 0.810 | 0.175 |
| **DFFBD** | $m\leq 2$ | 1.092 | 0.066 | 1.056 | 0.101 | 1.159 | 0.135 |
| | $2<m\leq 4$ | 1.100 | 0.130 | 1.023 | 0.105 | 1.135 | 0.164 |
| | $4<m\leq 6$ | 1.136 | 0.126 | 1.017 | 0.155 | 1.053 | 0.186 |

- The results indicate that for the bilinear model, DDBD and CSM methods tend to underestimate the displacements, i.e. conservative design strengths; while the DFFBD methods is more likely to overestimate structural displacements. This trend is reduced for the three methods with the stiffness degrading models showing better convergence to the optimal value of unity in the tables.

## 5 CONCLUSIONS

It can be concluded from the above that a displacement focus in seismic design is not a feature that is associated with a specific seismic design philosophy but rather a procedural modification that can be implemented in any approach, such as force based design. The three methods investigated showed comparable convergence in results for the range of hysteretic models reviewed. Hence this could be seen as a support for Displacement Focused Forced Based Design as its adoption does not require a major departure from a widely accepted existing design approach.

## 6 ACKNOWLEDGEMENTS

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