

# Performance-Based Design of a Self-Centering Concentrically Braced Frame using the Direct Displacement-Based Design Procedure

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## **SUMMARY:**

The design of structures using code prescribed methods often relies on a force-based design for life safety at the design level earthquake. Recent developments in earthquake engineering have seen the development of performance-based design to define specific performance objectives under a specified seismic intensity. The direct displacement-based design (DDBD) method has become increasingly popular among researchers and its benefits over force-based methods have been widely discussed. This paper introduces the design of a self-centering concentrically braced frame (SC-CBF) system using a DDBD approach and an example 3-storey SC-CBF is designed to a set of performance objectives for two levels of seismic intensity. Time-history analyses of the structure show that all of the performance objectives are met for each intensity level, demonstrating the benefits of DDBD when designing a SC-CBF to set performance objectives. Furthermore, by using a SC-CBF system, better performance can be achieved than in conventional CBFs.

*Keywords: self-centering, residual drift, displacement-based design, performance-based design.*

## **1.0. INTRODUCTION**

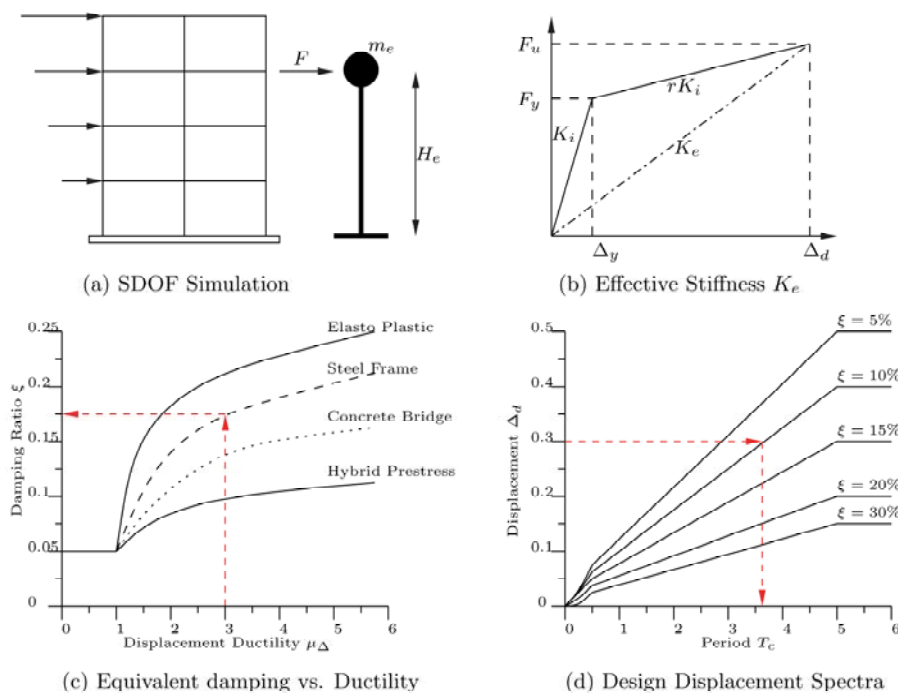
The design of structures towards specific performance objectives is becoming more and more important in seismic design. While many codes still specify the life-safety performance criteria under the design basis earthquake, many engineers are striving towards a more accurate way of describing damage states and designing systems to undergo prescribed amounts of damage under specific seismic hazard. One of the first set of performance levels was prescribed in the 'Vision 2000' document (OES, 1995), which was drawn up following the occurrence of the Northridge earthquake in 1994. This document described four different performance levels along with a performance matrix for various levels of seismic intensity. Using this, the performance of a structure could be accurately represented. This concept has become the blueprint for many later refinements of the performance based design concept.

The focus of this paper is to establish a set of performance goals for a newly developed self-centering concentrically braced frame. The details and behaviour of this SC-CBF is presented in an accompanying paper (O'Reilly *et al.*, 2012) and are not discussed here. The performance limits prescribed correspond to two different levels of seismic hazard for the downtown Los Angeles area. An example 3-storey structure is designed using the direct displacement-based design method (DDBD) to meet the performance goals for each of the seismic hazard levels specified.

The DDBD method is first introduced to the reader, followed by the establishment of a number of performance goals for the given seismic hazard levels. A series of ground motions representing these hazard levels are then used to perform nonlinear time-history (NLTH) analyses to evaluate the performance of the system. The results of the NLTH are then discussed and compared with the initial performance goals to evaluate the design method in adhering to the prescribed performance objectives.

## 2.0. DIRECT DISPLACEMENT-BASED DESIGN

Current design codes use a method of design that is primarily based on the forces rather than displacements. This is intuitive to a designer to think in terms of forces and by using simple prescribed force reduction factors and the equivalent lateral force method, a preliminary design can be readily obtained. One of the major downfalls of this method is its control of the structure displacements, which can be obtained with reasonable accuracy. However, the equal-displacement rule is widely known to be inaccurate for structures with short fundamental periods, and using the equal displacements approximation can lead to an underestimation of the structures deformations. This is just one of the many downfalls of the so called force-based method of design that exists in current design codes, and further discussion can be found in Priestley *et al.* (2007). An alternative to the force-based method is the direct displacement-based design (DDBD) method, which is presented in Priestley *et al.* (2007) and has been further developed by many researchers for a variety of structural systems. Fig. 2.1 shows the basis of the method, which is largely based on the concept of using a substitute structure approach. With reference to Fig. 2.1, the DDBD method represents a MDOF structure with an equivalent SDOF representation. Using this SDOF representation, the structure that has initial stiffness  $K_i$  and post-yield stiffness  $rK_i$ , is represented with an effective secant stiffness  $K_e$  to the desired design displacement  $\Delta_d$ , as in Fig. 2.1(b). Using this substitute structure and knowing something about the characteristics of the hysteretic behaviour of the structural system, the equivalent viscous damping can be obtained for the structure as shown in Fig. 2.1(c) for specified system ductility. Using this equivalent viscous damping (EVD) and design displacement set at the start of the design, the effective period for the substitute structure can then be obtained using the spectral displacement spectrum for a given seismic hazard Fig. 2.1(d). Using this effective period, the base shear can be obtained and the structure designed accordingly.



**Figure 2.1.** Basis of the DDBD procedure.

The DDBD of conventional CBFs has been investigated by many (Wijesundara, 2009; Salawdeh, 2012), and hence not discussed in detail here. However, the major differences between conventional CBFs and the SC-CBF are noted and the DDBD for conventional CBFs is adjusted accordingly. One of the main limitations of the DDBD when applied to CBF systems was the availability of an appropriate EVD model, with Goggins and Sullivan (2009) noting that at the time of publication, no

such model was available. An expression for the EVD in CBFs has since been developed by Wijesundara (2009) and also verified in an independent study by Salawdeh (2012). The expression developed for the EVD ( $\xi$ ) is as follows:

$$\xi_{CBF} = 0.03 + \left(0.23 - \frac{\bar{\lambda}}{15}\right)(\mu - 1) \quad \text{for } \mu \leq 2 \quad (2.1a)$$

$$\xi_{CBF} = 0.03 + \left(0.23 - \frac{\bar{\lambda}}{15}\right) \quad \text{for } \mu \geq 2 \quad (2.1b)$$

where  $\bar{\lambda}$  is the normalized slenderness (CEN, 2005) of the brace member and  $\mu$  is the system ductility as per Fig. 2.1. Wijesundara (2009) states that this expression is derived for braces for a  $\bar{\lambda}$  between 0.4 and 1.6. For braces with values outside this range, Wijesundara (2009) suggested to use the limit of either 0.4 or 1.6 for  $\bar{\lambda}$  in Eqns. 2.1a and 2.1b. Salawdeh (2012) has shown that a more accurate prediction for the EVD can be obtained without imposing these limits to  $\bar{\lambda}$  in Eqn. 2.1. Thus, no limits were imposed in Eq. 2.1 in the current study. Since the SC-CBF consists of both a CBF system and a post-tensioning (PT) system, the EVD model used for the SC-CBF must consider the combined response of these two structures. Thus, for a SC-CBF with N number storeys, the EVD expression for a SC-CBF ( $\xi_{SC-CBF}$ ) is as follows:

$$\xi_{SC-CBF} = \frac{\sum_{i=1}^N V_i \Delta_i \alpha_{CBF,i} \xi_{CBF,i} + \sum_{i=1}^N V_i \Delta_i \alpha_{PT,i} \xi_{PT,i}}{\sum_{i=1}^N V_i \Delta_i} \quad (2.2)$$

where  $V_i$  and  $\Delta_i$  are the storey shear and displacement,  $\xi_{CBF,i}$  is the EVD for the braces as given in Eqn. 2.1 and  $\xi_{PT,i}$  is the EVD due to the PT system, which is assumed here to be 5% throughout. The  $\alpha_{CBF,i}$  and  $\alpha_{PT,i}$  terms represent the ratio of storey shear resisted by the CBF and PT systems respectively, where their sum is unity.

This represents the major change in DDBD of the SC-CBF compared to the conventional CBF. The rest of the procedure is carried out as described by Wijesundara (2009), and the base shear is obtained for the equivalent system. The SC-CBF is then designed and detailed in a similar fashion to an accompanying paper (O'Reilly *et al.*, 2012), where the forces and displacement were obtained using the code-based equivalent lateral force procedure.

### 3.0. PERFORMANCE OBJECTIVES

The principle goal of this paper is to demonstrate the applicability of the DDBD procedure in the design of SC-CBF to specified performance goals. These performance goals are set out here for a SC-CBF, where an example 3-storey will be analysed under sets of earthquakes corresponding to the seismic hazards set out in the performance matrix. Table 3.1 list two hazard levels for which the SC-CBF is designed with the corresponding performance objectives. These hazard levels are the 10% probability of exceedence in 50 year event, which is labelled the design basis earthquake (DBE), and the 2% probability of exceedence in 50 year event, which is termed the maximum considered earthquake (MCE).

An essential performance goal that is included in all performance levels is the behaviour of the beams, columns and PT elements. Since the SC-CBF relies on the elastic behaviour of the beams and columns, these must be designed to remain elastic and are capacity designed to an interstorey drift ratio (IDR) of 4%. Even more critical to the performance of the SC-CBF, is the behaviour of the PT

elements. Since these provide the restoring force to the SC-CBF, yielding of these elements must be mitigated to avoid losing the initial prestress that is applied. In order to ensure this, the PT elements are designed to remain elastic up to an IDR of 5%. The next performance goals are the maximum IDR's and residual drifts (RD) that are allowed. For the DBE, an IDR of 2.5% is specified in accordance with Eurocode 8 (EC8) (CEN, 2004). For the MCE, an IDR of 4% is specified which is based on engineering judgement. It is also a limit used by Clayton *et al.* (2012) in a similar study for the performance based design of a self-centering steel plate shear wall system. This limit may not apply as the brace fracture ductility may dictate that a lower drift be used to avoid brace fracture, which will be seen later. For the residual drifts, a maximum RD of 0.2% was specified as this was used in similar studies (Clayton *et al.*, 2012; Henry, 2011) in other self-centering systems, and also as it is a more stringent limit that the construction tolerance level specified in Eurocode 3 (CEN, 2005), which gives a limit of 0.272% for the building examined later in this paper. For the MCE, a limit of 0.3% was set as per the performance matrix, which was set out by Henry (2011) for the same seismic hazard levels.

In order to avoid brace fracture, the IDR must remain sufficiently low in order to not exceed the brace fracture ductility. Experimental and numerical investigation by Nip *et al.* (2010) resulted in the development of a series of expressions for the brace fracture ductility in terms of the brace properties. These expressions are given in terms of the brace non-dimensional slenderness ( $\bar{\lambda}$ ) and the width-to-thickness ratio. If the brace fracture ductility is exceeded at the design IDR, then the target IDR must be lowered or a different brace member be selected.

**Table 3.1.** Performance objectives for the 2 levels of seismic hazard.

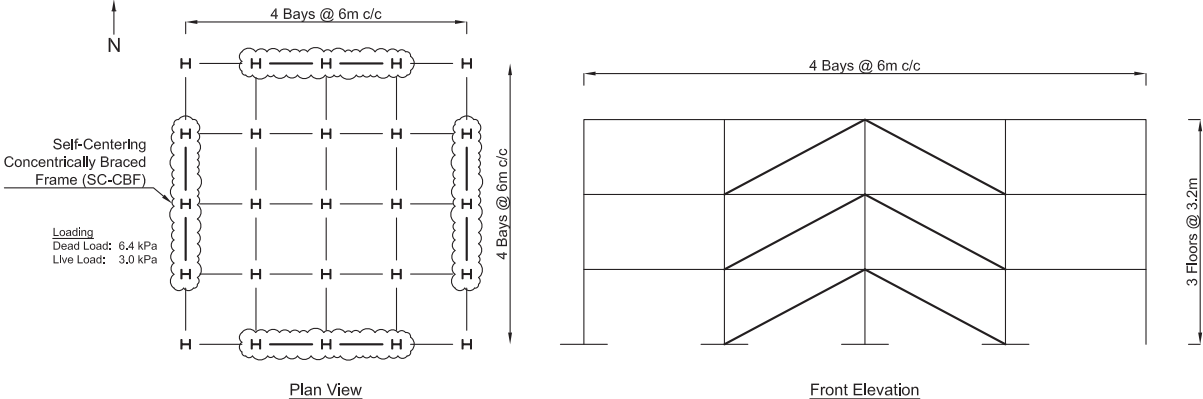
Hazard Level	Performance Objectives
10% in 50 years (DBE)	<ol style="list-style-type: none"> <li>1. Beams remain elastic.</li> <li>2. Columns remain elastic.</li> <li>3. PT Elements remain elastic.</li> <li>4. IDR &lt; 2.5%</li> <li>5. RD &lt; 0.2%</li> <li>6. Brace remain ductile and avoid fracture.</li> </ol>
2% in 50 years (MCE)	<ol style="list-style-type: none"> <li>1. Beams remain elastic.</li> <li>2. Columns remain elastic.</li> <li>3. PT Elements remain elastic.</li> <li>4. IDR &lt; 4.0%</li> <li>5. RD &lt; 0.3%</li> <li>6. Brace remain ductile and avoid fracture.</li> </ol>

## 4.0. DESIGN AND ANALYSIS OF 3-STOREY SC-CBF

### 4.1. Description of Building and Ground Motions

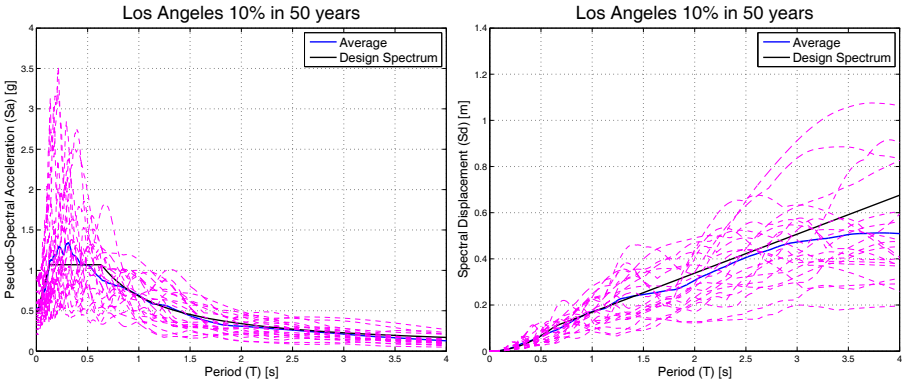
The design example presented here is a 3 storey SC-CBF (Fig. 4.1) assumed to be located in downtown Los Angeles, which is designed using the DDBD procedure as described above, and to two different seismic hazard and performance levels. The initial seismic design is conducted as per the DDBD procedure in order to obtain seismic forces, but the design of the members such as beams, columns and braces are as per EC8 specifications. O'Reilly *et al.* (2012) describes the design according to EC8 in more detail and are not discussed here. The method of design to meet the performance objectives in Table 3.1 are such that a design to the MCE level is first carried out to the specified drift and design spectrum. Similarly, a design is also carried out to the DBE and its corresponding design spectrum. Whichever design is more critical is the one that is adopted for the final design. For the case of the 3 storey SC-CBF, a design to 4% IDR was carried out first for the MCE event, followed by a design to 2.5% IDR for the DBE event. The base shear obtained in the MCE at 4% IDR was larger than the base shear for the DBE at 2.5%, so the MCE design base shear

both DBE and MCE, the target IDR would need to be reduced to approximately 1.3% for the DBE design, so it is expected that the response of the 3 storey SC-CBF will have IDR approximately equal to this for the DBE event.

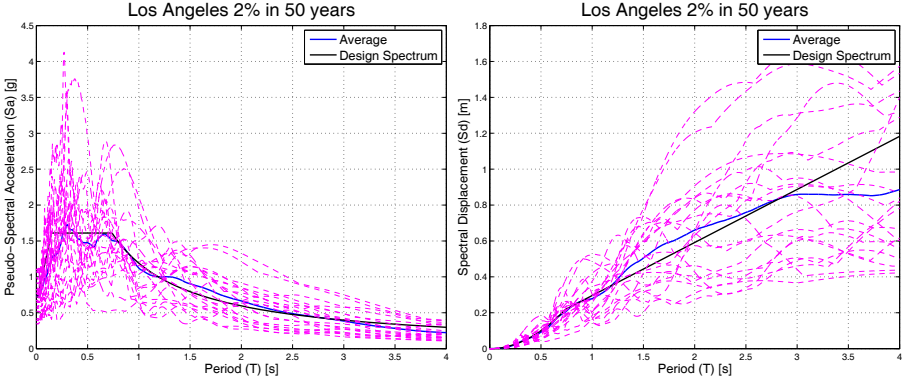


**Figure 4.1.** Layout of 3-storey SC-CBF.

For the two seismic hazard levels, ground motions from the SAC Steel project (Somerville *et al.*, 1997) are used here. These correspond to the specified hazard levels for the Los Angeles area and are scaled to match the spectral values set out in Somerville *et al.* (1997). Details for the ground motions are provided in Somerville *et al.* (1997), and a plot of the design spectra for both hazard levels are shown in Figs. 4.2 and 4.3. The ground motions for the DBE were further scaled by 0.9 to better match the design spectrum, and similarly the MCE ground motions were scaled by 0.83.



**Figure 4.2.** Design spectrum and ground motions used for the 10% in 50 years event (DBE).



**Figure 4.3.** Design spectrum and ground motions used for the 2% in 50 years event (MCE).

The building is then designed to meet the specified performance goals using the DDBD as described by Wijesundara (2009) for CBFs with the appropriate modifications for the SC-CBF as previously mentioned. The material strength and assumptions for the design are all as per the force-based design carried out on the same building in O'Reilly *et al.* (2012) where Grade S355 steel is used for the beams, columns and braces, and Grade S1650 steel is used for the PT Strands. The resulting design for the DDBD of the SC-CBF to the performance objectives listed in Table 3.1 is listed in Table 4.1.

**Table 4.1.** Prototype design for the 3 storey SC-CBF according to the DDBD procedure.

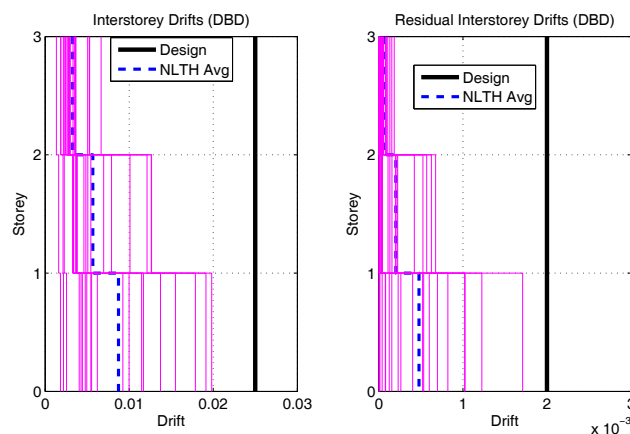
Storey	Braces	Columns	Beams	PT Force [kN]	No. of Strands
3	120x120x8-HSS	W12x12x120	W24x9x103	561	12
2	150x150x12.5-HSS	W12x12x190	W24x9x114	611	12
1	180x180x12-HSS	W12x12x210	W24x9x146	763	14

## 4.2. NLTH Analysis Results and Discussion

Using the parameters listed in Table 4.1 for the SC-CBF and the modelling parameters developed in O'Reilly *et al.* (2012), a series of nonlinear time-history analyses were carried out for the ground motions previously described. The results from the DBE event and MCE event will be presented and the performance of the SC-CBF designed using the DDBD procedure to meet the performance objectives listed in Table 3.1 will be evaluated.

### 4.2.1. DBE Results

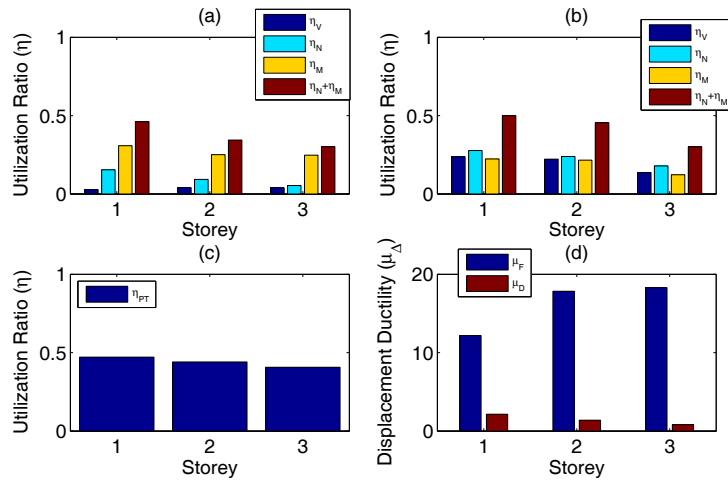
Table 3.1 lists six performance goals to be checked in order to evaluate the performance of the system. These include the behaviour of the beams, columns and PT elements, the level of interstorey drift and residual drift, and the ductility of the braces. Fig. 4.4 shows a plot of the IDR's and RD's observed during the response to the DBE event. Firstly it is noted that the IDR's are less than the 2.5% limit set out for the DBE event, and secondly that the RD's are also less than the 0.2% limit specified in Table 3.1. Furthermore, it can also be seen from Fig. 4.4 that the IDR's are not greater than ~1.3%, which is because the MCE governed the design process as previously mentioned.



**Figure 4.4.** NLTH IDR's and RD's for the DBE event.

The next performance goals are for the beams, columns and PT elements to remain elastic, and also for the brace ductility not to exceed the fracture ductility. Fig. 4.5 shows a plot of the utilisation ratio ( $\eta$ ) for all of these performance objectives, where the combination of axial and moment interaction is the most critical utilisation ratio for the beams and columns. Since all of these utilisation ratios are less than unity for the beams, columns and PT elements, this satisfies the performance objective that they should all remain elastic for the DBE event. The brace fracture ductility is calculated for the braces at the various storeys of the SC-CBF using the expressions developed by Nip *et al.* (2010) for the fracture ductility of tubular brace members. Since the demand ductility ( $\mu_D$ ) of the braces in the analysis is less than the fracture ductility ( $\mu_f$ ) calculated using Nip *et al.* (2010)'s equations, this

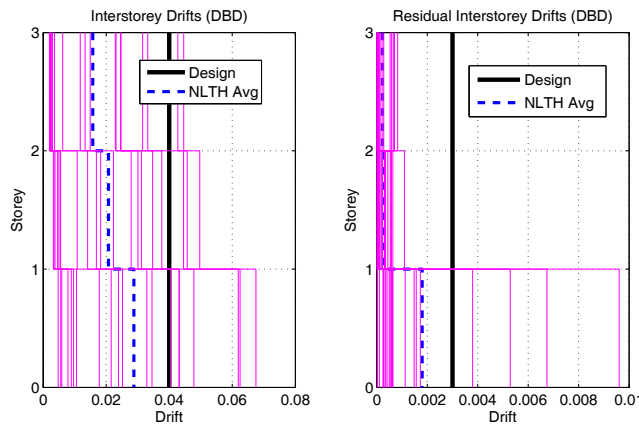
satisfies the performance objective that the braces remained ductile and did not fracture during the DBE event.



**Figure 4.5.** Utilisation ratios for (a) beams, (b) columns, (c) PT elements and (d) brace ductilities for the DBE event.

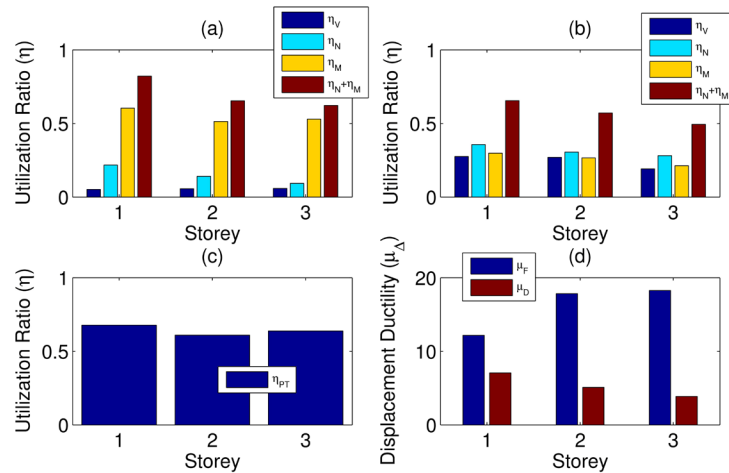
#### 4.2.2. MCE Results

Fig. 4.6 shows a plot of the interstorey drifts and residual drifts for the SC-CBF when subjected to the ground motions corresponding to MCE event. Again, when the response of the SC-CBF to the ground motions is compared to the prescribed performance goals for that seismic hazard level, it can be seen that these goals are met. The average IDR is less than the limiting 4%, and the average residual drift of the structure is less than the prescribed 0.3%. It is also observed from Fig. 4.6 that the average residual drifts actually are less than 0.2%, which actually satisfies the DBE performance goals also at the MCE event intensity level.



**Figure 4.6.** NLTH IDR's and RD's for the MCE event.

Fig. 4.7 shows a plot of the utilisation ratios of the beams, columns, PT elements and the ductility demands for the MCE event. It can be seen that the performance goal of elastic behaviour in the beams, columns and PT elements is met as all of the utilisation ratios of the members remain less than unity. For the braces, it can be seen that the ductility demand at each level are well below the fracture ductility calculated using the expression developed by Nip *et al.* (2010).



**Figure 4.7.** Utilisation ratios for (a) beams, (b) columns, (c) PT elements and (d) brace ductilities for the MCE event.

## 5.0. CONCLUSIONS

The design of a SC-CBF according to the DDBD procedure was presented. The basic concept of the DDBD procedure was introduced followed by how existing methods of DDBD for conventional CBFs may be modified for the design of SC-CBFs. A set of performance goals were defined for two different seismic hazard levels and an example 3-storey SC-CBF was designed using DDBD to meet those performance goals. These goals included interstorey drifts, residual drifts and the behaviour of the beams columns and PT elements. NLTH analyses were performed using two sets of ground motions representative of the hazard levels defined. The results of the NLTH analyses were then evaluated and compared to the performance goals specified at the start of the design process.

Comparing the results of the NLTH analyses with the performance goals, it was shown how all of the performance goals were met for each of the seismic hazard levels and that the DDBD of SC-CBFs can be integrated effectively into a performance based framework for various seismic hazard levels. This not only demonstrates the effectiveness of the framework, but also how by using a SC-CBF, superior performance objectives are possible than would be if conventional CBFs had been used, namely in the mitigation of residual deformations. While the result presented are promising in terms of the performance of the SC-CBF at different intensity levels, and the use of the DDBD procedure in a performance based design framework, further parameter studies are necessary in order to develop this framework into a set procedure for a variety of SC-CBF types.

## ACKNOWLEDGEMENTS

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