Issues with the seismic design of mixed MRF Systems

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SUMMARY:

Engineers may be asked to design mixed MRF buildings in which a change in material occurs at a certain level in a building. This work reviews current code design recommendations for such scenarios. Following this, a series of 8-storey mixed MRF systems of steel and reinforced concrete (RC) construction are designed using both the direct displacement-based design (DDBD) method (Priestley *et al.*, 2007) and the ASCE-SEI 7-10 (ASCE, 2010) equivalent lateral force (ELF) method for ULS.

The ELF method of ASCE-SEI 7-10 produces designs that are governed by drift limits and is shown to be conservative for the scenarios considered during assessment using non-linear time-history analyses (NTHA). For the DDBD method, peak displacements of the systems match the design displacements well. Overall, the study indicates that changes in inelastic behaviour can, however, influence the response of mixed MRF systems, particularly for what regards higher mode drift response and residual deformations.

Keywords: DDBD, FBD, Mixed systems, Steel MRF, Reinforced Concrete MRF

1. MIXED MRF SYSTEMS

In practice it is common for a building to be constructed making use of different materials to take advantage of the strengths and weaknesses of various materials for structural purposes. It is, however, less common for a seismic lateral force resisting system to use mixed construction that involves a change in material at a certain point or points in the structure. Cases do exist of mixed systems where a complete change in construction material occurs at some point over the height of a building as depicted in Figure 1.1. Such a transition in materials requires special attention to ensure the adequate transfer of design actions and consideration of continuity of both strength and stiffness. For example, during the 1995 Kobe earthquake the change in construction material from steel encased reinforced concrete (SRC) construction to reinforced concrete (RC) only or to steel only construction was identified as a contributing factor in many mid-storey collapses observed in frame buildings (Chung, 1996). These two scenarios, SRC to RC and SRC to steel construction, can be considered indicative of a lack of continuity of strength and of stiffness, respectively.

Given such complications, the use of a single material system is generally favoured for simplicity and may, in fact, be a requirement of building standards. However, when permitted, either as a retrofit or new build scenario, a key difficulty for any designer considering the use of mixed construction for seismic lateral force resisting systems is that building standards and design codes generally lack provisions for mixed systems. Design code procedures are traditionally based on a single material type and often contain material specific assumptions or models. In the design for gravity and wind loading, a piecewise approach can be taken when using different construction materials provided appropriate attention is given to detailing of mixed connections. However, for seismic design, where non-linear behaviour is often allowed to occur and displacement compatibility and dynamic effects are of greater significance, such a piecewise design approach may no longer be considered valid and a system level approach is required. Consequently, the difficulty lies in the seismic design of such mixed systems and the application of code design procedures intended for use with a single material-type system. This presents a major uncertainty for the seismic design of mixed systems and forms the basis for the motivation of the research. The work presented here summarises the results of initial studies on the issues faced during system level design and assesses the performance of case study frames designed using both Displacement-based design (DBD) and Force-based design (FBD) procedures.

Figure 1.1. Examples of concrete/steel and concrete/timber mixed construction with a change in construction material over the height in North Carolina (image courtesy of the Independent Weekly)

Moment resisting frame systems (MRFs) provide a natural starting point for investigating the seismic design of mixed systems. Columns and beams of different composition may be used together and/or changed over the system height. Due to their flexible nature, the design of MRFs is usually controlled by limiting the interstorey drift response meaning that the drift or displacement response of the system must be adequately allowed for during design. For taller MRFs, higher mode drift amplification becomes a significant factor requiring consideration to ensure adequate design level response. Different materials and non-linear behaviour will have differing effects on the displacement response and the magnitude of drift generated by higher modes, thus for mixed MRF systems the influence of changing properties on these response quantities requires careful consideration.

2. DBD OF MIXED MRF SYSTEMS

Direct displacement-based design (DDBD) has been developed by Priestley *et al.* (2007) as a more rational approach to seismic design than traditional FBD methods as design carried out to a target displacement or drift from the outset. Recent development of the method has seen the publication of a displacement-based design model code DBD12 (Sullivan *et al.*, 2012). In DDBD the displacement response of the system under design is the focus and the system strength, and subsequently stiffness, is set with the goal of achieving the target level response for a design level earthquake. The method uses the substitute structure approach of Shibata & Sozen (1974), together with equivalent viscous damping (EVD) expressions as explained by Priestley *et al.* (2007).

Figure 2.1 presents a brief outline of the DDBD method where the multi-degree of freedom (MDOF) system is converted into a single-degree of freedom (SDOF) substitute structure to represent the fundamental mode response (Figure 2.1a). This SDOF structure is defined by an equivalent system mass and height and is characterised by the secant or effective stiffness at the peak displacement (Figure 2.1b). For design, a target peak displacement response is set according to deformation limit states corresponding to the desired performance level of structural and non-structural elements. At this point, knowledge of the yield displacement of the structure is required in order to estimate the system displacement ductility at the peak response and allow an estimation of the system EVD (Figure 2.1c). If the yield displacement can be established independently of the strength within the system, the system ductility demand is given directly without the need for iteration.

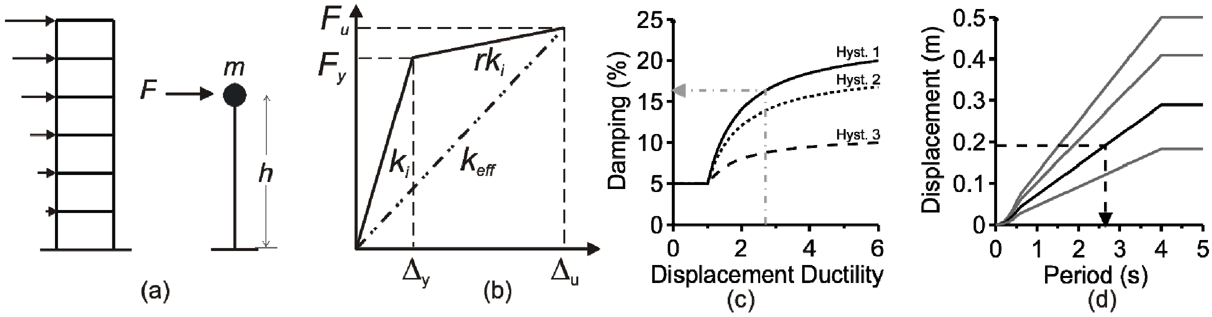

Figure 2.1. Key steps of DBD for MODF systems: (a) equivalent SDOF system, (b) effective stiffness and ductility, (c) EVD vs. ductility, (d) design displacement spectra (adapted from Priestley *et al.*, 2007)

In order to estimate the EVD from the ductility of the system at maximum response, an appropriate damping-ductility relationship calibrated to the expected hysteretic response of the system is used as illustrated in Figure 2.1c. The EVD represents the combined effects of elastic and hysteretic energy dissipation within the system. Thus, with the EVD and the design displacement of the system known, the required secant or effective period of the system is obtained from the reduced design displacement response spectrum as shown in Figure 2.1d. From this effective period, the design base shear of the system is given directly by simple calculation from Equations 1 and 2.

$$K_e = 4\pi^2 m_e / T_e^2 \tag{1}$$

$$V_B = K_e \Delta_d \tag{2}$$

where K_e is the effective stiffness, m_e the effective mass, T_e the effective period, V_B the design base shear, and Δ_d the equivalent SDOF system design displacement.

It is also noted that for MRF systems the design base shear is applied to the structure using the distribution given by Equation (3) where 90% percent of the base shear is applied in proportion to the mass and the expected displacement profile whilst the remain 10% is applied at the roof level of the structure. The use of this redistribution of 10% of the base shear to the roof level, similar to that prescribed by the New Zealand code NZS 1170.5 (NZS, 2004) is to aid in the control of higher modes.

$$F_i = F_t + 0.9 V_B \left(m_i \Delta_i\right) \Big/ \sum_{i=1}^{n} \left(m_i \Delta_i\right) \tag{3}$$

where F_t=0.1V_B for the top level and F_t=0 everywhere else.

For DDBD, the system EVD, ξ_{sys}, may be found from Equation 4 where the EVD of each storey i is estimated and then weighted by the work done of the storey (storey shear, V_i and storey drift, θ_i) over the height of the system to give an estimate for the system EVD.

$$\xi_{sys} = \frac{\sum V_i \theta_i \xi_i}{\sum V_i \theta_i} \tag{4}$$

Equation 5 and Equation 6 are given by Priestley *et al.* (2007) for estimating EVD as a function of ductility μ for concrete and steel frame systems respectively.

$$\xi = 0.05 + 0.565\left(\frac{\mu - 1}{\mu\pi}\right) \tag{5}$$

$$\xi = 0.05 + 0.577\left(\frac{\mu - 1}{\mu\pi}\right) \tag{6}$$

3. FBD OF MIXED MRF SYSTEMS

As explained in the introduction there is little guidance available for an engineer when designing a mixed system in using current code (force-based) design methods. The work presented here focuses on the equivalent lateral force (ELF) procedure given by ASCE/SEI 7-10 (ASCE, 2001) which does give some guidance for the horizontal or vertical combination of framing systems. In contrast, in the European and New Zealand codes (Eurocode 8 (CEN, 2008) and NZS 1170.5 (NZS, 2004) respectively) no direct consideration of such systems is given.

The ELF method of ASCE/SEI 7-10 is applicable to all structures without vertical irregularities that do not exceed 160ft or 48.8m and structures higher than this with no irregularities although with a restriction on the fundamental period of 3.5 times the corner period of the design acceleration spectrum. For the ELF method, the fundamental period can be estimated from approximate equations based upon height and structural type that tend to underestimate actual period values.

For vertical irregularity, ASCE/SEI 7-10 (ASCE, 2010) gives weak or soft storey irregularity limits that are relative to the strength and stiffness of the storey or storeys above a given storey. Thus, if any change in stiffness over the height of a mixed MRF system is limited to a reduction in stiffness with height, and increases in stiffness with height are avoided, these irregularity limits are satisfied. Such a restriction on the stiffness properties can be considered prudent for design in areas with significant seismicity. A further weight or mass irregularity limit of no storey having a mass greater than 150% of any adjacent storey with the exception of the roof level is given. This is perhaps the only likely vertical irregularity limit that may not always be met for mixed systems due to large differences in mass between steel & RC systems.

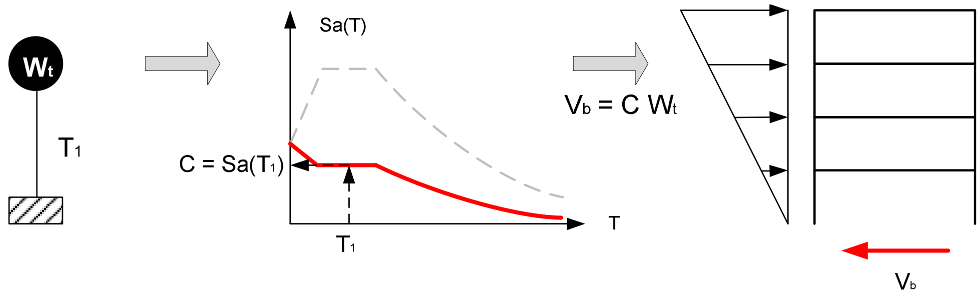

Figure 3.1. Outline of ASCE/SEI 7-10 ELF method based on the fundamental mode response

Figure 3.1 summarises the main steps of the ELF method of ASCE/SEI 7-10 graphically where the estimated fundamental mode response is used to define a seismic coefficient from an inelastic design spectrum. The seismic coefficient is then combined with the seismic weight of the system to give the design base shear that is applied to the structure using a triangular distribution. Note that the elastic design spectrum is reduced as a function of the response modification factor R to give an inelastic spectrum. In addition to this, a displacement check is carried out under these design lateral loads to ensure that, when the displacements obtained from static analyses are amplified by the deflection amplification factor C_d, the drift limit is respected. Exceeding the drift limit requires the design process to be repeated with a reduced response modification factor R.

ASCE/SEI 7-10 gives design coefficients for MRF systems of steel, RC, and steel and RC composite construction for use with the ELF or modal response spectrum (MRS) procedures in addition to means of estimating the initial period of such systems. The values given for these systems are given in Table 3.1 below based on the type or ductility class of the system being designed.

Table 3.1. ASCE/SEI 7-10 design coefficients for RC, steel, & RC & steel composite MRFs

MRF Type	Response modification factor, R	Overstrength factor, Ω_o	Deflection amplification factor, C_d
Special MRF	8	3	5.5
Intermediate MRF	5 (4.5)	3	4.5 (4)
Ordinary MRF	3 (3.5)	3	2.5 (3)

*where given values in brackets are for steel only MRFs

For the vertical or horizontal combinations of framing systems in the same direction the provisions of ASCE/SEI 7-10 state that the most stringent of the applicable structural limitations must be applied. An exception is granted for vertical combinations where the upper system has a smaller response modification factor, R, than the lower system. In this case the design coefficients R, Ω_o, and C_d of the upper system can be used for the upper system and the larger R and corresponding coefficients Ω_o and C_d may be used for the lower system provided the forces transferred between the upper and lower systems are amplified by the ratio of the larger R coefficient to the smaller R coefficient.

Finally, for completeness it is noted that a two-stage ELF method, where upper and lower portions are designed separately, is allowed under certain circumstances. However, one of the conditions is that the stiffness of the lower portion must be at least 10 times the stiffness of the upper portion which is likely to be excessively restrictive for MRF only systems.

4. DBD & FBF OF CASE STUDY SYSTEMS

Following the DBD model code DBD12 (Sullivan *et al.*, 2012) and the ELF procedure of ASCE/SEI 7-10 (ASCE, 2010), DBD and FBD solutions have been found for 8-storey MRF systems of steel, reinforced concrete (RC), and mixed RC and steel construction where the lower 4-storeys are of RC construction and the upper 4-stories are of steel construction (Figure 4.1). For both the DBD and FBD solutions the design response spectrum has been taken from ASCE/SEI 7-10 for a high level of seismicity (Figure 4.2) and an allowable drift level of 2.5% has been assumed for the ultimate limit state (ULS). In all cases rigid full strength connections have been assumed including column base connections to a rigid foundation.

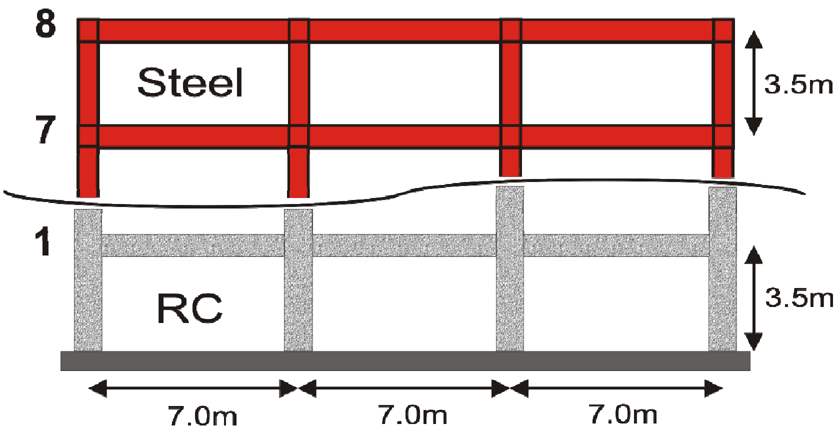

Figure 4.1. Generic elevation for case study MRFs considered

For each of the designs 5% elastic damping has been assumed and the seismic weight kept constant. For the DBD of the MRFs uniform RC beam and column sections have been considered of 0.6x0.4m and 0.65x0.45m, respectively, over the height of the system. For steel members, the W18 and W14

AISC (AISC, 2001) section groups and their characteristic Z/I properties have been used. These section properties have been considered for both the FBD and DBD solutions during the performance assessment carried out in the following section. The resulting design solutions as summarised in Table 4.1 and Table 4.2 for the DBD and FBD procedures respectively.

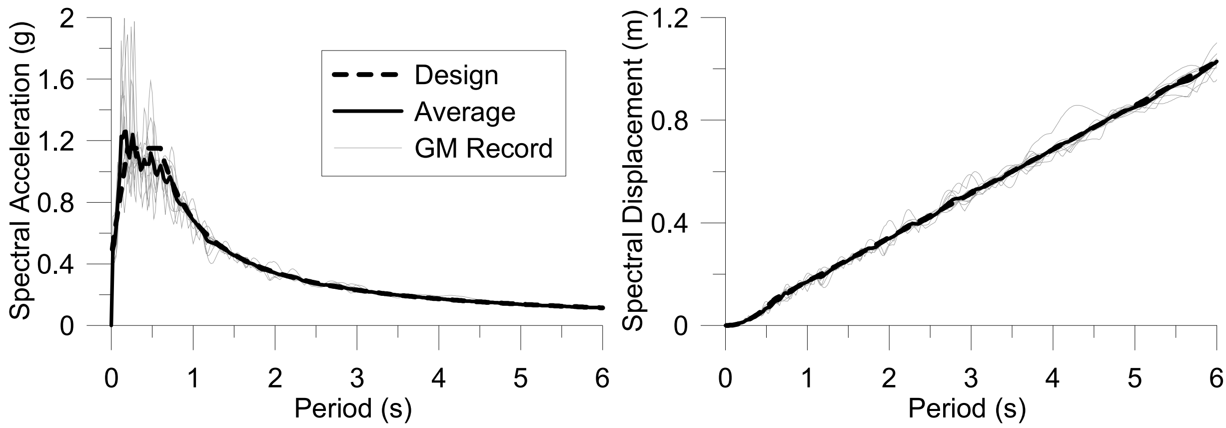

Figure 4.2. Design acceleration spectra (left panel) and displacement spectra (right panel) with spectra from ground motion set used for NTHA

Table 4.1. Design results for DBD systems

	Steel	Mixed	Concrete
μ_{sys}	1.16	1.51	1.60
ξ_{sys} (%)	7.62	10.5	11.5
T_e (s)	3.24	3.59	3.70
V_b (kN)	1925	1569	1474
V_b/W_t	0.128	0.105	0.098
R^*_F	1.60	1.84	1.88
T_1 (s)	2.76	2.91	3.04
T_2 (s)	1.01	1.09	1.18
T_3 (s)	0.55	0.64	0.70

Table 4.2. Design results for FBD systems

	Steel	Mixed	Concrete
R^*	2.11	2.26	2.58
C_d^*	1.45	1.55	1.77
T_a (s)	1.041	0.988	0.935
V_b (kN)	3850	3758	3541
V_b/W_t	0.257	0.251	0.236
C_s	0.26	0.25	0.24
T_1 (s)	2.03	1.84	1.84
T_2 (s)	0.76	0.72	0.72
T_3 (s)	0.45	0.43	0.42

* values used to comply with storey drift limit of 2.5%

5. NTHA PERFORMANCE ASSESSMENT OF DESIGN SOLUTIONS

In order to assess the performance of each of the design solutions, NTHAs using RUAUMOKO3D (Carr, 2004) have been carried out. For these analyses lumped mass and plasticity models have been used to assess the system response of the designs using the spectrally matched accelerograms given previously in Figure 4.2 (Pennucci *et al.*, 2009). In all cases the member stiffness properties used are those related to the design member strength and the expected section yield curvature ($EI=M/\phi_y$), analogous to the secant to yield stiffness, thus approximating cracked section properties for the RC sections.

Capacity design is enforced for the analyses by permitting hinges to form only at the beam ends and the column bases thus imposing a beam-sway mechanism. Gravity loads have been neglected during modelling and were not considered when setting member strengths. The bi-linear and Takeda 'fat' (α =0.3, β=0.6) hysteretic rules are used to characterise the rigid connection steel and reinforced concrete (RC) frames respectively (see Carr, 2004). Note that for the column base level the Takeda 'thin' (α =0.5, β=0) hysteretic rule has been used to simulate the behaviour of RC sections under bending and axial load. For all cases a post-yield moment-curvature stiffness ratio of 0.02 has been assigned.

A tangent stiffness proportional damping approach has been adopted for this study over the more traditional elastic stiffness proportional damping following the reasoning outlined in Priestley *et al.* (2007). As pure tangent stiffness proportional damping is not available within Ruaumoko3D (Carr, 2004) for MDOF systems, tangent-stiffness Rayleigh damping has been used with an adjustment made to the elastic damping for a damping level of 5% using the procedure given by Priestley *et al.* (2007). For this study P-Δ effects have been neglected. Using these modelling assumptions the resulting periods are given in Table 4.1 and Table 4.2 for the respective design scenarios considered.

The peak drift results for all of the design solutions presented in this work are given in Figure 5.1. Note that the results from the DBD and FBD methods differ significantly. The DBD solutions respond at a level consistent with the drift limit used during design whilst the FBD solutions respond at a level significantly below the drift limit. This relative difference in response is not unexpected considering the increased design base shear required by the FBD method over the DBD method as can be seen in Table 4.1 and Table 4.2. The FBD method requires a design base shear of 2 to 2.4 times that of the DBD method which reduces the average drift response level from around 2.5% for the DBD method to around 2%, where much of the system undergoes little inelastic behaviour. It is worth noting that the altered base shear distribution used for DBD to help control higher mode effects reduces the response in the upper levels and results in more uniform drift response, thus assigning strength more efficiently.

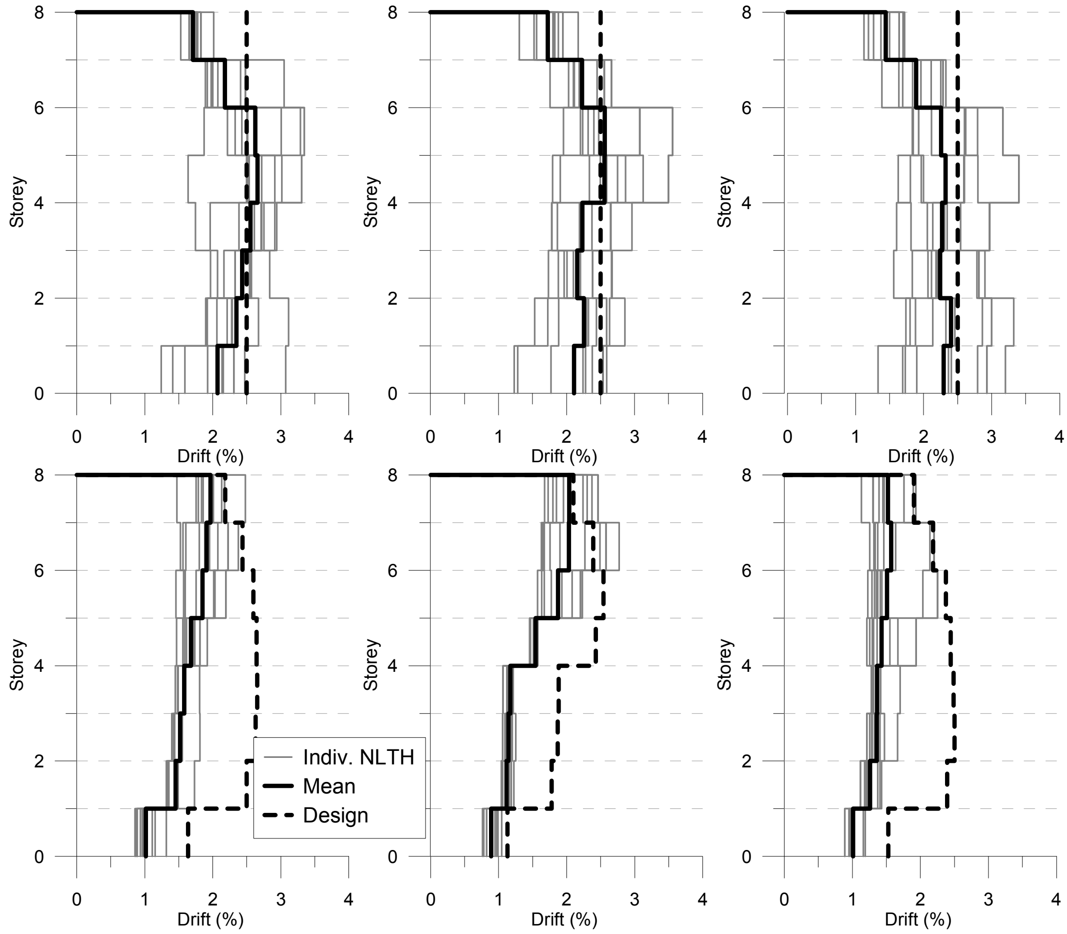

Figure 5.1. NTHA peak drift results for steel (left panels), mixed (central panels), and concrete (right panels) systems for DBD (upper panels) and FBD (lower panels) systems at 100% of the design intensity

Between the different scenarios considered in Figure 5.1, the effect of the reduction in stiffness at mid-height of the mixed system (where there is a transition from RC to steel construction) is noticeable for both design methods, although more so for the FBD solution due in part to the altered strength distribution used for DBD. To examine more closely the response of the mixed systems, peak displacement and residual drift profiles are given together with the peak drift profiles in Figure 5.2 where it can be seen that the reduction in stiffness and change in hysteretic behaviour at the transition also influences residual drift levels.

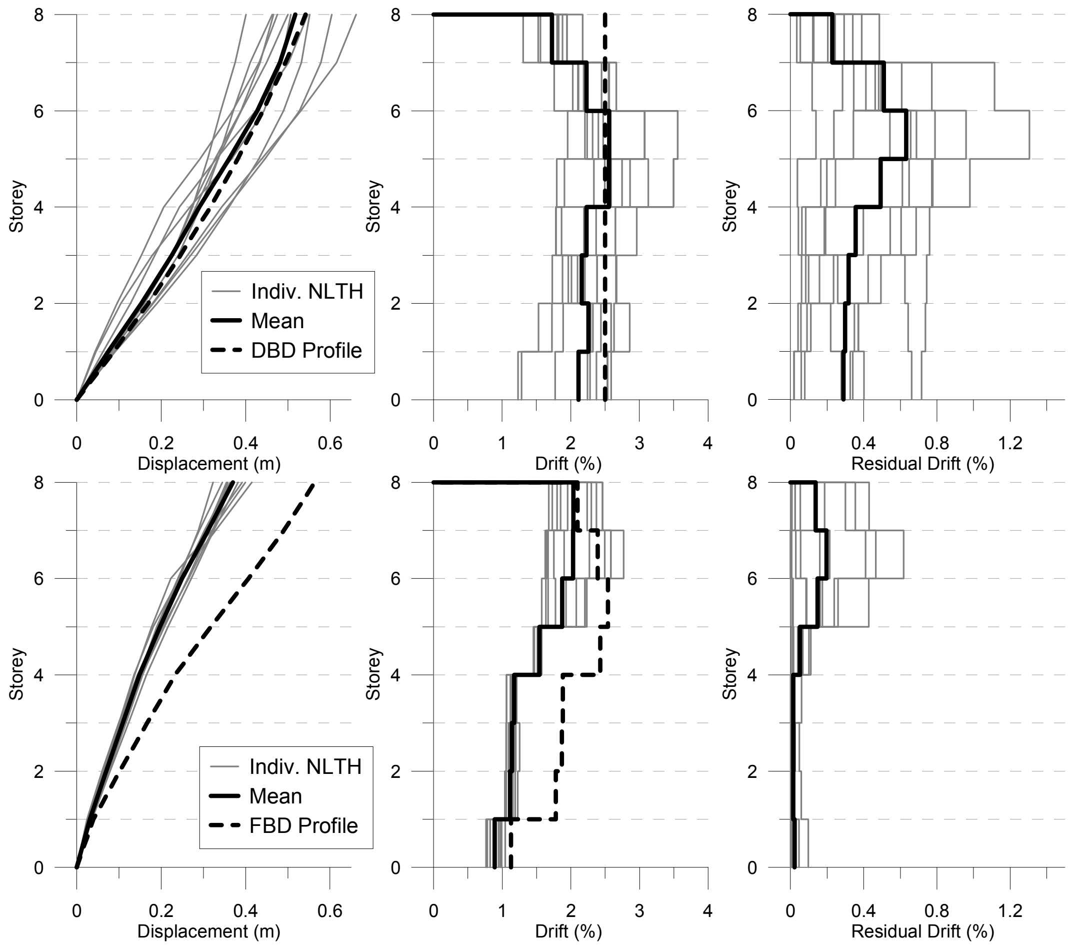

Figure 5.2. NTHA peak displacement (left panels), drift (central panels), and residual drift (right panels) results for DBD (upper panels) and FBD (lower panels) mixed systems at 100% of the design intensity

Figure 5.3 presents the same results for analyses run at 150% of the design intensity where similar effects are observed with the response increasing for the upper levels with the change in construction type although to a lesser degree than observed for the 100% intensity level. Subsequent work reported in Maley *et al.* (2011) has found the lessoning of this effect to be due to differences in the hysteretic rules used to characterise the steel and RC behaviour that become apparent when ductility levels become significant. As an example, the effect of this is highlighted in Figure 5.4 where the bi-linear (BL) hysteretic model has been replaced with the Takeda thin (TT) rule, which could be used to characterise the behaviour of steel T-stub connections, for the FBD mixed system. The result is an increase in the peak transient response when compared to the previous results. Whilst it is acknowledged that the increases in system transient response due to a reduction in stiffness could be expected to be captured using modal response spectrum (MRS) methods, the effect of different inelastic properties can not. Given the significant effect of the reduction in stiffness on the response, it could be argued that an MRS procedure should be required by ASCE/SEI 7-10 where a significant reduction in stiffness occurs as is the case for other major codes.

Returning to Figure 5.3, the altered base shear distribution used for the DBD method, given by Equation 3, again results in a more uniform distribution in the drift response and effectively controls the higher mode response. It could be said that the FBD system gives a more desirable response due to the lower transient and residual drifts, but if such a response were desired the DBD method could provide for this by designing to a reduced drift limit. Finally, it is noted that for both intensity levels the residual drifts observed in the upper steel construction levels tend to be noticeably higher than those for the lower levels with RC construction. This is despite transient drifts showing differing trends and is likely due to the increased unloading stiffness of the bi-linear hysteretic rule used to characterise the inelastic behaviour of the steel members.

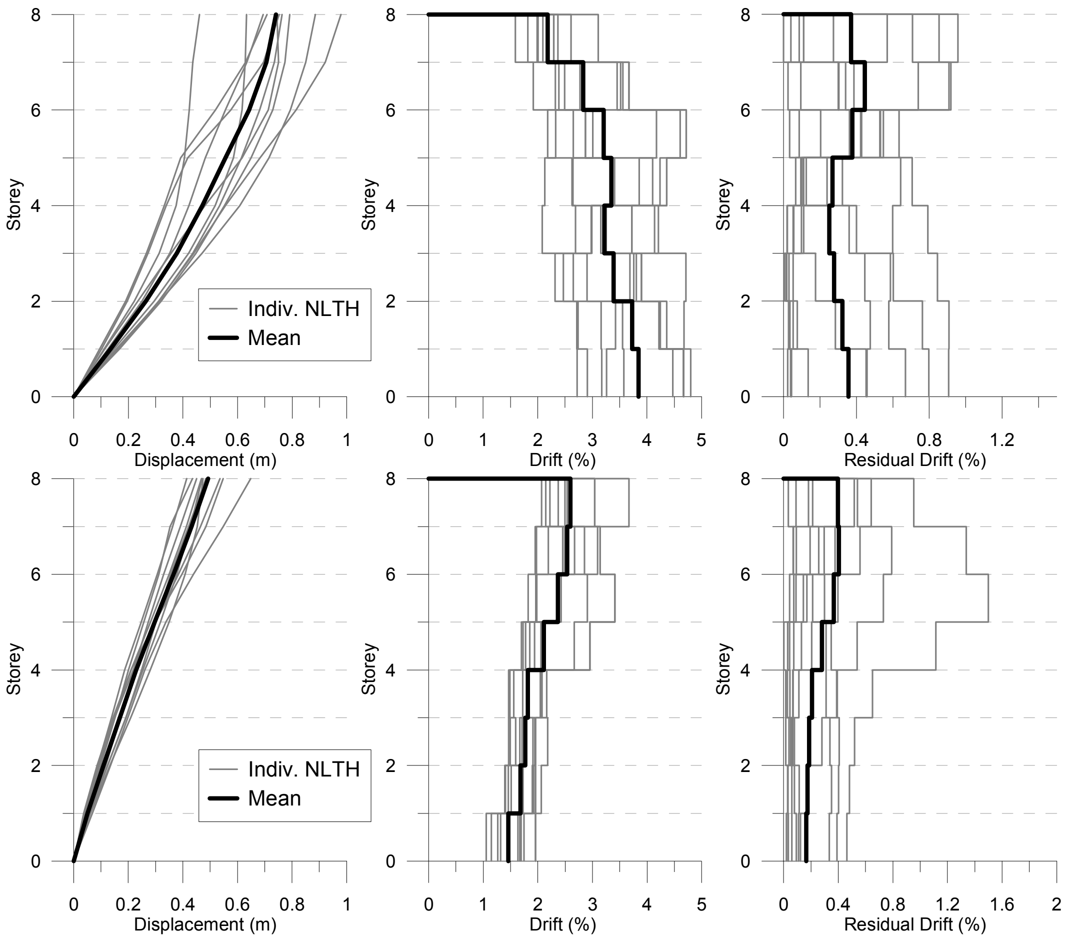

Figure 5.3. NTHA peak displacement (left panels), drift (central panels), and residual drift (right panels) results for DBD (upper panels) and FBD (lower panels) mixed systems at 150% of the design intensity

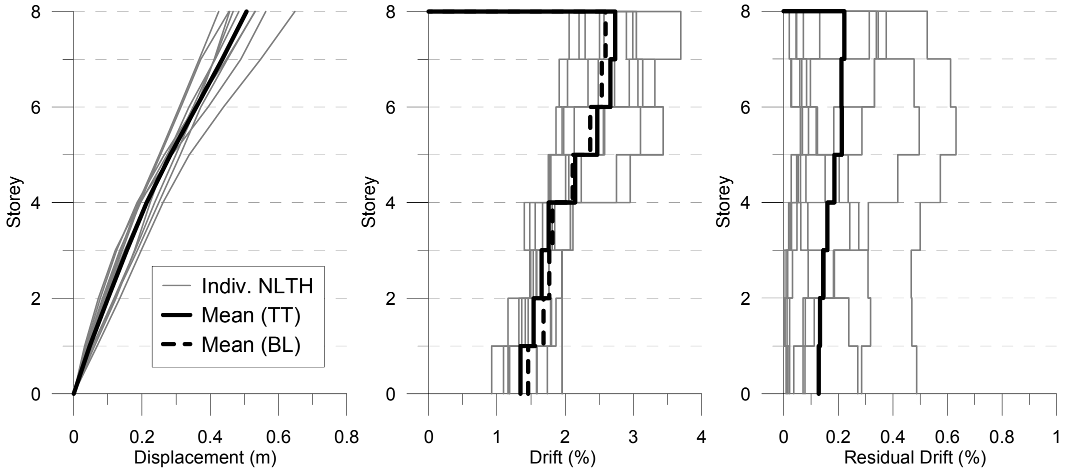

Figure 5.4. NTHA peak displacement (left panel), drift (central panel), and residual drift (right panel) results for FBD mixed systems with Takeda thin (TT) rule used for steel portion of frame at 150% of the design intensity

5. CONCLUSIONS

The application of the DDBD (Priestley *et al.*, 2007) and ASCE-SEI 7-10 (ASCE, 2010) design provisions for mixed MRF systems has been reviewed and the design procedures have been applied to an 8-storey steel/RC case study mixed MRF system. For comparison, the methods have also been applied to steel only and RC only systems. The review has found that the methods can be applied relatively easily to mixed MRF systems and the design and subsequent NTHA assessment of the mixed case study building has shown similar trends to steel and RC only systems for both procedures. By running NTHAs, the change in construction material has been shown to have greatest influence on the residual drifts which is something a designer should be aware of when considering such systems.

The DDBD method was found to give more economical designs and an improved response overall due to the superior ability of the method to control the level and form of the response. On this later point, the altered base shear distribution used by the DBD method has been shown to improve the system performance and aid in the control of the higher mode response. The use of the DDBD method can be seen as advantageous for performance based design where the more accurate control of system response offered by DDBD will improve performance estimates. It is noted that more advanced modelling could be used in future research to strengthen conclusions made here, especially to consider local effects in systems with such changes in material construction. Finally, it is noted that further research on the topic has shown that changes in inelastic behaviour can have a significant influence on the transient drift response of mixed MRF systems (Maley *et al.*, 2011).

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