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Accelerogram-scaling procedures for near-fault motions

J. Zhang
G. McVerry

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NON-TECHNICAL ABSTRACT

This study tackles the problem that the procedures of the New Zealand standard *NZS1170.5:2004* for earthquake actions on structures lead to different seismic demands on structures from near-fault earthquake motions depending on the method of analysis that is used. The requirements appear to penalise the numerical-integration time-history analysis (NITHA) method for which the estimated responses are generally greater than for the modal response spectrum analysis (MRA) method. This conflicts with the desire to encourage designers to use the NITHA method, which is preferred because it has features that are likely to provide more realistic representations of structural response than other analysis methods.

Two modifications to the NZS1170 procedures have been identified to overcome these problems. These modifications relate to how to scale the records of earthquake motions ("accelerograms") that are used as input to NITH analyses, and how to combine the results from the analyses for individual records.

The first modification is to increase the number of records required from three to seven or more. These are selected and scaled in a similar way to the current NZS1170 procedures, but the maximum inter-storey drifts are averaged across the total number of records rather than taken as the largest of the individual drifts. The second modification, to be used in conjunction with the first, is to increase the upper period limit used for determining the record scale factors to the effective period T_{eff} associated with the maximum response, which could be up to about double the current limit. This second modification has only slight effect on the average maximum response, but generally changes the more extreme responses considerably, leading to reduced scatter across the records.

The study has been successful in identifying simple modifications to the NZS1170 procedures for scaling earthquake records and combining NITH analysis results from different records, modifications that in general produce similar or reduced seismic demand estimates for NITH analyses compared to MRA methods.

TECHNICAL ABSTRACT

This study tackles the problem that the procedures of the New Zealand standard *NZS1170.5:2004* for earthquake actions on structures lead to different seismic demands on structures from near-fault earthquake motions depending on the method of analysis that is used. The requirements appear to penalise the numerical-integration time-history analysis (NITHA) method for which the estimated responses are generally greater than for the modal response spectrum analysis (MRA) method. This conflicts with the desire to encourage designers to use the NITHA method, which is preferred because it has features that are likely to provide more realistic representations of structural response than other analysis methods.

Two modifications to the NZS1170 procedures have been identified that generally lead to smaller estimated inter-storey drifts from NITHA than from MRA methods. These modifications relate to how to scale the records of earthquake motions ("accelerograms") that are used as input to NITH analyses, and how to combine the results from the analyses for individual records.

The first modification is to use seven or more records, selected and scaled in a similar way to the current NZS1170 procedures, but to average the maximum inter-storey drifts across the records. About one-third (two or three of seven) of the records should have strong forward-directivity characteristics for locations where near-fault factors are required by NZS1170.

Current procedures allow as few as three records to be used, but require the maximum calculated response across all the records to be taken as the design quantity. Seven records seems sufficient to remove the need for the family scale factor k_2 that was found to artificially enhance the scaling of the input accelerograms by a factor of up to 1.26 for the structures and accelerograms considered. The drift estimates can be increased by considerably more than the k_2 factor, because of nonlinear response behaviour. Also, averaging the results reduces the influence of the near-fault forward-directivity records to a weighting of about one-third, consistent with the forward-directivity factors used in the NZS1170 spectra.

The second modification, to be used in conjunction with the first, is to increase the upper period limit used for determining the record scale factors to the effective period $T_{eff} = \sqrt{\mu}T_0$ associated with the maximum response, where μ is the ductility of the structure and T_0 is the elastic fundamental mode period in the direction of interest. For high-ductility structures, this limit could be almost about double the current limit. This modification is based on the conjecture that the nonlinear response governing the maximum inter-storey drifts is influenced by components beyond the maximum period of $1.3T_0$ considered in the period-band used for determining the record scale factor in the current NZS1170 procedures. Increasing the upper period limit to T_{eff} produced changes of up to ±30% for some of the individual scale factors. The nett effect was generally only a slight change in the maximum drifts averaged across the family of records, but usually a reduction in the more extreme values, leading to much less scatter across the analyses for the family of scaled records.

The study has been successful in identifying simple modifications to the NZS1170 procedures for scaling accelerograms and combining NITHA results from different records, modifications that in general produce similar or reduced seismic demand estimates for NITHA compared to MRA methods.

1.0 INTRODUCTION

1.1 Background to this study

NZS1170.5:2004 (Standards New Zealand, 2004) includes, for the first time in a New Zealand earthquake-design standard, detailed requirements for the selection and scaling of earthquake records ("accelerograms") used for numerical-integration time-history analysis (NITHA). The requirements were developed by modifying procedures that are recommended in US codes such as the NEHRP 2000 Provisions (BSSC, 2000). Among other changes, the NZS1170.5 requirements take into account the shapes of the New Zealand spectra and recognise that they represent the motions of the stronger rather the mean horizontal component. The current recommended procedures were based on or have been evaluated by a number of studies on a range of structures (King, Davidson & McVerry, 2002; Bell & Davidson, 2002; Tremayne & Kelly, 2005). The general observations were that the procedures adopted by US codes to scale earthquake records appeared unnecessarily conservative, producing results that are almost certain to exceed those from response spectrum analysis (Tremayne & Kelly, 2005). The NZS1170.5 numerical-integration time-history (NITH) procedures overcome this problem for many records. For example, NZS1170 requires that the upper envelope of the selected scaled records exceed the target design spectrum. The equivalent NEHRP 2000 requirements are based on the average of the scaled record spectra. The NZS1170.5 procedures have been evaluated recently by Dhakal et al. (2007), although their study was restricted to records not exhibiting directivity effects. They found that the NZS1170.5 scaling method was the most effective of three considered in giving least scatter in estimated drift across a large suite of scaled earthquake records, but that more than the three records allowed by NZS1170 are required to obtain well-constrained estimates of seismic demands.

An area of concern remains where NZS1170.5 requires near-fault motions with forward-directivity effects to be considered. This arises for structures at sites within 20 km of 12 listed major active faults. In these situations, the NZS1170.5 spectra incorporate a near-fault factor. This factor reflects systematic polarisation and rupture-directivity effects that occur at near-fault locations but are not included in the hazard models used in deriving the standard spectra. The near-fault factor of the code was derived using the Somerville at al. (1997) "broad-band" model for rupture-directivity effects. NZS1170.5 presents a reasonably simple form for the near-fault factor N(T,D), as the product of a term involving the spectral period T and one involving the distance D from the fault. A particularly important simplifying assumption was that strong forward-directivity occurs for one earthquake in three, leading to a one-third weighting of the directivity-effect in deriving the near-fault factor. This weighting is also reflected in the requirement when choosing input accelerograms for NITHA that one in three of the selected records should have strong forward-directivity characteristics for locations where the near-fault factor comes into play.

The drifts calculated from NITH analyses for records with strong forward-directivity features are generally greater than those that result from the modal response spectrum method applied to the spectra incorporating the near-fault factor. To avoid undue penalty from using the NITHA method for structures subjected to records incorporating strong near-fault effects, the Standard scales the maximum inter-storey deflection from NITH analyses for forward-directivity records by 2/3 in determining the design inter-storey deflections, while using the unscaled values for other records. This is a rather artificial approach, and it would be preferable to use the maximum calculated values for both types of record, with the MRA and NITHA methods adjusted to produce similar results. In this study, it is proposed to investigate the accelerogram-scaling procedures and methods of combining results from different analysis runs to produce better agreement between the results of the various methods, or alternatively to modify the other methods to better approximate the NITHA results.

Approaches to be considered include: (i) using larger families of records to allow averaging rather than enveloping of results, thus better replicating assumptions made in deriving the code near-fault factor; (ii) modifying the scaling procedure appropriately to better recognise the longer-period components that control strain and drift; and (iii) extending the upper-bound period of the matching procedure, for similar reasons. As a last resort, consideration may be given to modification of the inelastic spectrum scaling factor k_μ if this appears to be the only way of reconciling NITHA and MRA results.

Emphasis will be given to developing scaling and result-combination techniques for near-fault records, but some analyses will be performed using "standard" accelerograms to ensure that the procedures are appropriate for those records as well.

1.2 Review of scaling procedures

In NITH analyses, the seismic hazard of a site in terms of structural response should be accounted for in selecting and scaling the earthquake ground-motion records. For this purpose, the elastic response spectra of the selected ground motions are scaled to a target design spectrum, which is based on the local seismic hazard, and the suite of records should be appropriate for the "seismological signature" of the site (see Section 4.1). Various scaling procedures have been proposed to scale ground motions to target design spectra. The NEHRP 2000 provisions recommend scaling procedures for two-dimensional and three-dimensional analyses. Their recommended scaling period range is between $0.2T_0$ and $1.5T_0$ (where T_0 is the natural period of the structure in the fundamental mode for the direction of response being analysed). For two-dimensional analysis, it is required that the average of the response spectra of the selected ground motions be not less than the corresponding ordinate of the design spectrum. For three-dimensional analysis, it is required that the average of the SRSS spectra (square root of the sum of the squares of a pair of horizontal components) from all horizontal component pairs is not less than 1.3 times the corresponding ordinate of the design spectrum. For nonlinear structural analysis, NEHRP 2000 provisions provide an alternative approach that, if at least seven ground motions are analysed, individual response parameters shall be permitted to be taken as the average of their values from the analyses, rather than the largest of the individual responses, as required for fewer records.

The scaling procedure recommended by New Zealand Standard NZS1170.5:2004 is different from those suggested by the NEHRP Provisions. The NZ standard requires: 1) scale 5% damped response spectra of a pair of horizontal motion components to the target design spectrum in a period range between $0.4T_0$ and $1.3T_0$; 2) select a principal component from the pair of horizontal motion components; and 3) apply the principal component in the selected direction, and the other component in the orthogonal direction. NZS1170.5 requires that the design values are based on the maximum rather than average structural responses across the family of individual record analyses regardless of how many records are used, with it envisioned that commonly only three records will be used.

Comparison of the scaling procedures of NEHRP and NZS1170.5:2004 shows that the procedures in NEHRP are more conservative in three-dimensional analysis. This is because the average of the SRSS spectra of all records is required to be not less than 1.3 times the corresponding ordinate of the design spectrum. On the other hand, the range of periods for scaling in NZS1170.5 is shorter than that in NEHRP. This is likely to cause a problem that, once the structure yields, the effective period of the structure may be greater than $1.3T_0$. In such cases, the scaling procedure implies that the effects of records at periods longer than $1.3T_0$ will not affect the structural response, because they are not considered in the scaling procedure. This case is particularly significant for near-fault motions with forward-directivity effects (FD motions), where spectral accelerations are abnormally large. In addition, we note that the ductility factor is an important factor in assessing the deflection capacity of structures. However, current scaling procedures do not clearly include the influence of the ductility factor on the effective values of the dynamic-response parameters. The only provision associated with modified structural parameters is the maximum period of $1.3T_0$ to reflect lengthening of structural period caused by structural yielding.

2.0 STRUCTURES USED IN THIS STUDY

Structures used in this study were initially designed as test structures using a prototype version of NZS1170.5 to assess the new Standard (Shelton, 2004). Later, BRANZ made minor modifications to the structures to satisfy the requirements of the published version of NZS1170. Only reinforced-concrete buildings were considered in this study. The following description of the buildings is largely taken from Shelton (2004).

The buildings were designed "to represent, as far as practicable, typical New Zealand design and construction practice. To cover a reasonable range of building types and sizes, three basic heights of buildings were selected (3, 10 and 20 occupied floors)."

The reinforced-concrete buildings "have moment-resisting frames in one direction, and with shear walls in the other. Floor heights were set at 4.50m ground to first floor, and 3.65m for all other floors, and each building had a roof structure 3.65m above the upper floor."

This study is concerned with developing procedures to ensure consistent treatment of near-fault effects in different analysis approaches allowed for design. Wellington is the location with most structures that are subject to the near-fault factor provisions of NZS1170.5:2004. Accordingly, the structures were designed to satisfy the NZS1170 requirements for Wellington structures. Two site classes were considered, Class C (shallow soil) and Class D (soft, or deep, soil).

"Parameters given to the designers for the suite of building designs are presented in Table 1. The building name shown in the first column of the table is that given for identification purposes and is used throughout this report." Table 1 also lists the fundamental periods in the two directions.

Table 1 Parameters of the designed building structures

Name	Number of stories	Plan regularity	Location	Soil Class	Ductility	Period T(S)	
						Frame Direction	Wall Direction
RC3RWCL	3	R	W	C	L	1.60	0.98
RC10RWCD	10	R	W	C	D	1.72	1.51
RC10IWCD	10	I	W	C	D	1.78	1.58
RC20IWCL	20	I	W	C	L	3.65	2.94
RC20RWDD	20	R	W	D	D	2.54	2.20
RC20IWDD	20	I	W	D	D	2.69	2.08

Notation: RC = reinforced concrete
Number = number of storeys
R/I = regular/irregular in plan
W = Wellington (high seismicity)
C/D = shallow/deep or soft soil conditions
L/D = limited ductile/ fully ductile

The typical building layout is shown in Figure 1. The layout shown represents a regular building. However, plan irregularity was also considered by altering the location of the two transverse shear walls (see Figure 1 and Table 2), within an otherwise constant building layout. Target ductility levels were set at $\mu = 3$ (limited ductility) and $\mu = 6$ (fully ductile).

Several features of the designed structures are listed as follows (based on Shelton, 2004):

The buildings are rectangular in plan, with a standard grid used for all buildings of a structural system:

Frame direction - 5 grids of 7.5 m,

Wall direction - 3 grids of 9.0 m.

For all the buildings considered, the two exterior frames were seismic-resisting frames, while the two internal frames were gravity-frames providing support to the floors (secondary seismic structure). The floor system comprised proprietary, precast-concrete, hollow-core floor units spanning between the main frames, with 65 mm thick cast in-situ concrete topping. Gravity frames were assumed to be detailed as continuous, and were therefore included in the analysis models.

A roof was included in each building above the upper occupied floor, resulting in the addition of a level of seismic mass to the specified number of storeys.

Structural members were sized so that as far as practical the design strength was the minimum code-compliant value for the specified level of ductility. For the reinforced-concrete structures, the minimum steel provisions were as prescribed by NZS 3101 (Standards New Zealand, 1995).

Accidental eccentricity was taken as 0.1 times the plan dimension, b as required by NZS1170.5.

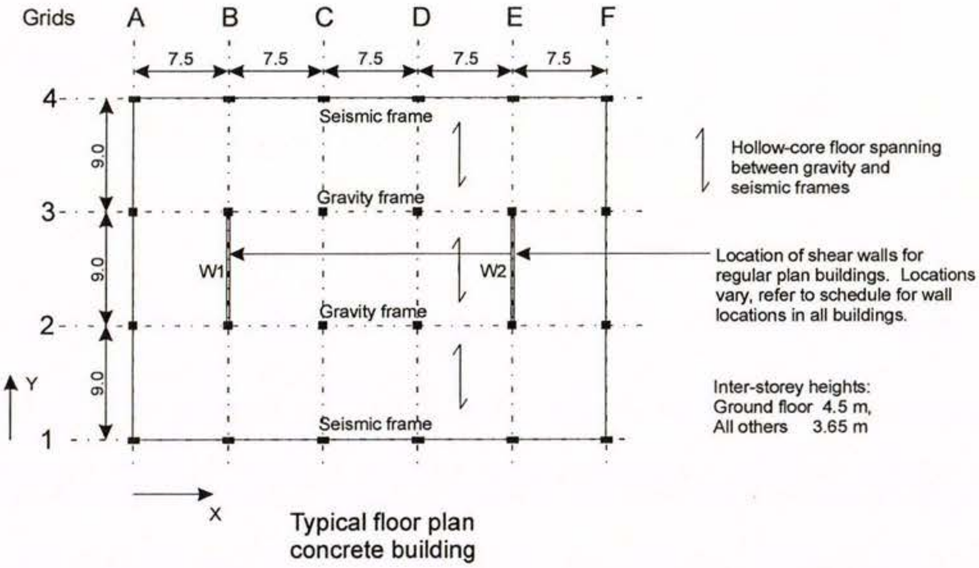

Figure 1 Plan of a typically-designed building (from Shelton, 2004)

Table 2 Location of shear wall of the designed structures

Name	Location of Wall 1	Location of Wall 2
RC3RWCL	B	E
RC10RWCD	A	F
RC10IWCD	B	D
RC20RWDD	A	F
RC20IWCL	A	D
RC20IWDD	A	D

Wall 1 and wall 2 are represented by W1 and W2 in Figure 1.

3.0 NZS1170.5 MRA AND NITHA METHODS

3.1 Modal Response Spectrum Analysis

NZS1170.5 allows modal response spectrum analysis as one method to perform structural dynamic analysis.

The first step is to calculate the inelastic horizontal design spectrum based on the elastic site hazard spectrum and structural performance factor S_p:

$$C_d(T) = \frac{C(T)S_p}{k_\mu(T_1)}$$

C(T) is the ordinate of the elastic site hazard spectrum, *T* is period, and T_1 is the largest translational period in the direction being considered. k_μ is determined as follows.

For soil classes A, B, C, and D

$$\begin{aligned} k_\mu &= \mu && \text{for} \quad T_1 \geq 0.7s \\ &= \frac{(\mu-1)T_1}{0.7} + 1 && \text{for} \quad T_1 < 0.7s \end{aligned}$$

For soil class E

$$\begin{aligned} k_\mu &= \mu && \text{for} \quad T_1 \geq 1.0s \text{ or } \mu < 1.5 \\ &= (\mu - 1.5)T_1 + 1.5 && \text{for} \quad T_1 < 1.0s \text{ and } \mu \geq 1.5 \end{aligned}$$

S_p is the structural performance factor, and for the ultimate limit state taken as 0.7 except that where $1.0 < \mu < 2.0$, S_p shall be defined as

$$S_p = 1.3 - 0.3\mu$$

By using the MRA method with the inelastic design spectrum $C_d(T)$, the structural actions and displacements are derived. However, the derived actions and displacements have to be modified by several scale factors given in NZS1170.5. They are: (i) base-shear scale factor (see 5.2.2.2 in NZS1170.5); (ii) P-delta scale factor (see 6.5.4 in NZS1170.5); (iii) deflection scale factor (see 7.2.1.1 in NZS1170.5); and (iv) drift scale factor (see 7.3.1.1 in NZS1170.5).

NZS1170 allows two methods, called Method A and Method B, to determine the P-delta scale factor. Method A is a simplified method, intended to be conservative compared to the more complicated Method B. In the present study, all the structures were designed using Method A. This can result in large inter-storey drifts being estimated, even if in reality the stiffness of the structure is sufficient.

To compare the effect of method A and method B in assessing the P-delta scale factor, P-delta scale factors were calculated based on the two methods, and listed in Table 3. Note that when using method B, P-delta scale factors are different at each floor. Here the P-delta scale factor listed for method B is the maximum one. The ratio of P-delta scale factors of method B to method A is then calculated, as also listed in Table 3. We find that the P-delta scale factor from method B is lower than that from method A, with typical ratios of about 0.6 to 0.8, particularly for high-rise structures (for example, 10- and 20-storey structures). The results verify that method A is more conservative, often by a considerable amount. The more complicated method B is assumed to be more accurate.

Table 3 Comparison of P-delta factors of Method A and Method B

Building		P-delta factor		Method B /Method A
		Method A	Method B	
RC3IWCL	frame	1.44	1.34	0.93
	wall	1.33	1.11	0.83
RC10IWCD	frame	1.99	1.4	0.70
	wall	1.91	1.27	0.66
RC10RWCD	frame	1.94	1.43	0.74
	wall	1.88	1.28	0.68
RC20IWCL	frame	1.89	1.22	0.65
	wall	1.7	1.18	0.69
RC20IWDD	frame	1.76	1.34	0.76
	wall	1.71	1.25	0.73
RC20RWDD	frame	1.77	1.43	0.81
	wall	1.68	1.25	0.74

Note: For Method B, the P-delta scale factors are the maximum values for each structure.

3.2 Numerical-Integration Time-History Analysis

Numerical-Integration Time-History analysis (NITHA) provides more detailed calculations of a structure's earthquake response than other methods of analysis. It provides the response both from time-step to time-step and for a large number of locations within a structure. It is also able to model a wide range of force-deformation characteristics of structural elements. These features are assumed to provide more realistic and thus more accurate representations of structural response than other analysis methods. Accordingly, it is currently widely applied in performance-based design. In New Zealand, this type of analysis is often performed using the programme Ruaumoko that has been developed by the University of Canterbury (Carr, 2001).

NZS1170.5 allows the use of NITHA for linear and nonlinear structural analyses. The first step in NITHA is to use a factor of $(1+S_p)/2$ to scale the elastic site hazard spectrum $C(T)$ to obtain the target design spectrum, where S_p is the structural performance factor. In our cases, $S_p=0.7$, and so the scale factor is 0.85. For NITHA, Clause 7.3.1.2 of NZS1170.5 specifies "the design inter-storey deflection between levels shall be taken as the maximum inter-storey deflection obtained for each required ground motion record that does not include forward directivity and 0.67 of that maximum for records that do include forward directivity motions". In the present study, we follow all requirements prescribed in NZS1170.5 for the MRA and NITHA methods. One exception is that the maximum inter-storey deflection from

FD motions is not scaled by a factor of 0.67, as we were investigating alternative ways of combining results from records with and without forward-directivity. For that purpose, we wished to use the full inter-storey deflections produced by NITH analyses for forward-directivity records, rather than the scaled down values.

4.0 ACCELEROGRAM SELECTION AND SCALING FOR NITHA

A key part of NITHA is the selection and scaling of appropriate earthquake accelerograms as the input for the analysis. The aim of this study is to modify the NZS1170.5 procedures for accelerogram scaling to obtain a better consistency between various structural response parameters, especially maximum inter-story drifts, calculated by the NITHA and MRA methods. The current procedures are described in the next two sub-sections.

4.1 Selection of Accelerograms

NZS1170.5 specifies that ground motions shall be selected from actual records that replicate to a reasonable degree the seismological signature (i.e. magnitude, source characteristic, source-to site distance, presence of near-fault directivity effects) of the events that contribute significantly to the target design spectrum of the site over the period range of interest, and are recorded on site conditions similar to those at the site. The target design spectrum produced by NZS1170.5 is a function of design return period, location, site conditions, and the near-fault factor, as defined in NZS1170.5 Section 3 Site Hazard Spectra. When scaled, the selected accelerograms should give a reasonable approximation to the target spectrum over the period band of interest for the specific structure. Also, the record scale factor k_1 (see Section 4.2) should lie between ⅓ and 3.

A particularly important feature for Wellington is the likelihood of near-fault directivity effects for Ultimate Limit State motions, because the hazard is dominated by the Wellington Fault. For sites within 20 km of the Wellington Fault, the NZS1170.5 spectra incorporate near-fault factors to account for forward-directivity effects. These affect the spectra for periods exceeding 1.5s. For NITHA, there is a requirement that not only must the target spectra include the appropriate near-fault factor, but also one in three of the selected records should have strong forward-directivity characteristics. One of the reasons for this study is the indication from previous studies (e.g. Tremayne & Kelly, 2005) that the records with strong forward-directivity characteristics produce greater inter-story drifts than non-forward-directivity records that have been scaled to the same target spectrum, even though the target spectrum incorporates near-fault factors. One of the aspects that we wished to investigate was whether the domination of the results by the near-fault forward-directivity records could be alleviated by adopting the US provision of being allowed to average the maximum responses when seven or more records are included in the analysis, rather than being required to select the strongest response when only three records are considered.

Often it is not possible to satisfy all aspects of the seismological signature and site class while retaining a good match to the spectral shape and a scaling factor in the recommended range. Often satisfaction of some of these aspects is sacrificed to obtain a good spectral match. In particular, records that give good spectral matches may have been recorded on other site classes, or tectonic type is ignored when records from large-magnitude earthquakes (exceeding about Mw 7.5) are required. Also, for locations like Wellington where the spectra represent motions of about 0.4g rock pga or stronger, recorded accelerograms may need to be scaled by more than the recommended maximum factor of 3.

The seismological signature can be determined by using deaggregation analysis of the seismic hazard. This breaks down the contributions to the estimated hazard by magnitude and source-to-site distance, including identifying the individual contributions of modelled fault sources. The accelerograms selected from candidate records with the appropriate seismic signature are those which, when scaled, provide good least-squares fits on a logarithmic scale to the target design spectra. Accelerograms have been selected for both shallow soil and deep/soft soil site conditions in Wellington. All ground motions selected are listed in Table 4.

In Wellington, two types of earthquakes dominate the seismic hazard associated with the Ultimate Limit State, strike-slip crustal earthquake events of around magnitude 7.5 at distances of no more than a few kilometres and subduction interface events of around magnitude 8 or larger at distances of about 25 km. Therefore, the selected ground motions should include some near-source records from large strike-slip crustal earthquakes and others from subduction interface events. In addition, NZS1170.5 requires that one-in-three of the records used for NITHA should incorporate strong near-fault forward-directivity (FD) motions.

To satisfy the requirements above, plus our desire to consider averaging the responses from seven records, we selected seven ground-motion records for each site class as listed in Table 4, and also considered a three-record subset for use when the strongest of three responses was required.

The 1940 Imperial Valley, 19787 Tabas, 1992 Landers, 1999 Kocaeli and 1999 Chi Chi earthquakes were selected as representative of crustal earthquakes, while the 1985 Mexico and 2003 Hokkaido earthquakes represent subduction interface events. The forward-directivity motions are Tabas, Lucerne, Arcelik, Yarimca, TCU50, and TCU51.

While the records in Table 4 are selected based on the requirements of NZS1170.5, not all of the records satisfy all requirements. For example, the k_1 factors of the La Union and Caleta records exceed 3, the upper limit in NZS1170.5. In particular, the ordinates of the Caleta spectra are very low compared to the target spectrum, requiring scale factors of up to 5.8, well outside the allowable range according to NZS1170. The La Union and Caleta records were retained in the selection because we were unable to find other subduction-interface records in world-wide record databases that better fit the shapes of the target design spectra for shallow soil and deep/soft soil sites, respectively.

The scale factor range of ⅓ to 3 was specified because of concerns that records with excessively small or large scalings may have properties different from those with more modest scalings. However, recent work by Baker & Cornell (2006) and Baker (2007) suggests that it is goodness-of-fit to the spectral shape that is important, with the results being insensitive to the amount of scaling required to match the target spectrum.

Table 4 All ground motions selected for shallow soil sites and deep/soft soil sites

Shallow Soil Sites				Deep/Soft Soil Sites		
No	Record	EQ	FD	Record	EQ	FD
1	El Centro	1940 Imperial Valley		El Centro	1940 Imperial Valley	
2	Tabas	1978 Tabas	Y	Duzce	1999 Kocaeli	
3	La Union	1985 Mexico		Caleta	1985 Mexico	
4	Lucerne	1992 Landers	Y	TCU50	1999 ChiChi	Y
5	K039Q8500	2003 Hokkaido		TCU51	1999 ChiChi	Y
6	Arcelik	1999 Kocaeli	Y	Yermo	1992 Landers	
7	Duzce	1999 Kocaeli		YPT Yarimca	1999 Kocaeli	Y

FD: Y in this column indicates near-fault motions with forward-directivity effects.

NZS1170.5 defines the principal horizontal component of an accelerogram for a particular direction of the structure as that with the smaller k_1 factor required to scale it to the target spectrum over the period band of interest, while the other horizontal component is referred to as the secondary component. It also provides a procedure for applying the principal and secondary components for the analysis of the structure, considering each direction of the structure in turn. At least two analyses of a structure are needed for each accelerogram in terms of the two directions of the structure (with different natural periods). We find that, sometimes the maximum inter-storey drift in a particular direction does not occur from the application of its principal component, but rather from the secondary component for the orthogonal direction. In the present analyses, therefore, the inter-storey drift profile plotted in the Figures is the maximum inter-storey drift in each orthogonal direction, whether it results from the principal component for that direction or the secondary component for the orthogonal direction.

4.2 Scale factors k_1 and k_2

NZS1170.5 requires that all ground-motion records selected for NITHA are scaled to approximately match a target design spectrum, as well as satisfying as best as possible the "seismic signature" of the site, as discussed above. The scaling procedure defined in Clause 5.5.2 of NZS1170.5 involves determining two factors, the record scale factor k_1 and the record family scale factor k_2. Ideally, the record scale factor k_1 should lie between ⅓ and 3. For k_2, which is applied to ensure that the target spectrum is exceeded at all periods in the scaling period band by the envelope of the spectra of the selected records, there is no limit except that values less than 1.0 may not be used, but Clause 5.5.2(e) of NZS1170.5 suggests that one of the records should be replaced by another if $k_2 > 1.3$.

First the k_1 factors were calculated for the two horizontal components of the seven records selected for the appropriate site class (see Table 4) for each structure. The k_1 factors were found by performing least-squares matches of $log(k_1 SA_{component}(T))$ to $log(SA_{target}(T))$ over the period range $0.4T_0$ to $1.3T_0$, where T_0 is the fundamental translational period of the structure in the direction being considered.

To satisfy the NZS1170 requirements, three records out of the seven for the appropriate site class were selected for each structure (Table 5), based on the minimum root-mean-square error for the match over the range $0.4T_0$ to $1.3T_0$ of the scaled record to the target spectrum, including at least one subduction interface earthquake record and one FD ground-motion record. The k_2 factor for each family of three records was calculated following the procedure in NZS1170.5.

According to the minimum rms error criterion, the Caleta record should be included as the subduction interface record in the family of three records for the deep/soft soil site class. However, as well as its k_1 factors being excessive, it was found that the family factors k_2 for cases including the Caleta record were also quite large. Accordingly, the Caleta record was replaced by the record K039Q8500 from a Japanese interface event in the three-record set for deep/soft soil sites, although K039Q8500 is recorded on a shallow soil site.

The family scale factor k_2 is less than 1.1, except for 3 cases. Two cases out of the three are from the two 20-storey structures situated on deep/soft soil sites and slightly greater than 1.1, and so their effect on structural responses is ignored. k_2 in the wall direction of RC3IWCL is 1.26, much greater than 1.1. At least one of the three records in the family should be changed, but to conveniently compare the effect of ground-motion records, the three records are retained. Table 5 shows the three-record families for all structures. In these records, the Lucerne record from the 1992 Landers earthquake and the YPT (Yarimca) record from the 1999 Kocaeli earthquake event are FD ground-motion records, and the K039Q8500 record from the 2003 Hokkaido earthquake event is a subduction interface record.

Table 5 also lists the k_1 and k_2 factors corresponding to the three selected records. The k_1 record scale factors shown here exclude the effect of the Sp factor of 0.7, so the final scale factors need to be multiplied by 0.85, corresponding to the multiplier $(1+S_p)/2$.

Table 5 k_1 and k_2 factors for the selected three-record families (excluding multiplier of 0.85 associated with S_p factor)

Building		Record1		Record 2		Record3		k2
		Name	k1	Name	k1	Name	k1	
RC3IWCL	xn_Frame	El Centro	1.43	Lucerne	0.84	K039	0.88	1.08
	yp_Wall	El Centro	1.03	Lucerne	0.97	K039	0.82	1.26
RC10IWCD	xn_Frame	El Centro	1.41	Lucerne	0.84	K039	0.88	1.10
	yp_Wall	El Centro	1.37	Lucerne	0.83	K039	0.79	1.06
RC10RWCD	xn_Frame	El Centro	1.42	Lucerne	0.84	K039	0.88	1.10
	yp_Wall	El Centro	1.38	Lucerne	0.83	K039	0.82	1.07
RC20IWCL	xn_Frame	El Centro	1.69	Lucerne	0.65	K039	1.21	1.05
	yp_Wall	El Centro	1.67	Lucerne	0.71	K039	1.09	1.07
RC20IWDD	xn_Frame	El Centro	2.70	YPT	1.51	K039	1.62	1.07
	yp_Wall	El Centro	2.55	YPT	1.59	K039	1.54	1.11
RC20RWDD	xn_Frame	El Centro	2.70	YPT	1.46	K039	1.65	1.07
	yp_Wall	El Centro	2.44	YPT	1.62	K039	1.49	1.15

Note: final scale factor $k = 0.85*k_1*k_2$

We then considered the family scale factors k_2 for each structure for its family of seven records and found that the k_2 factors were equal to 1.0 for each structure. This result suggests that, if seven records are selected to perform NITHA, the effect of the k_2 factor can be ignored. Because of different k_2 factors used in the three- and seven-record cases, structural responses from the two cases are different, even for the same earthquake record.

Once appropriate accelerograms and scaling factors were selected, NITHA was performed by using appropriate structural analysis software. In the present study, we used Ruaumoko to perform all NITHA.

5.0 INTER-STOREY DRIFTS FROM MRA AND NITHA

5.1 Three-record NITH analyses consistent with NZS1170.5:2004

The three selected records with scale factors k_1 and k_2 listed in Table 5 were used to excite the structures. The resulting maximum inter-storey drifts, deflection profiles, and peak floor accelerations were each calculated. Comparison of inter-storey drifts from MRA and NITH analyses are plotted in Figures 2a-f. Note that two inter-storey drifts from MRA are shown in Figure 2, one using method A and the other using method B to calculate the P-delta scale factor. Comparisons of the maximum inter-story drifts from MRA and NITH analyses and the ratio of NITHA to MRA are listed in Table 6a for method A and Table 6b for method B. Maximum inter-storey drifts from the NITHA results that are larger than the value from MRA are shown in bold.

Table 6a Comparison of the maximum inter-storey drifts of MRA and NITH analyses using method A to calculate P-delta factor

Building		Maximum Inter-storey Drift (Method A)				Ratio of NITHA/MRA		
		MRA	NITHA(ELC)	NITHA(K03)	NITHA(LUC)	ELC	K039	LUC
RC3IWCL	frame	110	75	73	195	0.68	0.66	**1.77**
	wall	42	39	40	102	0.93	0.95	**2.43**
RC10IWCD	frame	84	34	35	62	0.40	0.42	0.74
	wall	41	20	22	47	0.49	0.54	**1.15**
RC10RWCD	frame	87	40	34	65	0.46	0.39	0.75
	wall	69	26	25	50	0.38	0.36	0.72
RC20IWCL	frame	95	68	60	88	0.72	0.63	0.93
	wall	78	34	34	43	0.44	0.44	0.55
		MRSA	ITHA(ELC)	ITHA(K03)	ITHA(YPT)	ELC	k03	YPT
RC20IWDD	frame	102	64	52	90	0.63	0.51	0.88
	wall	97	36	35	47	0.37	0.36	0.48
RC20RWDD	frame	118	63	54	100	0.53	0.46	0.85
	wall	88	41	37	37	0.47	0.42	0.42

Table 6b Comparison of the maximum inter-storey drifts of MRA and NITH analyses using method B to calculate P-delta factor

Building		Maximum Inter-storey Drift (Method B)				Ratio of NITHA/MRA		
		MRA	NITHA(ELC)	NITHA(K03)	NITHA(LUC)	ELC	K039	LUC
RC3IWCL	frame	102	75	73	195	0.73	0.71	**1.91**
	wall	35	39	40	102	**1.11**	**1.14**	**2.91**
RC10IWCD	frame	59	34	35	62	0.58	0.59	**1.05**
	wall	27	20	22	47	0.73	0.81	**1.72**
RC10RWCD	frame	64	40	34	65	0.62	0.53	**1.01**
	wall	47	26	25	50	0.55	0.53	**1.06**
RC20IWCL	frame	61	68	60	88	**1.11**	0.98	**1.44**
	wall	54	34	34	43	0.63	0.63	0.79
		MRA	ITHA(ELC)	ITHA(K03)	ITHA(YPT)	ELC	k03	YPT
RC20IWDD	frame	81	64	52	90	0.79	0.65	**1.12**
	wall	73	36	35	47	0.49	0.48	0.64
RC20RWDD	frame	95	63	54	100	0.66	0.57	**1.05**
	wall	65	41	37	37	0.63	0.57	0.57

Figure 2 and Table 6a shows that the inter-storey drifts from NITH analyses are less than those from MRA Method A for most buildings, and for all buildings if the strong forward-directivity Lucerne record is excluded. This is in line with the expectation that the MRA Method A results are conservative. However, in three of the cases considered, the drifts calculated from NITHA are larger than those from the MRA Method A, in two cases by a substantial amount, in line with the studies that triggered this investigation.

Similar results hold even when comparing the NITHA inter-storey drifts with those from the MRA Method B, for which all inter-storey drifts are lower than those from method A. The maximum NITHA results exceed the MRA Method B results for only 2 structural systems out of 12 (i.e. frame and wall directions for the 6 structures) if the forward-directivity Lucerne and YPT records are excluded. However, the NITHA results for the Lucerne and YPT forward-directivity records exceed the MRA Method B values for 9 out of 12 cases.

These results justify the need for this study. It appears that inter-storey drifts derived using scaled MRA results provide a reasonable match with NITHA results for "conventional" non-FD records, but may underestimate drifts for records incorporating FD effects. Structural analysts using NITHA will obtain the expected benefit of reduced inter-storey drift estimates with respect to the MRA method for "conventional" non-FD records, but the more sophisticated NITH analyses produce larger inter-storey drift than MRA Method B for forward-directivity records.

5.2 Comparison of 7-record analyses with MRA results

The NZS1170.5 procedures require that "the most critical value of any response parameter....across the family of records shall be used to determine acceptability" (Clause 6.4.7), with the family to consist of no fewer than three records. They do not allow the alternative offered in the NEHRP 2000 provisions that the average rather than the maximum of the response values from the analyses for the individual records may be used if at least seven ground motions are analysed.

This section compares the results of averaging the most critical values obtained from performing NITH analyses for seven records with the MRA results. The seven records for the relevant site class in Table 4 were used to excite all the structures in Table 1.

As stated earlier, the family scale factors k_2 for all structures for their family of seven records were equal to 1.0, while the values for the three-record families range from 1.05 to 1.26. These different k_2 factors for the three- and seven-record cases lead to different structural responses from the two cases for the same earthquake record.

The result that seven records are apparently sufficient to avoid the need for a k_2 factor greater than 1.0 is in itself a benefit. For some records, the response even without the k_2 factor may be greater than indicated by the MRA method. The k_2 factor artificially enhances the excitation and response even further. Dhakal et al. (2007) also found problems with the k_2 factor: ".. the use of k_2 factor to scale all three records as currently specified in NZS110.5 significantly overestimates the seismic demand thereby leading to an overly conservative design if the nonlinear time history analysis method is used in seismic design."

The comparison of inter-storey drifts from MRA (for both method A and method B) and from NITHA for each of the scaled earthquake records are plotted in Figures 3a to 3f. Several features shown in Figure 3 are:

- In the shear-wall direction, the FD ground-motion records (denoted LUC,TAB, ARC, YPT, T50 and T51 in the plots) have strong influence on the inter-storey drifts of the 3- and 10-storey structures, with the mean inter-storey drifts from the FD ground-motion records about 1.5 to 2 times those from other records.
- In the shear-wall direction, the effect of the FD ground-motion records on the inter-storey drifts of the 20-storey structures (for both the shallow soil and deep/soft soil sites) is slight.
- In the shear-wall direction, the inter-storey drifts from the records without forward directivity are close to each other for most cases, implying that the scaling method in NZS1170.5 provides consistent results for these records.
- In the frame direction, the effect of the FD ground-motion records on inter-storey drift is remarkable, for both low- and high-rise structures.
- Similar to the finding in point 3, the inter-storey drifts from the records without forward-directivity effects are also close each other in the frame direction.

In the frame direction, the inter-storey drifts from one or more of the FD ground-motion records exceed that from MRA (method B), except for the two structures, RC10IWCD and RC10RWDD. For the previous 3-record analysis, the maximum inter-storey drift for the LUC record exceeded the MRA value for all 6 structures. In the wall direction, the inter-storey drifts from one or more of the FD ground-motion records exceed that from MRA (method B) for 3 of the 6 structures, namely RC3IWCL, RC10IWCD, and RC10RWCD, the same as in the 3-record analysis.

Following the NEHRP 2000 provisions, we considered using the mean across the 7 records of their largest inter-storey drifts, rather than their maximum. Comparison of the mean inter-storey drift at each level from NITHA and the two MRA methods are plotted in Figures 4a to 4f. Table 7 summarises the results from the NITH and MRA method B analyses.

Figure 4 shows that the inter-storey drifts from MRA method A are larger than the mean inter-storey drifts from NITHA, except for the wall direction for building RC3IWCL. The maximum inter-story drift from NITHA exceeds that from MRA method B for one further case, the frame direction for building RC3IWCL. This compares with the NITHA drift estimates for the LUC record exceeding the MRA method B values for 9 of the 12 cases for the 3-record analysis (Table 6b).

Table 7 shows the ratio of the maximum inter-storey drifts of NITHA (from mean inter-storey drift) to MRA (method B). It also shows the value of the ratio averaged across the twelve cases. The average ratio is 0.83 (0.80 in the frame direction and 0.86 in the wall direction).

These results indicate that the influence of the near-fault records with forward-directivity characteristics on estimated inter-storey drift can be reduced by using the mean value from 7 records rather than the largest from 3 records, so that in most cases the results from NITHA will fall below those from MRA method B, as desired.

To give further justification to averaging the maximum inter-storey drifts from the seven records, we compare the design spectrum and the mean response spectrum for the seven scaled input motions for the ten cases in Figure 5. The series of figures shows that the mean spectra match the design spectra very well in the period range of 0.7s to 3.0s. Bearing in mind that the determination of the k_1 scale factor is determined across the period range from $0.4T_0$ to $1.3T_0$ for each structure, the maximum range included in determining the scale factors was 0.64s to 4.25s for the frame direction, and 0.39s to 3.82s for the wall direction. This explains why the mean spectra provide somewhat poorer matches to the target spectrum at short periods.

Table 7 Comparison of the mean maximum inter-storey drift from NITHA and MRA (method B)

Building		MRA(method B)	NITHA	NITHA/MRA
	frame	102	110	1.08
RC3IWCL	wall	19	36	1.89
	frame	59	37	0.63
RC10IWCD	wall	27	27	1.00
	frame	63	40	0.63
RC10RWCD	wall	46	32	0.70
	frame	60	58	0.97
RC20IWCL	wall	63	34	0.54
	frame	82	67	0.82
RC20IWDD	wall	73	38	0.52
	frame	96	66	0.69
RC20RWDD	wall	67	35	0.52
			Average=	0.83

5.3 Sensitivity of maximum inter-storey drift to the excitation strength

From the comparison of the maximum inter-storey drifts from the 3-record and 7-record analyses, we find that the inter-storey drift of the building RC3IWCL in the wall direction in the 3-record case (102mm) is much larger than that in the 7-record case (62mm) when the Lucerne record is used to excite the structure, and also much larger than the difference in the input excitations for the two cases corresponding to the 3-record family scale factor k_2=1.26. This result roused our interest in investigating deformation characteristics of the building subjected to various excitation strengths. The investigation was carried out by using a wide range of scale factors for the Lucerne record for the building RC3IWCL. Residual displacement was selected to compare the structural responses to the different levels of excitation. Often the residual displacement provides a good measure of the post-yield displacement of a structure. On the other hand, we think that the sudden change in structural displacement is caused by the hinge at the bottom of the shear wall.

The results plotted in Figure 6 show that as the scale factor increases, initially the residual displacement increases slightly. Once the scale factor exceeds 0.86, the residual displacements increase quickly. From Table 5, it is known than the scale factor for RC3IWCL for the Lucerne record in the wall direction is 0.82 (0.97*0.85=0.82), which is lower than 0.86. However, the product 0.85 k_1k_2 is about 1.03, larger than 0.86. This is the likely reason why the inter-storey drift for the RC3IWCL in the wall direction in the 3-record case is much larger than that in the 7-record case.

6.0 NITHA USING A NEW PERIOD RANGE FOR SCALING

6.1 Scale factor ratios

Section 5 showed that FD ground-motion records can produce larger inter-storey drifts than far-field records. Sometimes this result is attributed to the use of an inappropriate scaling method for the FD ground-motion records, because a scaling method that is appropriate for far-field records is applied directly to the FD ground-motion records. However, the FD ground-motion records have different characteristics from far-field records.

Structural response is affected by many factors, but vibration frequencies and ductility factor are two important factors. Structural responses are affected by not only the first mode, but also by higher modes. This is the reason that the period range of scaling in NZS1170.5 starts at $0.4T_0$, where T_0 is the fundamental period of the structure.

On the other hand, inter-storey drift is a displacement-based quantity, so is likely to be governed by long-period components of the motion. This suggests that greater weighting should be given to the longer-period components in determining the record scale factors.

Also, once a limited- or fully-ductile building yields, its fundamental period will be lengthened. In consideration of this lengthening, NZS1170.5 uses $1.3T_0$ as the end of the period band for scaling. However, it is noted that the period-lengthening will depend on the ductility factor. Figure 7 shows an idealised force-displacement relation for a structure excited to different displacements, but with the same yield displacement. The effective period T_{eff} is often taken to be defined in terms of the secant stiffness, i.e. the ratios $F_i/Dmax_i$ indicated by the lines of different slope in Figure 7, with the effective period inversely proportional to the square root of the secant stiffness. For an elasto-plastic system,

$$T_{eff} = \sqrt{\mu}T_0$$

Even for a moderate ductility of 2, T_{eff} is greater than $1.3T_0$. For large ductilities, T_{eff} may approach twice this value. For a system with a positive post-yield stiffness, its secant stiffness for a given displacement will be greater than for an elasto-plastic system, and the corresponding period shorter. However, the effective stiffness as defined above is a simple, easily determined quantity for a given ductility factor. It is plausible that T_{eff} may be a more appropriate value than $1.3T_0$ for the upper end of the period range used for determining the record scale factor.

In light of the probable importance of the long-period part of the spectrum in determining drifts and the effective period extending well beyond $1.3T_0$, two modifications to the NZS1170.5 procedure for determining the record scale factors k_1 were considered:

- To give greater emphasis to long-period components, use a weighting factor T in performing the least-squares matching of $log(k_1SA_{record}(T))$ to $log(SA_{target}(T))$, while retaining the period band of $0.4T_0$ - $1.3T_0$ for the matching;
- Use a scaling period band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$, where μ is the ductility factor.

We investigated the effectiveness of the two methods in achieving two aims:

1) to reduce the effect of the FD ground-motion records, and
2) to reduce the scatter of inter-storey drifts produced by using families including combinations of far-field records and FD ground-motion records.

In order to assess the appropriateness of the two methods, we calculated the ratio of scale factors k_1 determined using the two methods above to those from the method in NZS1170.5. Figure 8a shows the ratio of the k_1 scale factors of the first method proposed to that in NZS1170.5. For shallow soil sites, we find that the ratio is about 1.0, with the ratio slightly lower than 1.0 for the Lucerne record. For deep/soft soil sites, the ratios are all larger than 1.0. The results show that the first method proposed is unlikely to be successful for achieving our purposes, as it produces only slight modifications to the scale factors. Therefore, we abandoned the method.

Figure 8b shows the ratios of the k_1 scale factors of the second method to those from the NZS1170.5 method. For shallow soil sites, the mean ratio produced by the Lucerne record is about 0.9 across the range of fundamental periods of the buildings considered, down about 10%.The ratios for the non-forward-directivity El Centro and K039Q8500 records are larger than 1.0, at short periods up to 1.2. For deep/soft soil sites, the ratios from the Yarimca record are about 0.8, and the ratios from the El Centro and K039Q8500 records are between 1.2 and 1.4. These changes in scale factors are promising in terms of reaching our requirements. In the next section, we concentrate on verifying the success of the second method proposed.

6.2 Inter-storey drifts from MRA and NITHA with the new scaling method

By consideration of the scale factors k_1, we identified that perhaps a period band of $0.4T_0$ to T_{eff} is suitable for scaling ground-motion records. To verify the new period band for scaling, we used 7 records, as listed in Table 4, and the scale factors as used in Figure 8b to perform NITHA for each structure listed in Table 1. Inter-storey drifts for each structure subjected to the excitation from the 7 records are plotted in Figures 9a to 9f. We then compare Figure 9 with Figure 3 visually. It is clear that the scatter of inter-storey drifts of the structures excited by the 7 records scaled by using the new method is smaller than that in Figure 3. To verify the result, the ratio of the maximum standard deviation from the new method to that in NZS1170.5 was calculated and listed in Table 8. This table shows that most ratios are less than or equal to 1.0, except those in the frame directions of RC10RWCD and RC20IWCL and in the wall direction of RC20RWDD. Figure 9 also shows that the new scaling method reduces the effect of the FD ground-motion records on the inter-storey drifts.

However, we noted that the Tabas record in Figure 9c produces larger inter-storey drift than that in Figure 3 for the structure RC10RWCD in both the frame and shear wall directions. To understand the result, we compare scale factors k_1 from the new method and those from NZS1170.5. For both directions, the scale factor k_1 from the new scaling method is slightly larger than that from the NZS1170.5 scaling method (from 0.49 to 0.53 in the frame direction and from 0.48 to 0.57 in the wall direction). In terms of the difference of the two sets of scale factors, the difference of the inter-storey drifts in the shear wall direction is easily understood (k_1 increased from 0.48 to 0.57), but it can not explain such a large difference of the inter-storey drifts in the frame direction. We then checked the principal components in the two calculations. We found that for the NZS1170.5 scaling period band, the second component of the Tabas record is the principal component, while for the new scaling period band, the first component of the record is the principal component. The difference in the inter-storey drifts in the frame direction arises from different components being used as the principal components for the RC10RWCD structure. It is important to be aware that such behaviour may arise from time-to-time, and it may be prudent to interchange the component of the record that is used as the principal component, with appropriate derivation of the scale factors k_1 and k_2 for the selected principal component, as prescribed in Section 5.5.2 of NZS1170.5.

Table 8 Ratio of maximum standard deviations from period bands $0.4T_0$-T_{eff} and $0.4T_0$-$1.3T_0$

	Ratio of Max.σ	
Building	Frame	Wall
RC3IWCL	0.67	0.63
RC10IWCD	0.87	0.57
RC10RWCD	1.27	0.97
RC20IWCL	1.25	0.97
RC20IWDD	0.89	1.00
RC20RWDD	0.95	1.16

We sought further confirmation of the effectiveness of the new scaling method by comparing the mean inter-storey drifts from the new and the NZS1170.5 scaling methods. All mean inter-storey drifts from the two scaling methods are plotted in Figures 10a-f. Figure 10 shows that for all structures, the difference of the mean inter-storey drifts from the two scaling methods is small, and in same cases the two inter-storey drifts are almost identical. This result demonstrates that while the new scaling method does not significantly change the mean inter-storey drift from the 7 records, it reduces the scatter of the inter-storey drifts and reduces the effect of the FD ground-motion records on inter-storey drifts.

7.0 CONCLUSIONS AND RECOMMENDATIONS

In the present study, six structures designed by BRANZ were used to perform modal response spectrum analyses (MRA) and numerical-integration time-history analyses (NITHA) to evaluate and improve these analysis methods in NZS1170.5:2004. In the MRA analyses, we compared the effect on the inter-storey drift profile of the different P-delta scale factors from method A and method B prescribed in NZS1170.5. To perform NITH analyses, we selected alternative families of three or seven records. We considered appropriate selections for both shallow soil sites and deep/soft soil sites. The three-record families each included one near-fault FD ground-motion record, while the seven-record sets included three FD records. We compared the NZS1170 method of using the strongest response from three records with using the average response of seven records. We also considered two alternative record-scaling methods, one with a weighting by period T and the other with a new scaling period band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$, where μ is the structural ductility. Various comparisons of the results from the old and new procedures were carried out. Some conclusions from the present study are:

1. For MRA, we found that the P-delta scale factor from NZS1170.5 method A was much larger than that from method B, leading to larger inter-storey drift estimates from method A.

2. For most structures, the inter-storey drifts estimated from NITHA were lower than those from MRA method A, except for the structure RC3IWCL, regardless of whether far-field or near-fault FD ground-motion records were considered.

3. Compared with the inter-storey drift from MRA method B, inter-storey drifts for most structures from the current NZS1170 NITHA method were higher, if the FD ground-motion records were used. For other records, the inter-storey drifts from NITHA for most structures were lower than those from MRA method B.

4. Using the period band of $0.4T_0$ to $1.3T_0$ for scaling and only non-FD records, the scatter of the inter-storey drifts was smaller. Thus the scatter in our results appears to have been caused mainly by the FD ground-motion records. This result illustrates that the scaling method recommended in NZS1170.5 is suitable for non-FD records.

5. We found that the mean input motion as measured by the mean response spectrum of the seven records selected for each structure was close to the design spectrum in the period range of 0.7s to 3.0s, suggesting that the mean responses from 7 records, including inter-storey drifts, are also likely to be representative of those for the target input motions specified by the NZS1170 spectra.

6. The mean inter-storey drift from the 7 records was lower than that from MRA method B by about 17% on average (20% in the frame direction and 14% in the wall direction).

7. The alternative scaling method of using the period T as a weighting factor in the least-squares measure-of-fit to increase the influence of long-period components was generally found unsuccessful in reducing the scale factors for FD records, so the method was abandoned.

8. For a second alternative scaling method of increasing the upper limit of the scaling period band to $T_{eff} = \sqrt{\mu}T_0$, the mean inter-storey drifts calculated for seven earthquake records were similar to those from the NZS1170.5 method, but their scatter was lower and the effect of the FD ground-motion records on the inter-storey drift was weakened.

   On the basis of these conclusions, we make the following recommendations for performing NITH analyses:

   1. Use the average response of seven or more records, of which about one-third (two or three of seven) should have strong forward-directivity characteristics for locations where near-fault factors are required by NZS1170, rather than the strongest response from three records. The average response reduces the influence of the forward-directivity records to a weighting of about one-third, consistent with the near-fault factors used in the NZS1170 spectra, and produces similar or reduced seismic demand estimates for NITH analyses compared to MRA methods.

   2. Increase the upper limit of the scaling period band to $T_{eff} = \sqrt{\mu}T_0$, to achieve much less scatter across the analyses for a family of scaled records.

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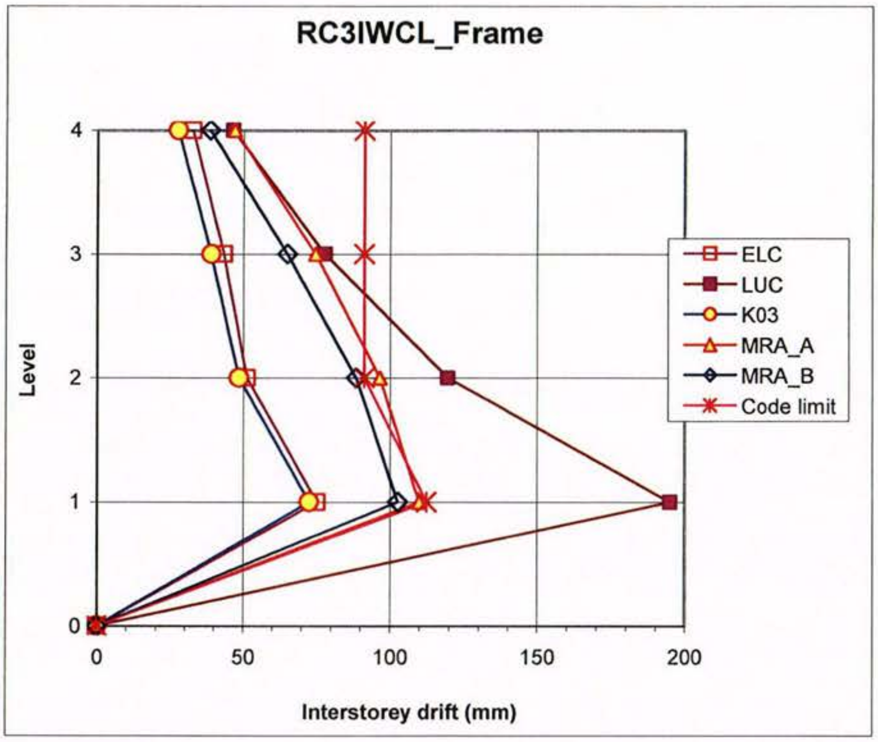
APPENDIX— FIGURES OF RESULTS



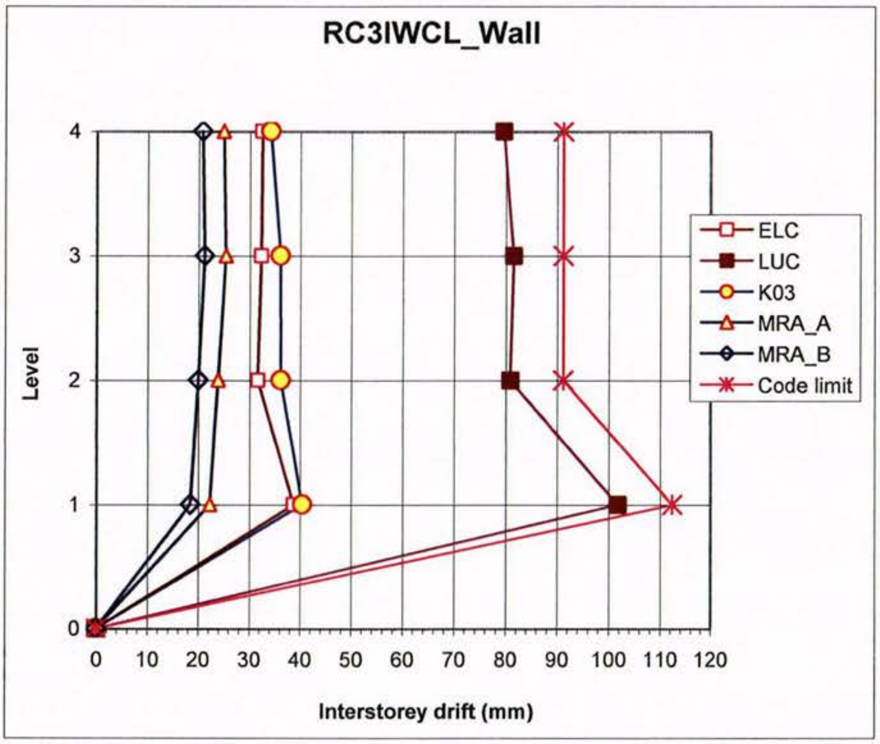
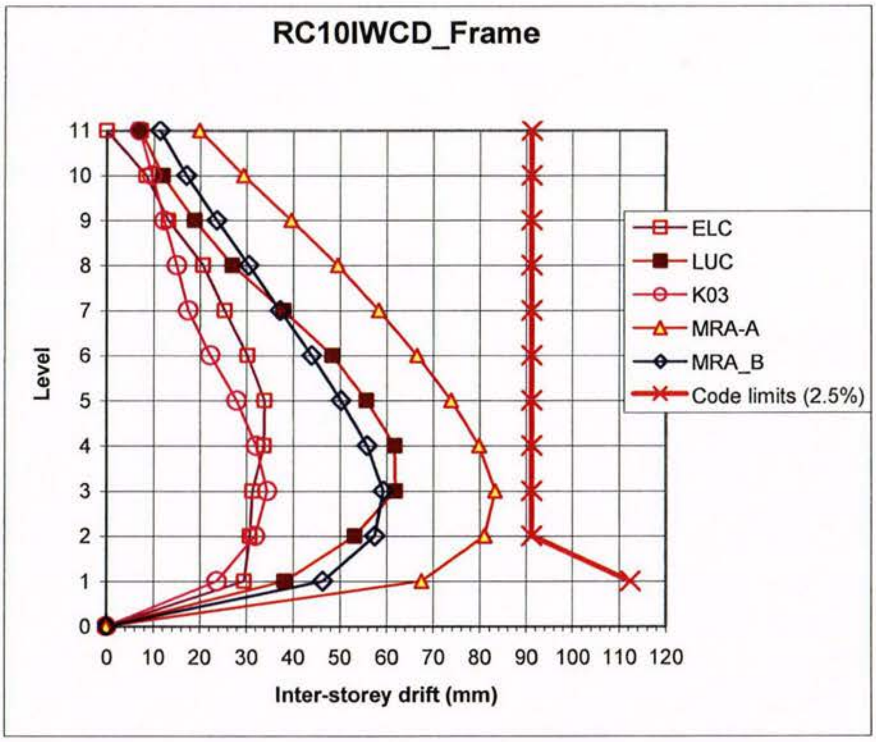


Figure 2a Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC3IWCL



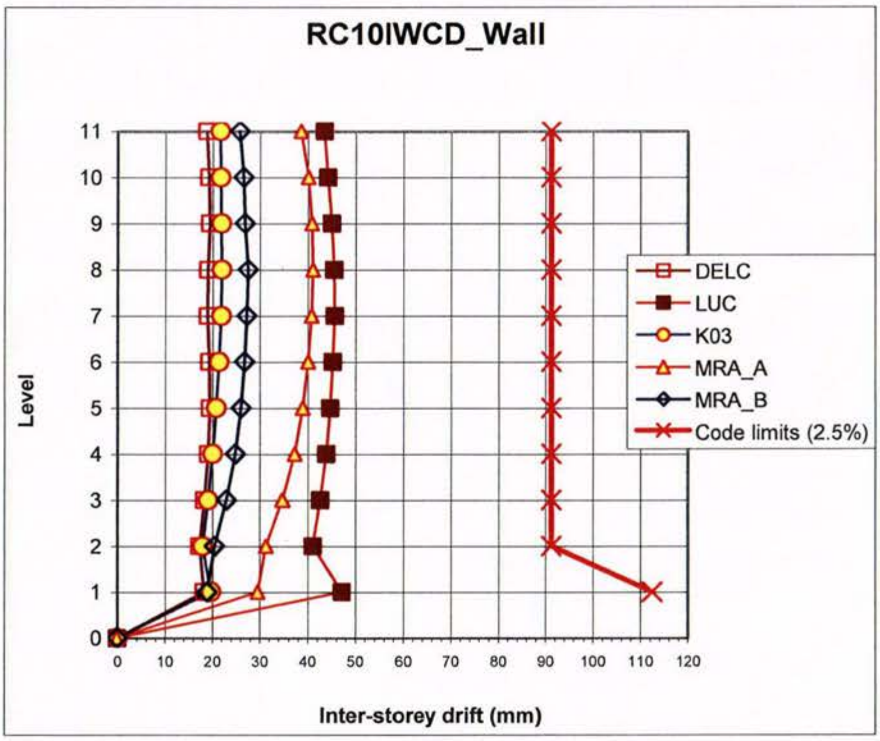
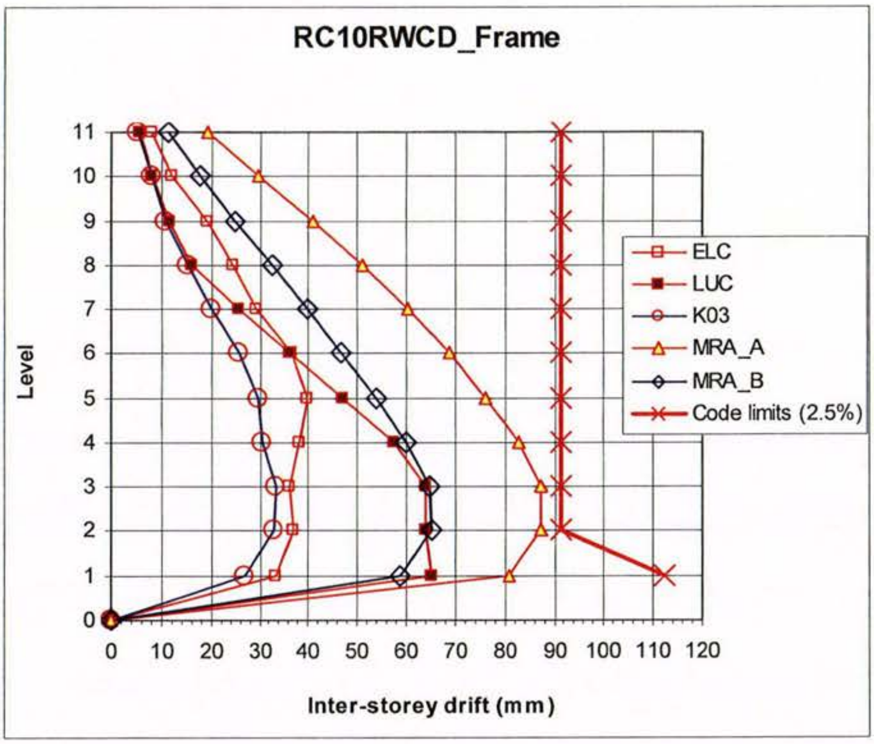


Figure 2b Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC10IWCD



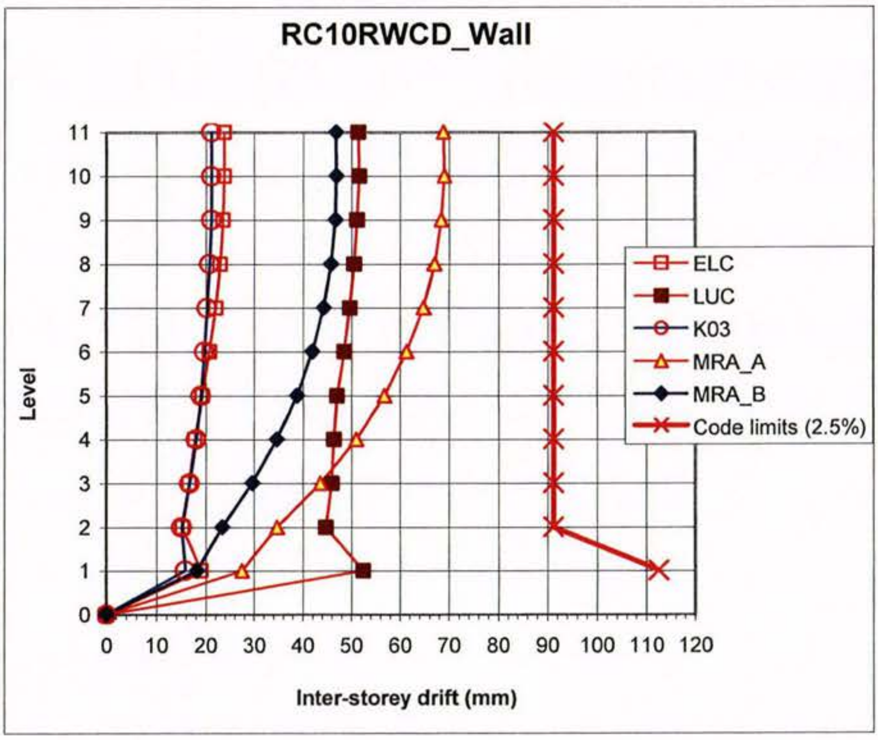
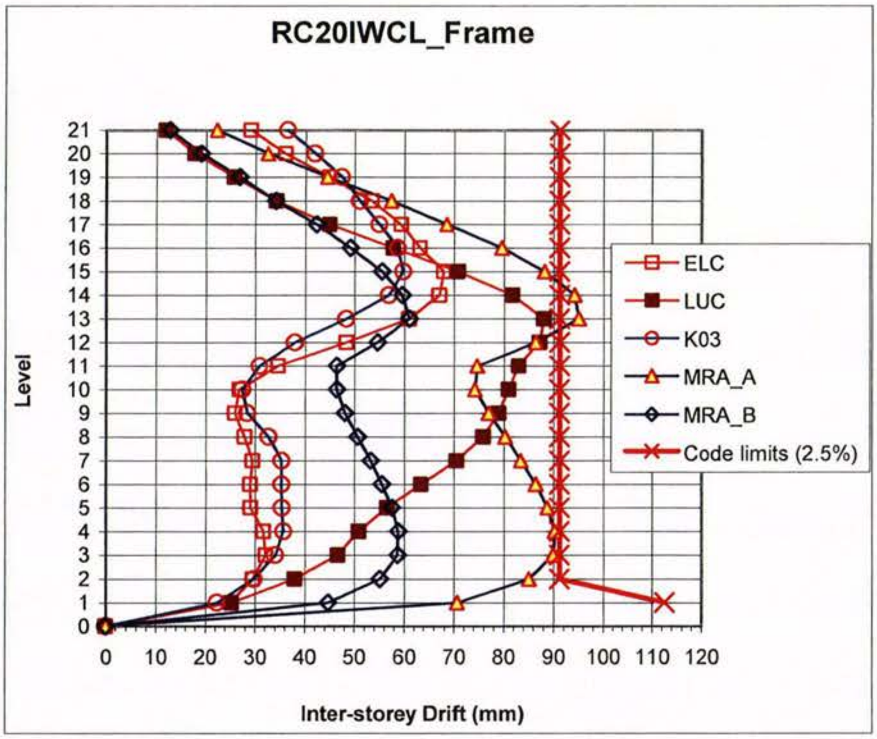


Figure 2c Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC10RWCD



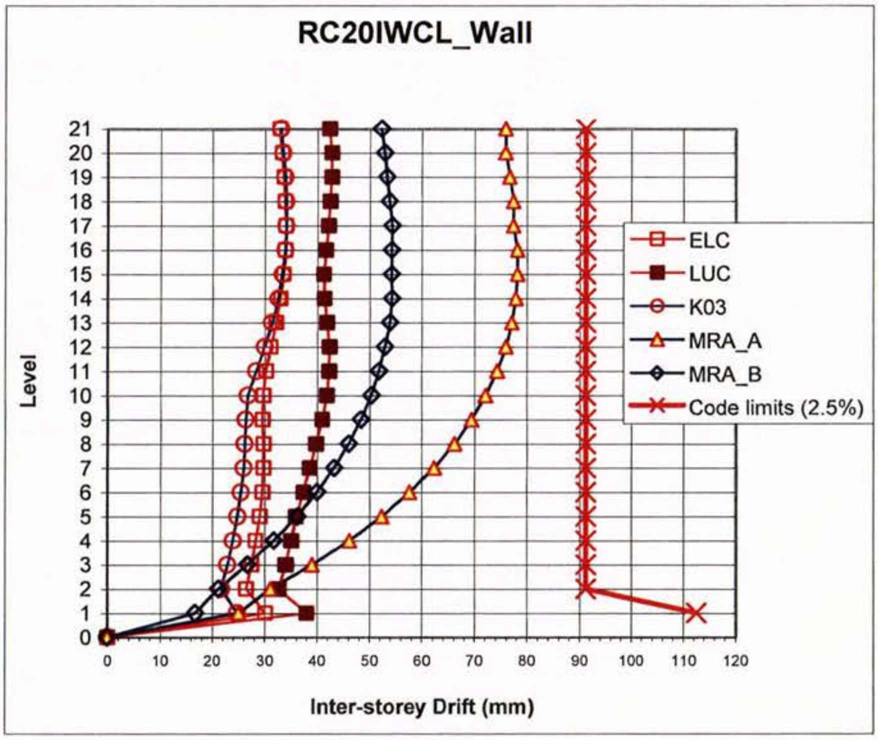
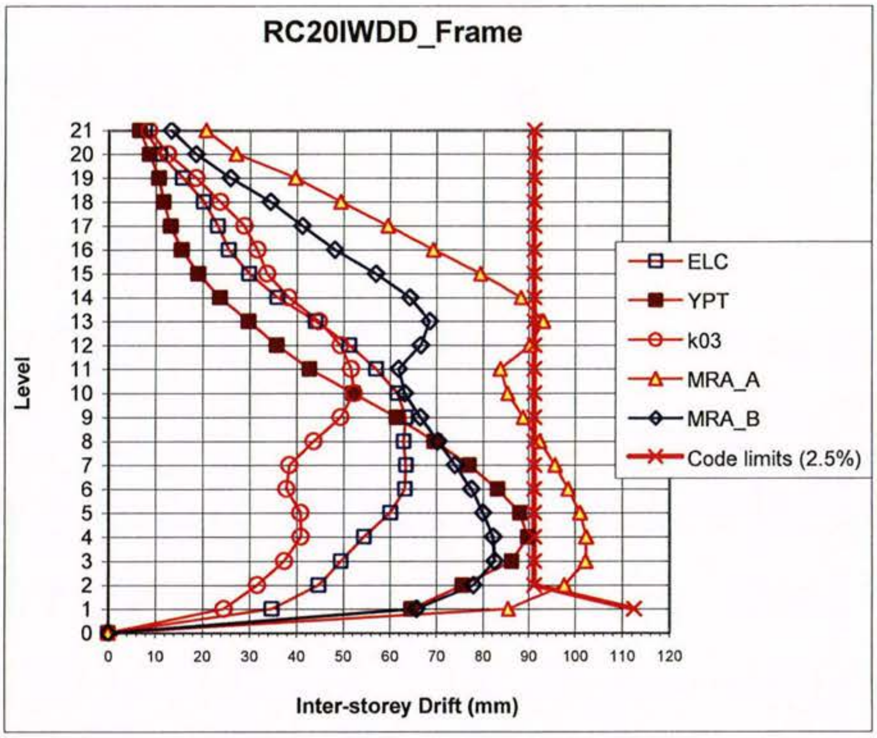


Figure 2d Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC20IWCL



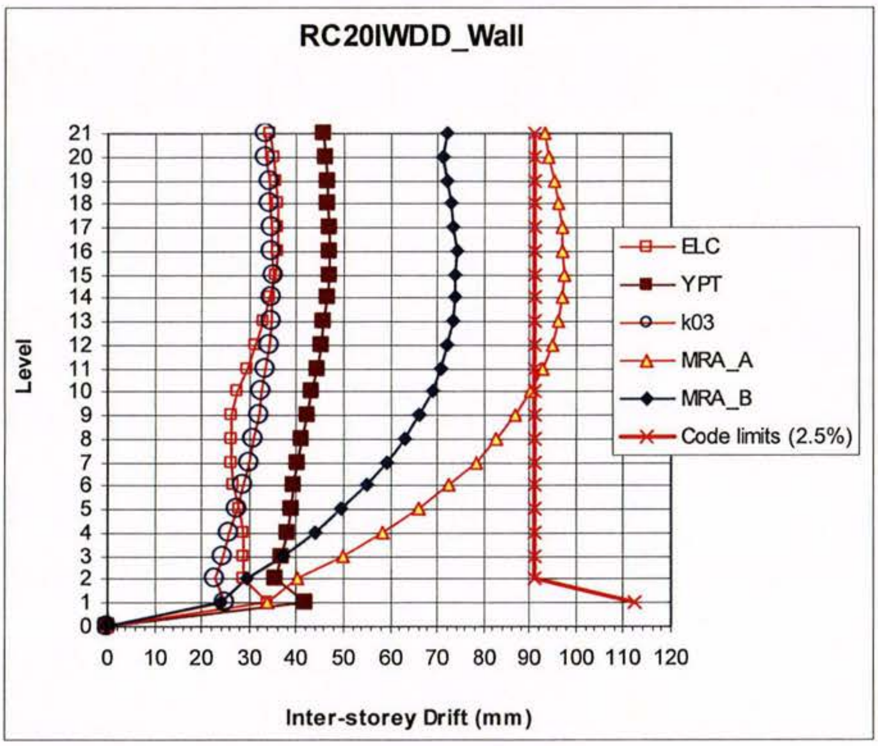
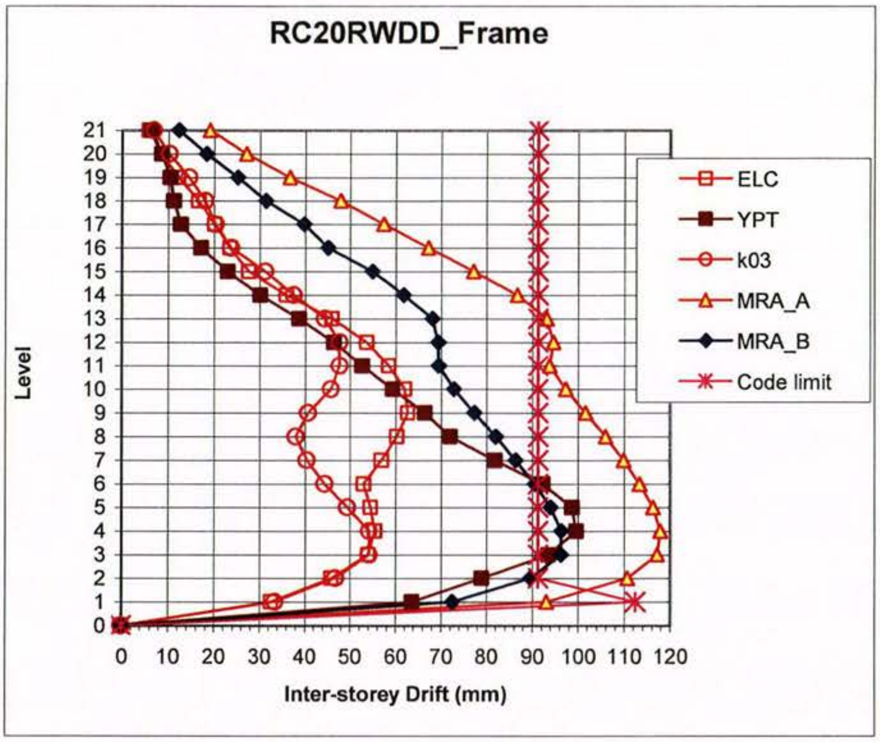


Figure 2e Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC20IWDD



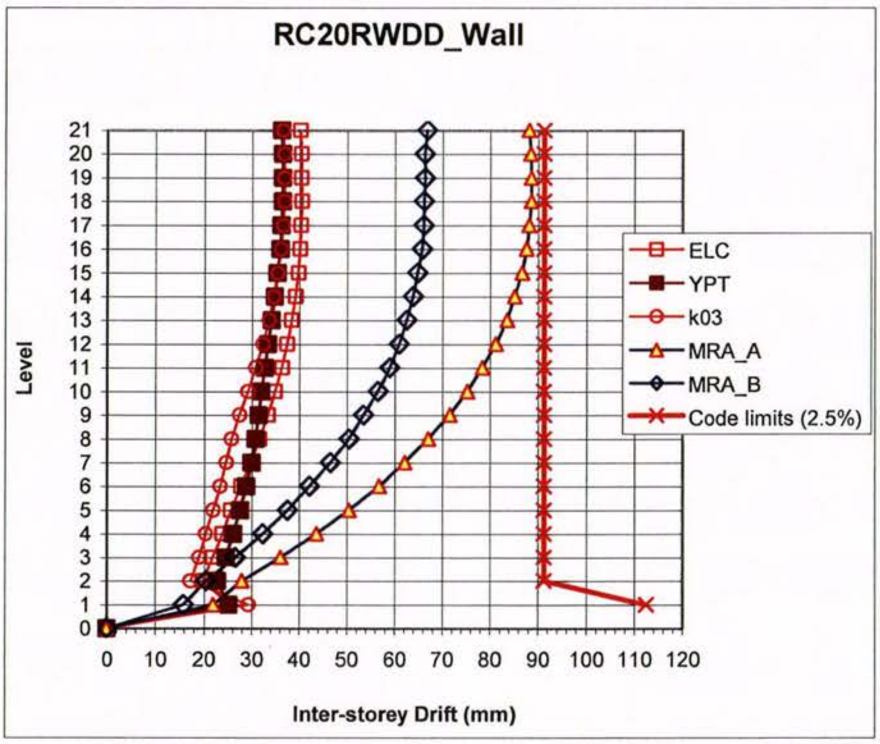


Figure 2f Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC20RWDD and 3 records

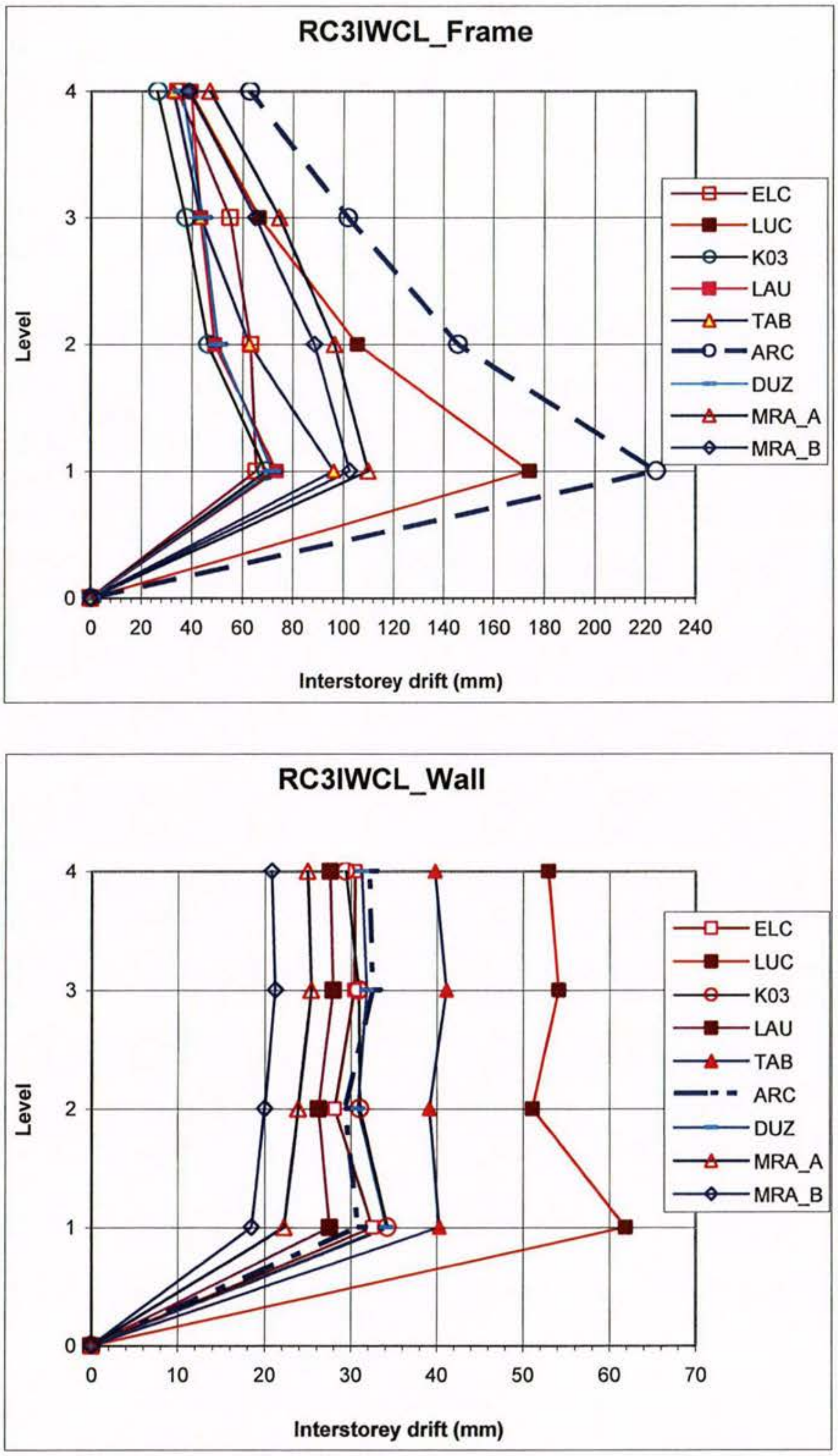
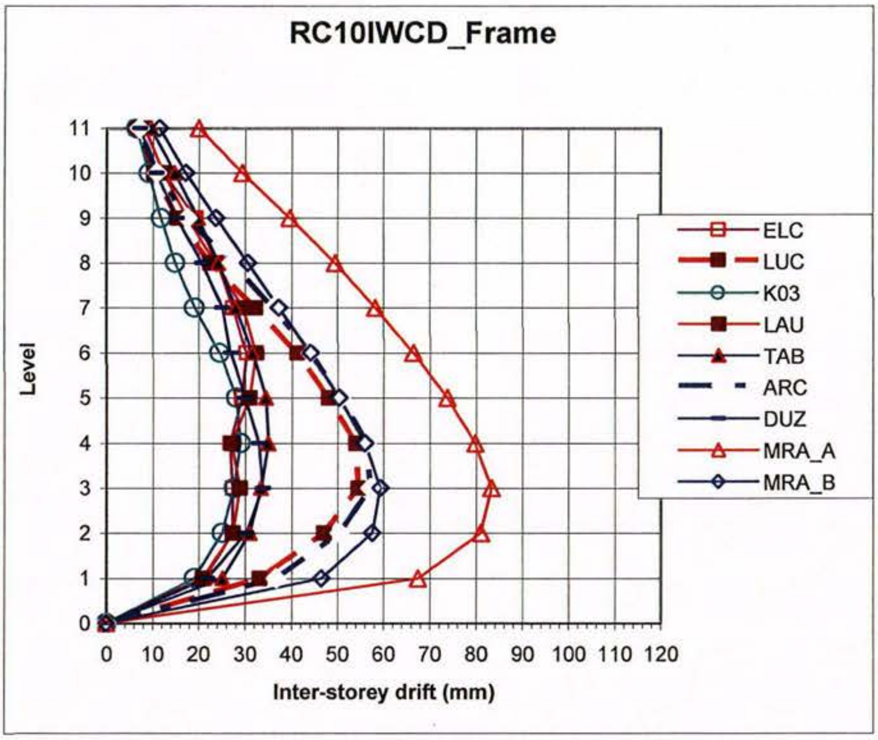


Figure 3a Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC3IWCL and 7 records



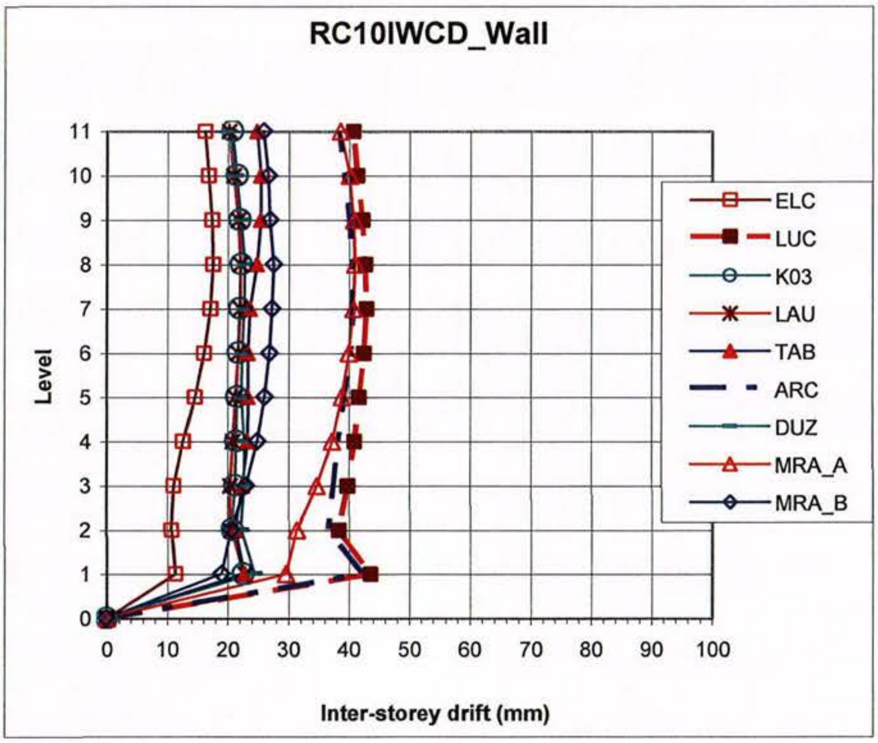


Figure 3b Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC10IWCD and 7 records

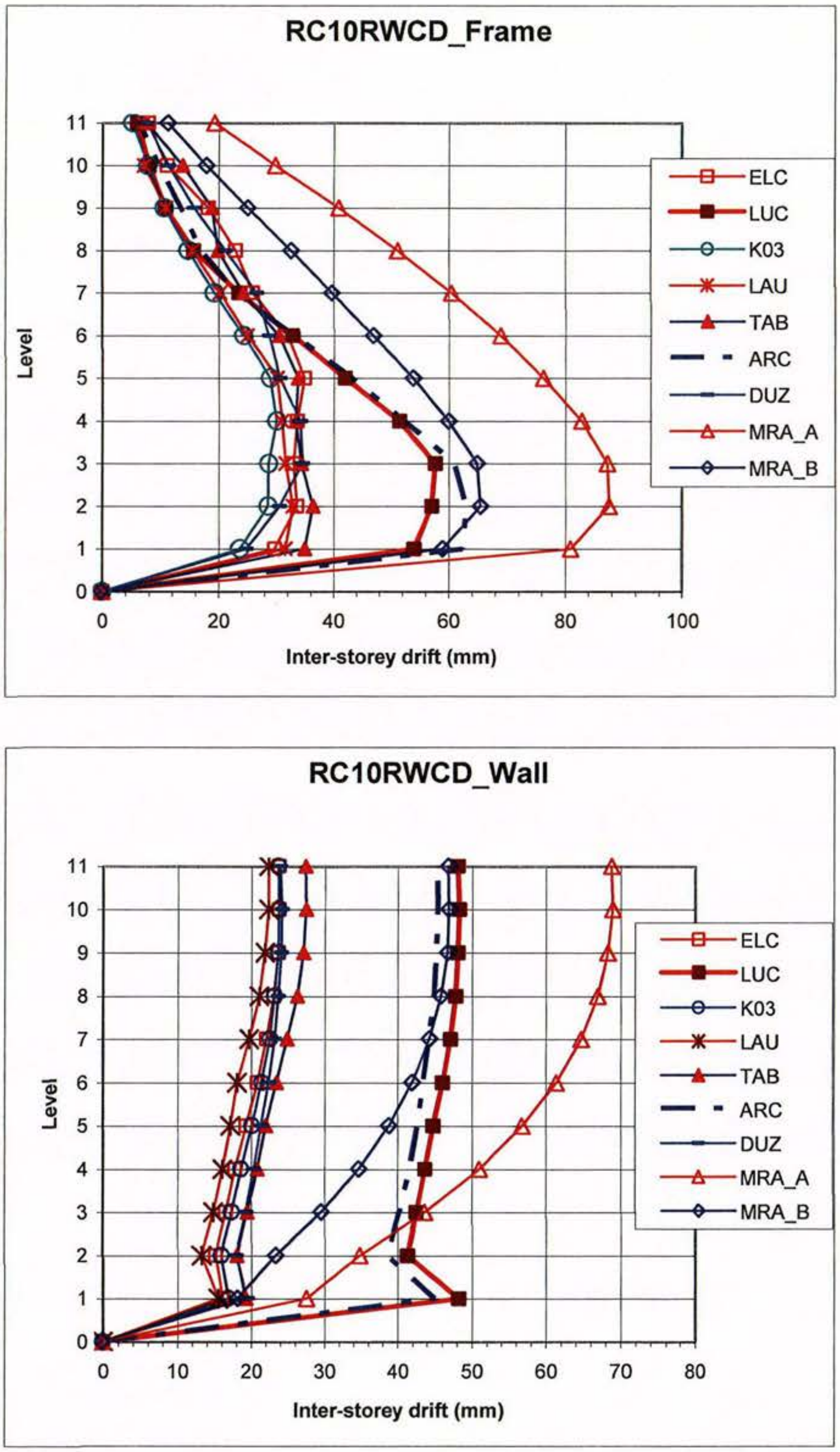
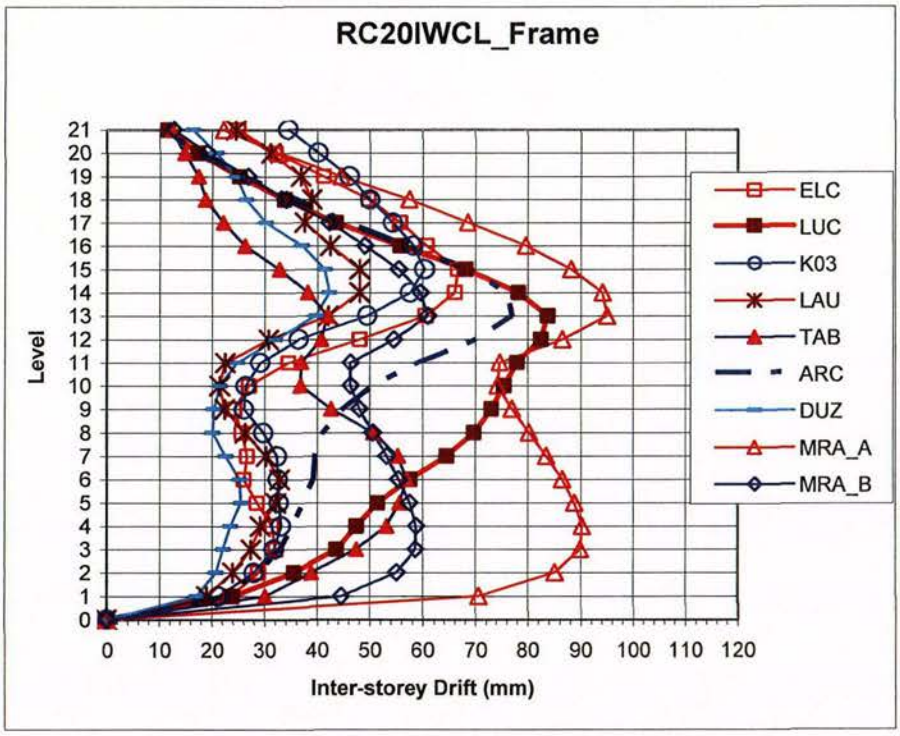


Figure 3c Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC10RWCD and 7 records



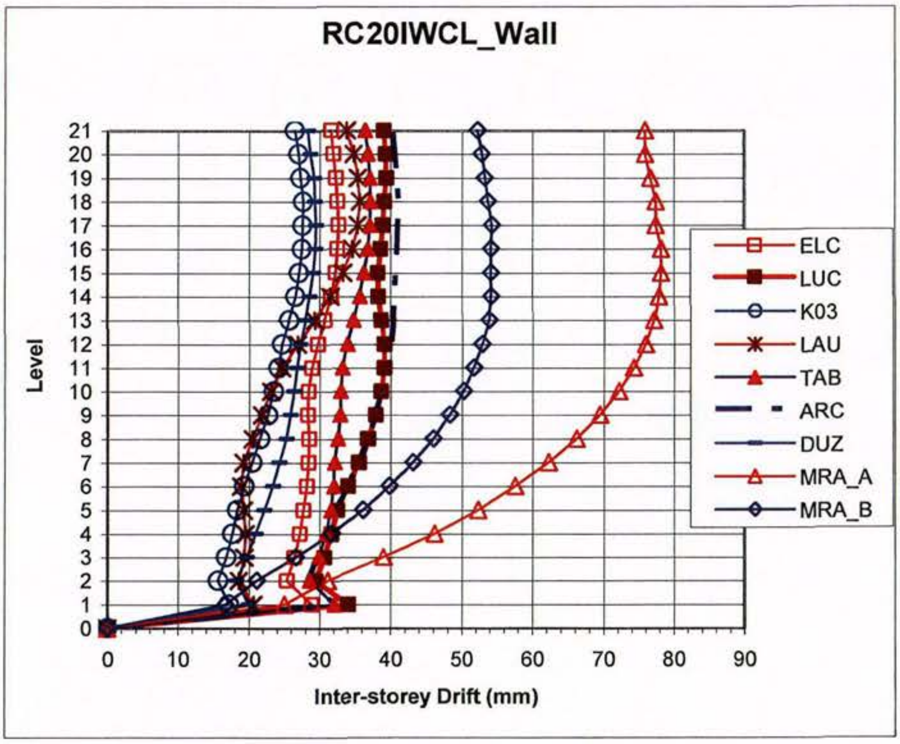
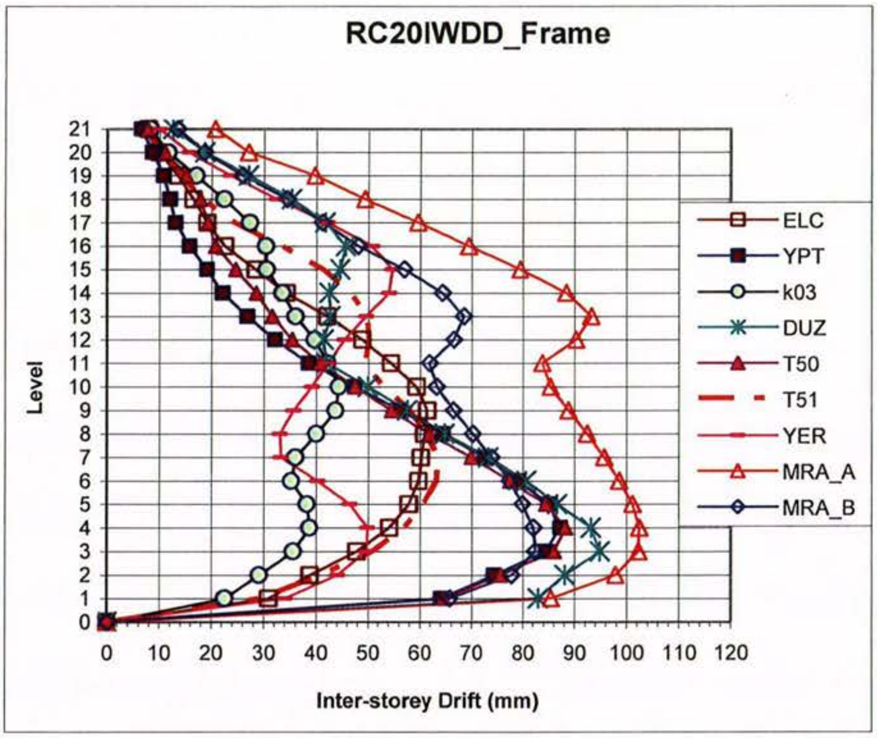


Figure 3d Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC20IWCL and 7 records



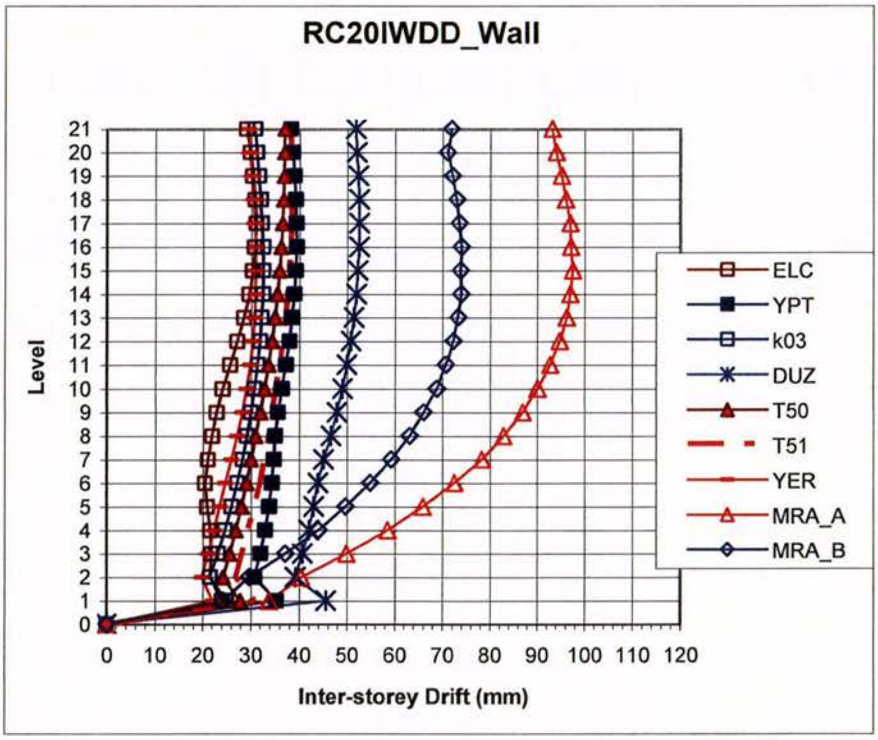
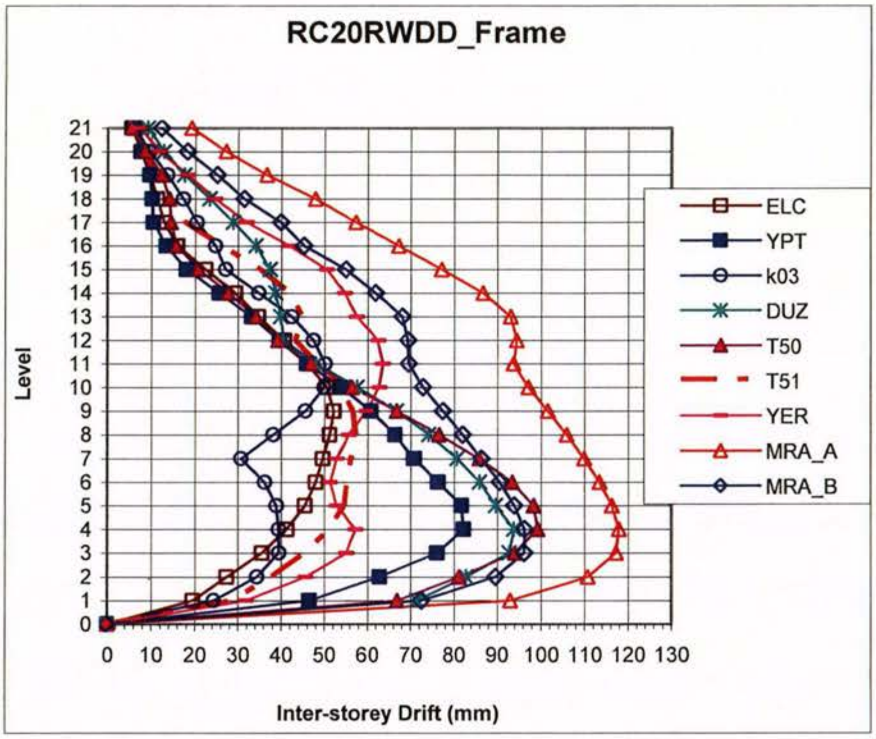


Figure 3e Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC20IWDD and 7 records



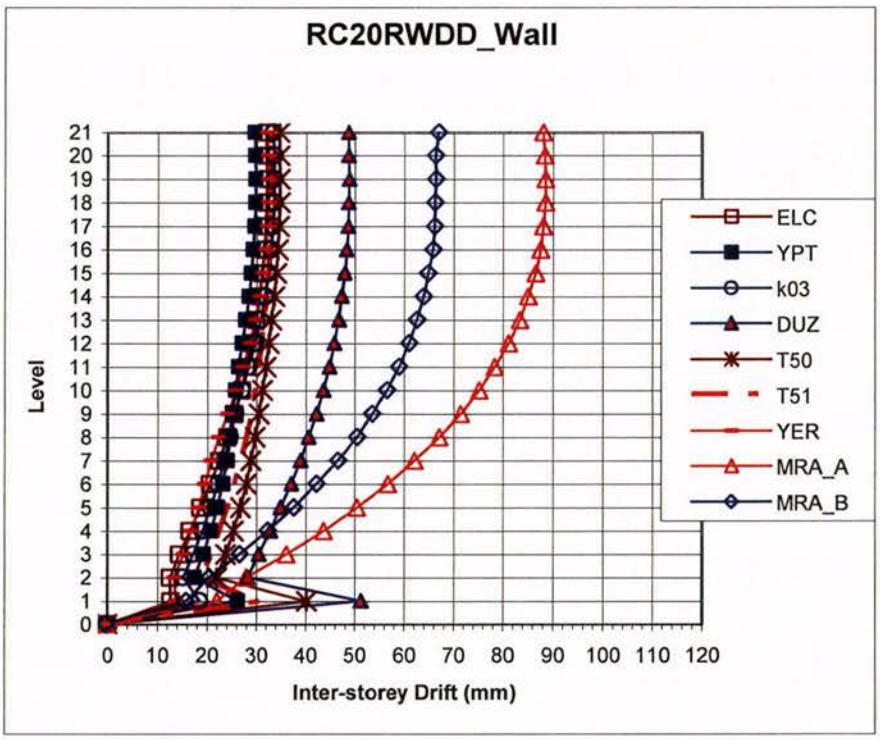
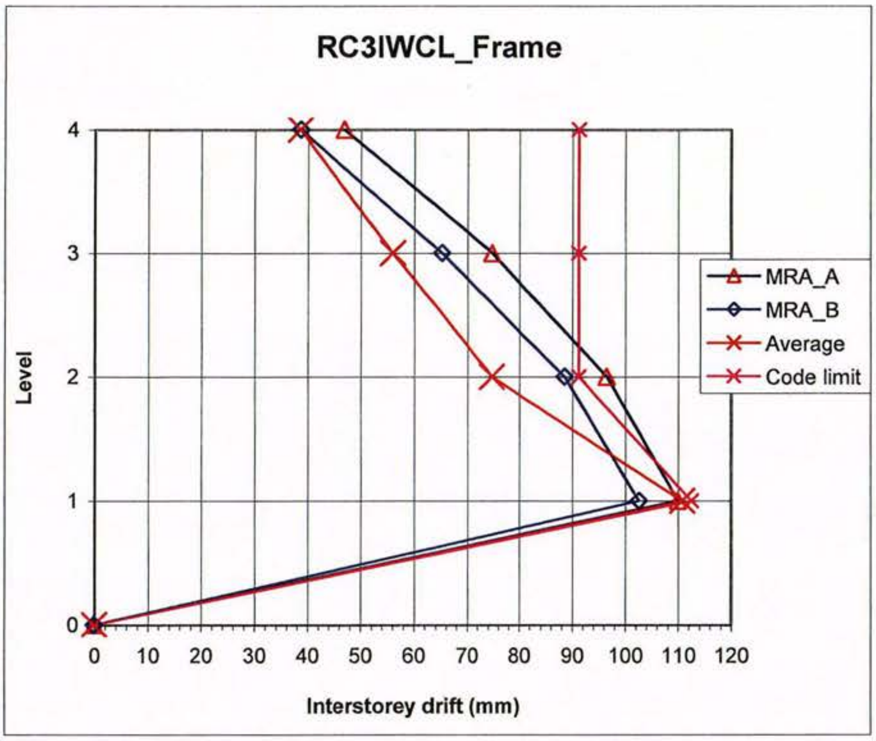


Figure 3f Comparison of maximum inter-storey drifts from MRA Methods A and B and NITH analyses for RC20RWDD and 7 records



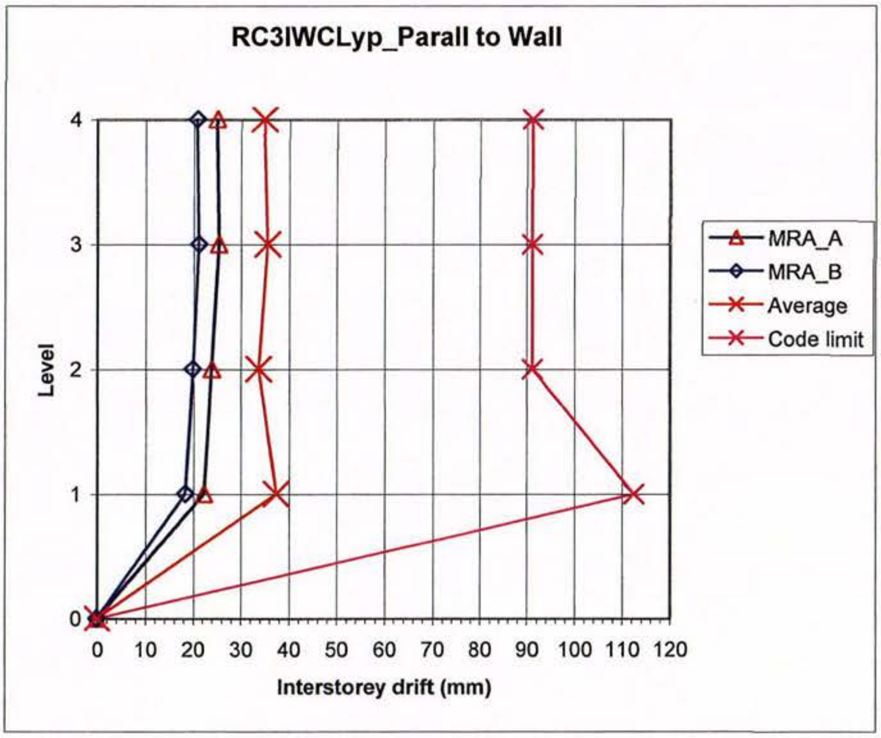
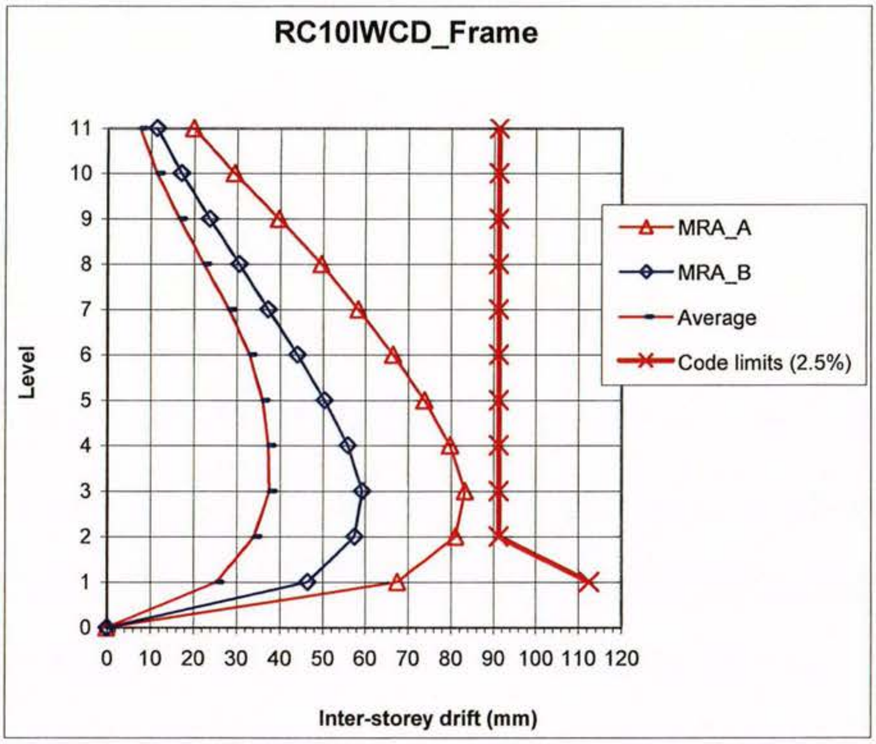


Figure 4a Comparison of mean inter-storey drifts from 7 records and MRA for RC3IWCL



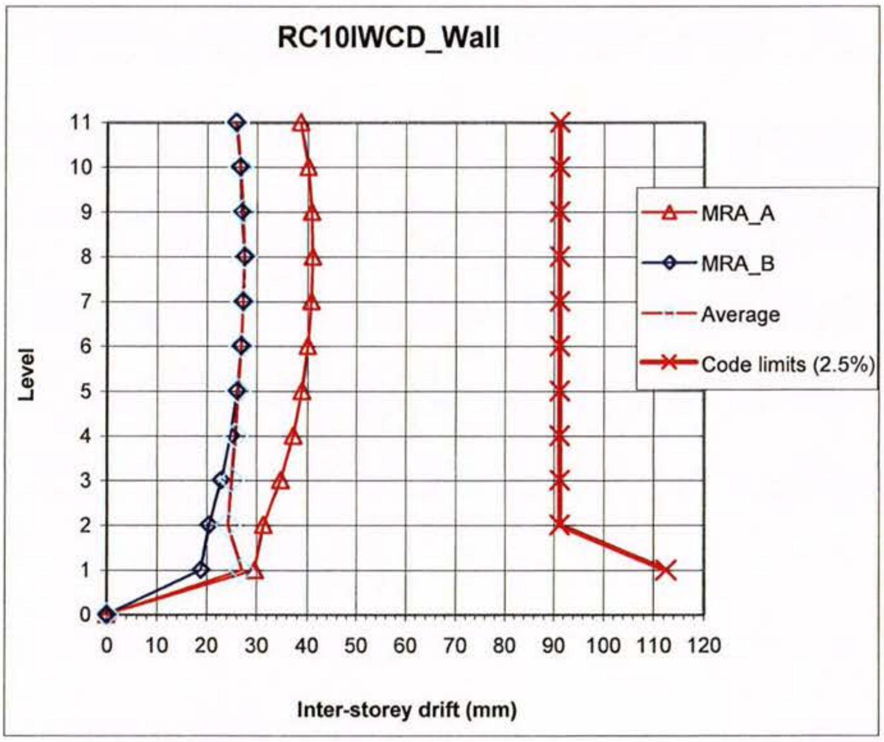
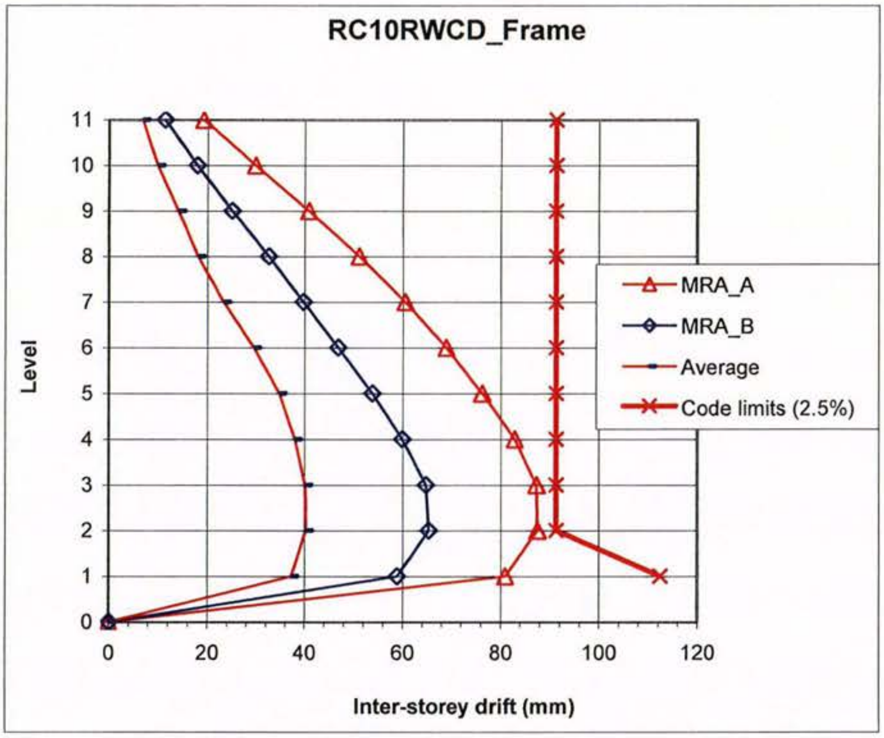
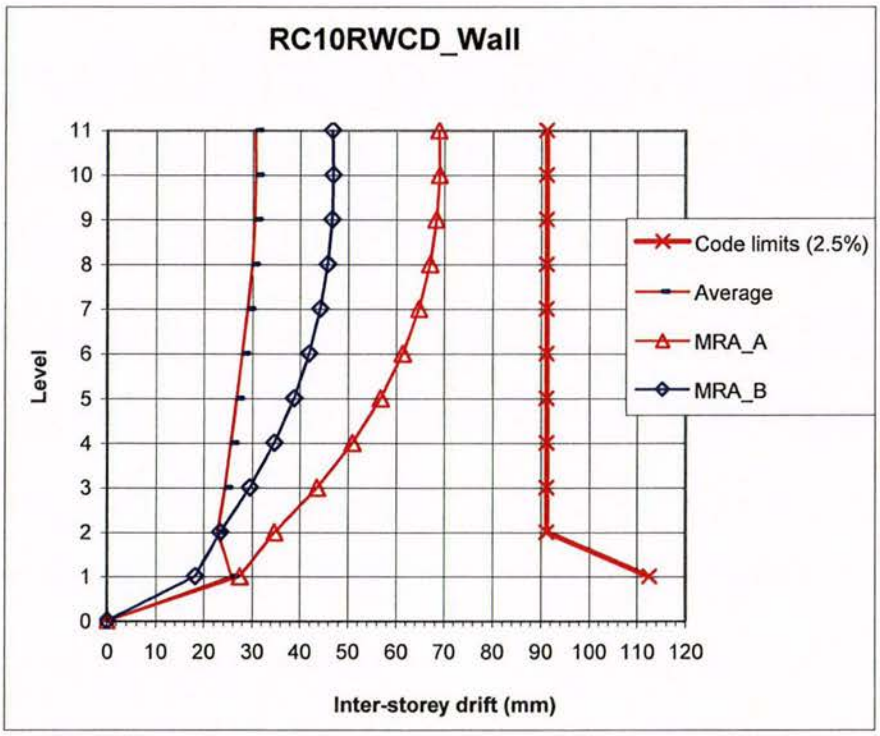


Figure 4b Comparison of mean inter-storey drifts from 7 records and MRA for R10IWCD





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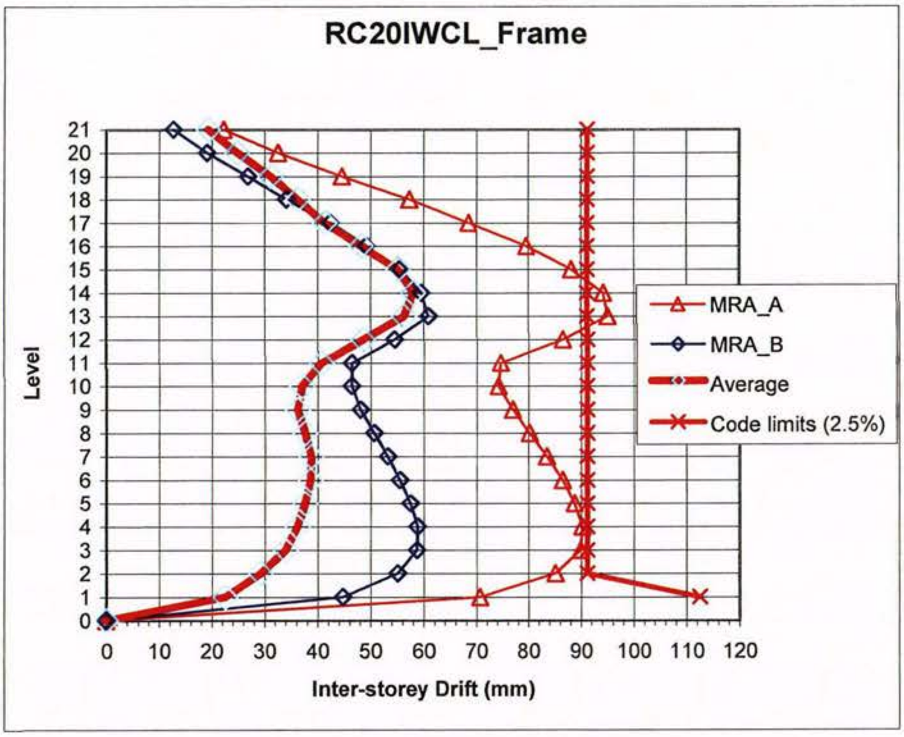


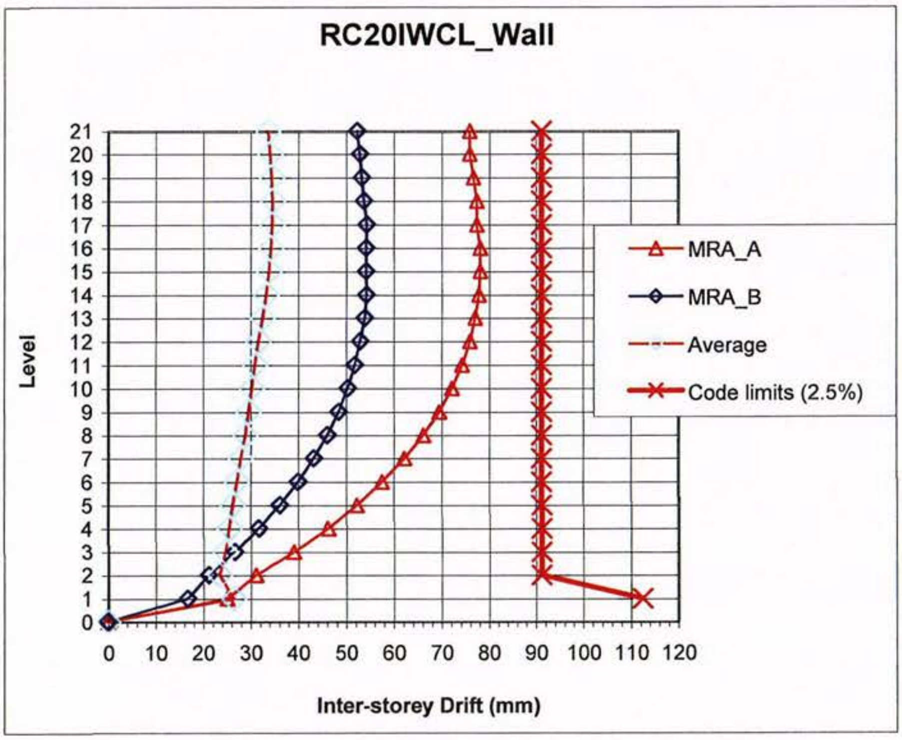
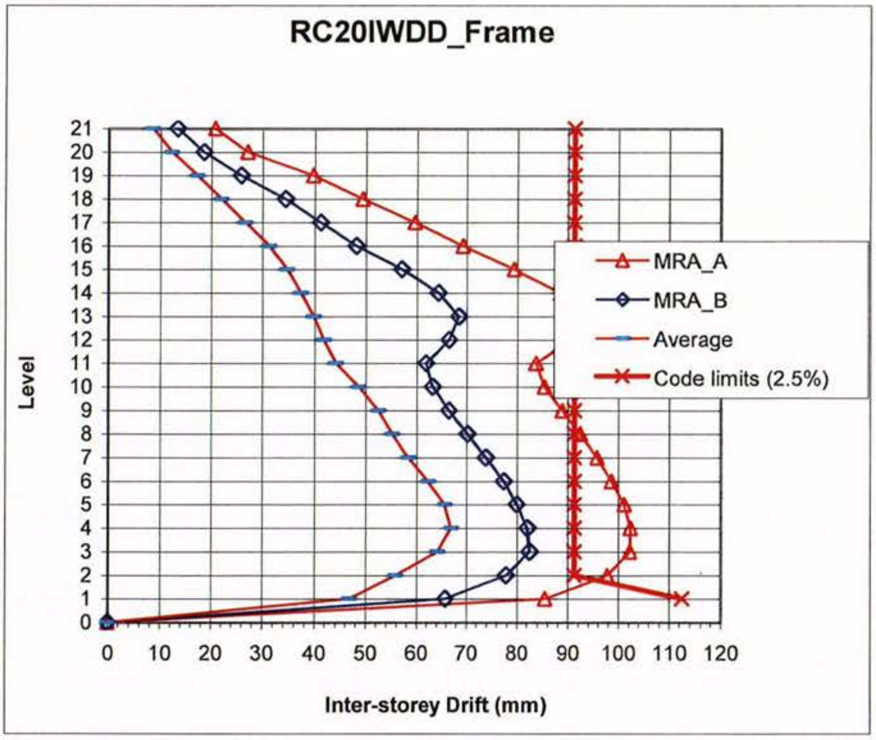
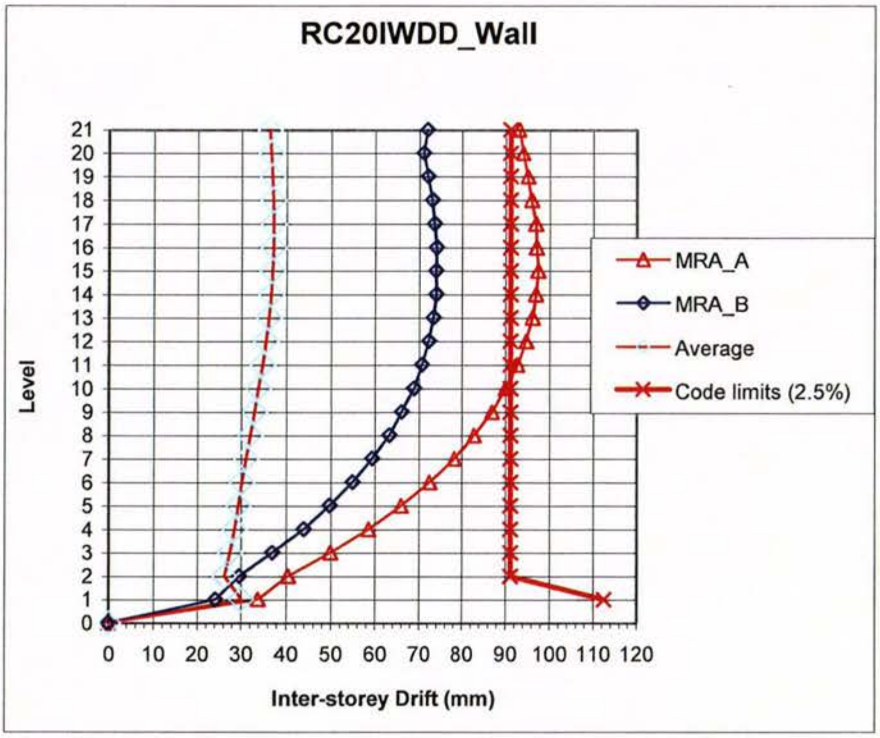


Figure 4d Comparison of mean inter-storey drifts from 7 records and MRA for R20IWCL





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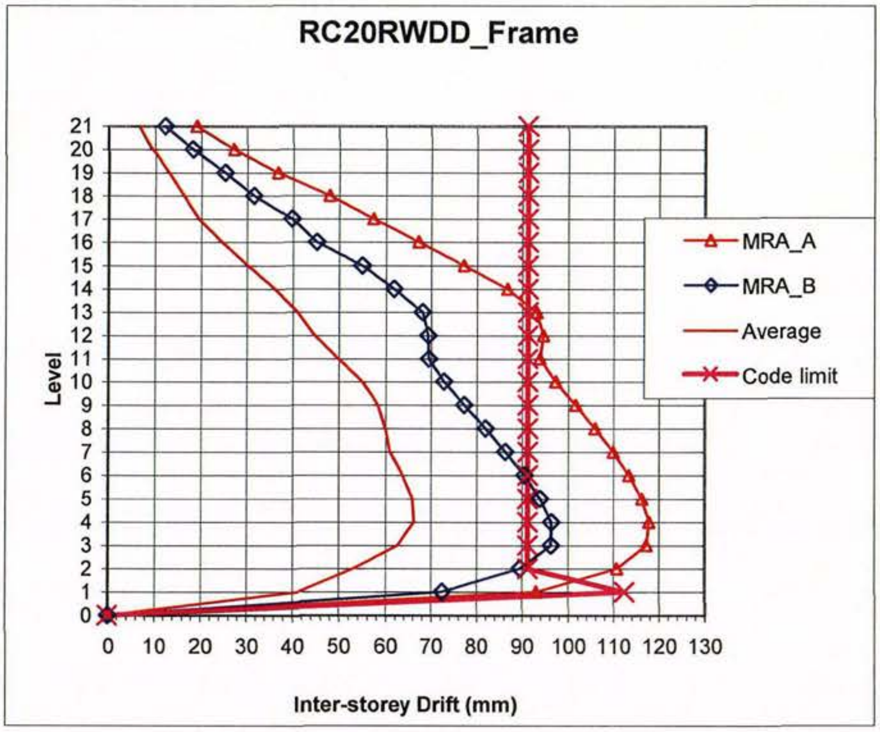

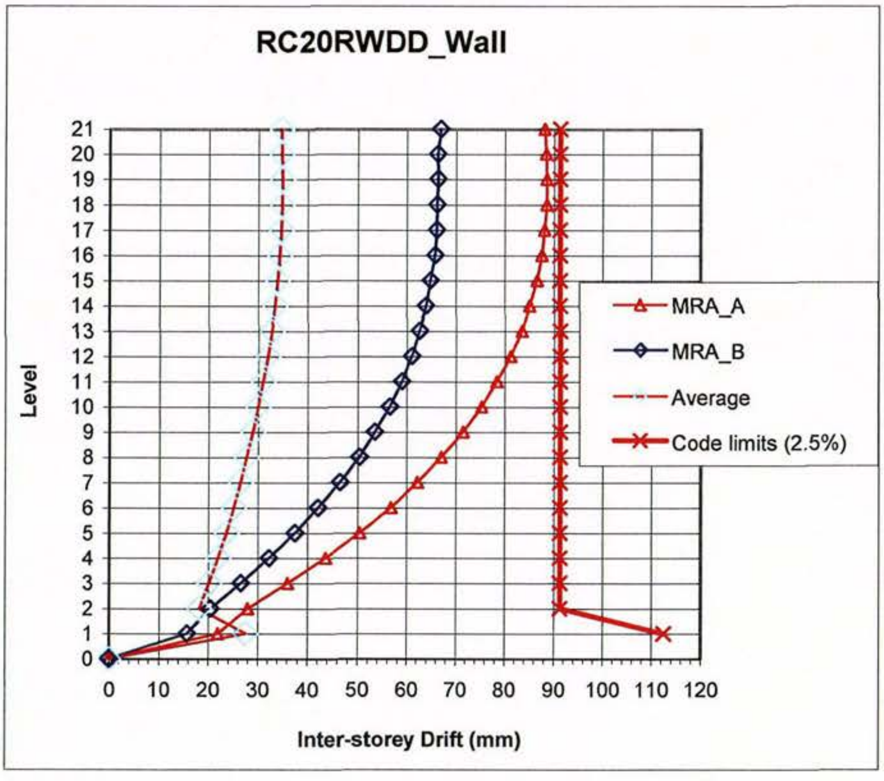

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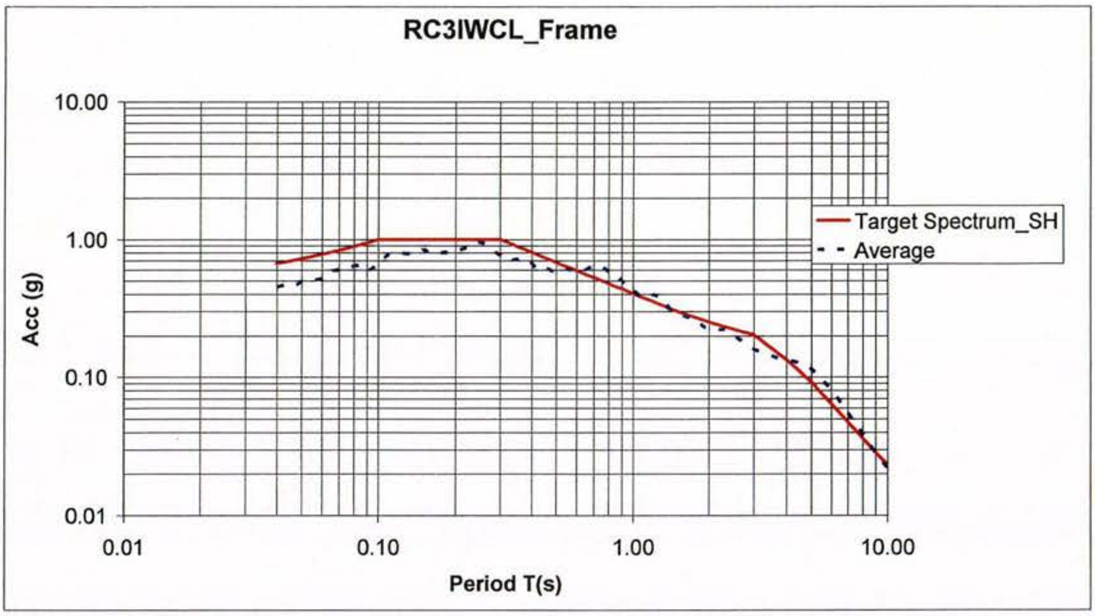


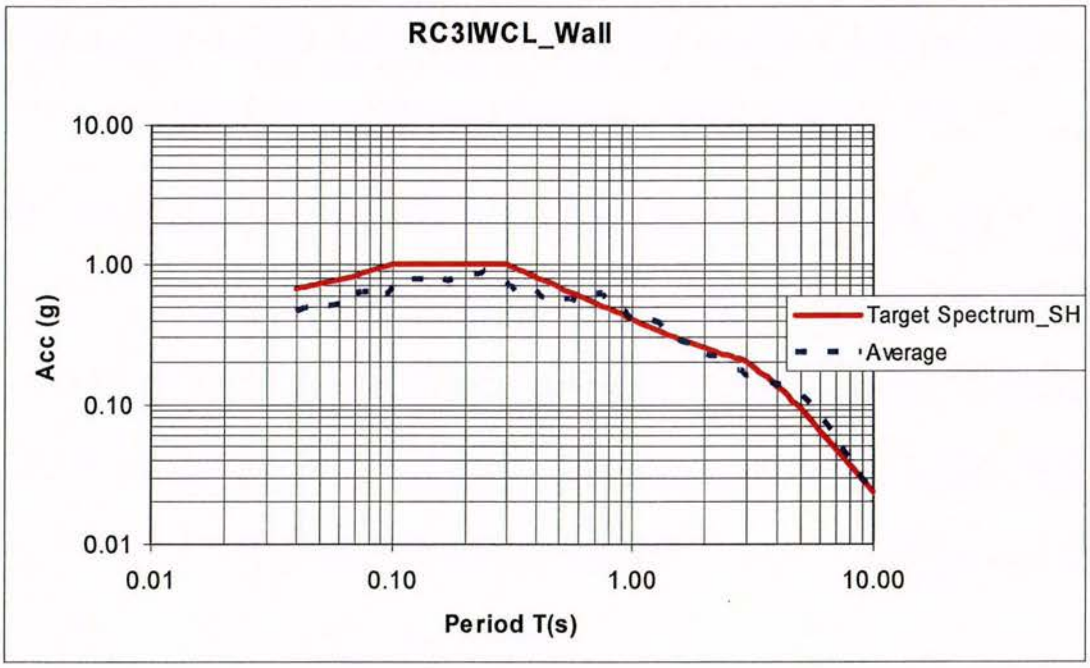
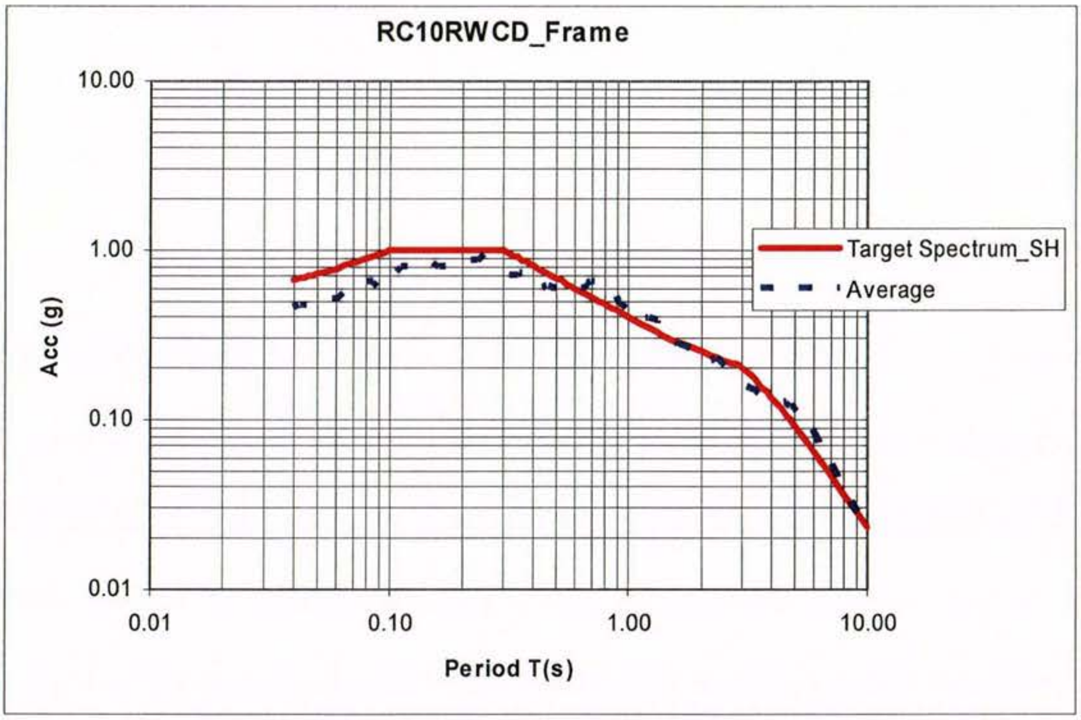


Figure 5a Comparison of target spectrum for NITHA and the mean response spectrum from 7 scaled records for RC3IWCL



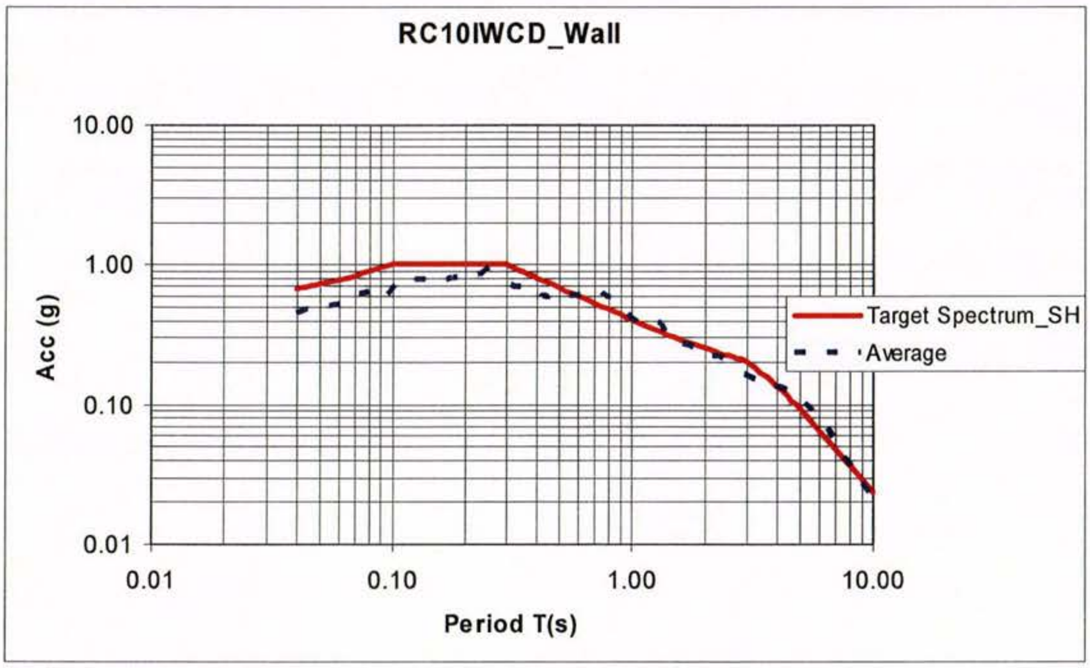
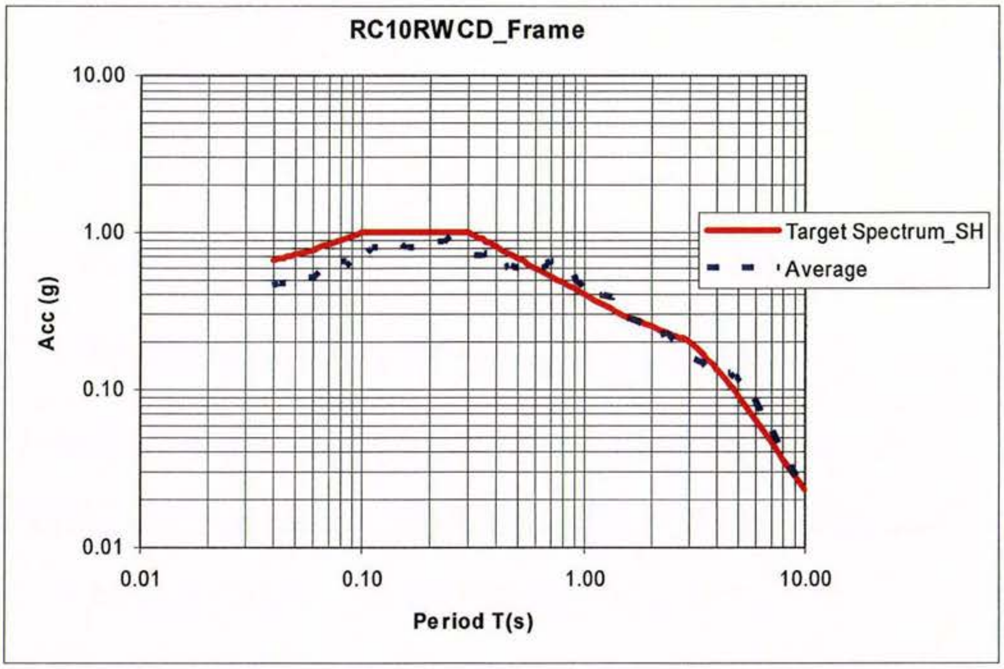


Figure 5b Comparison of target spectrum and the mean response spectrum from 7 records for RC10IWCD



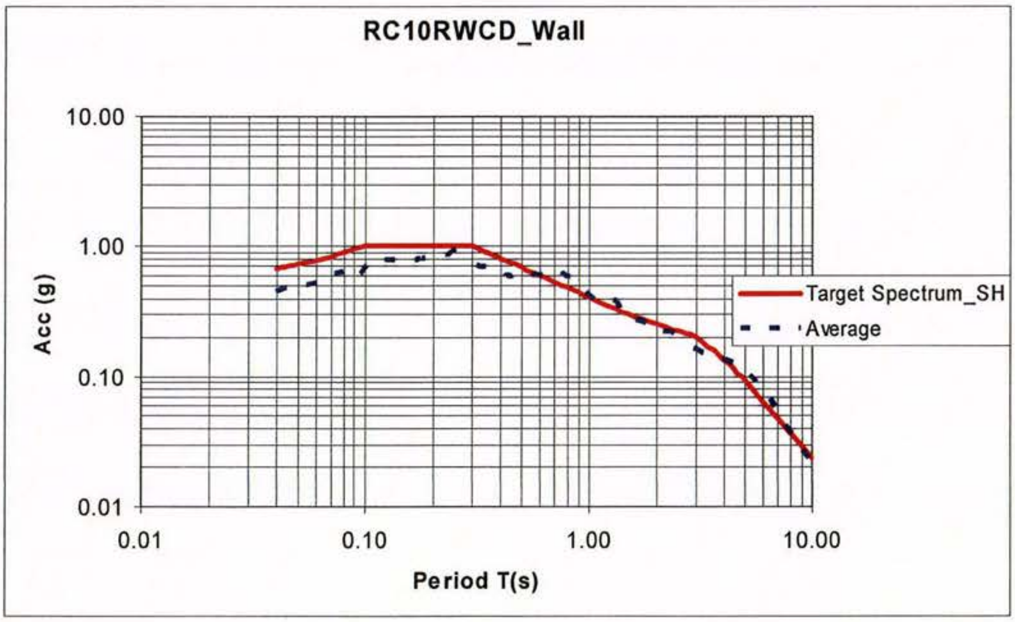
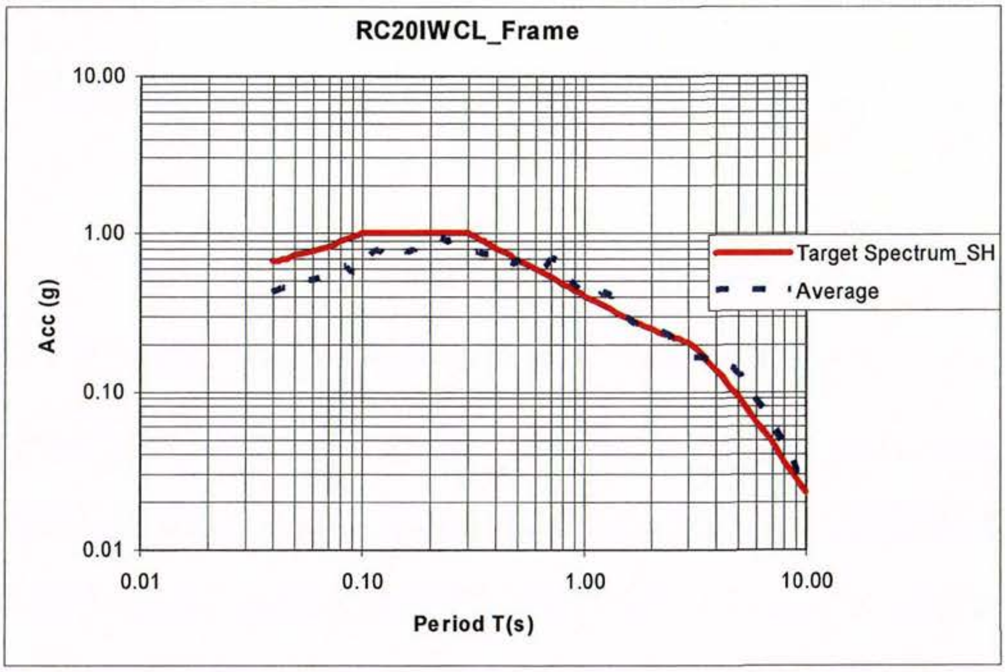


Figure 5c Comparison of target spectrum and the mean response spectrum from 7 records for RC10RWCD



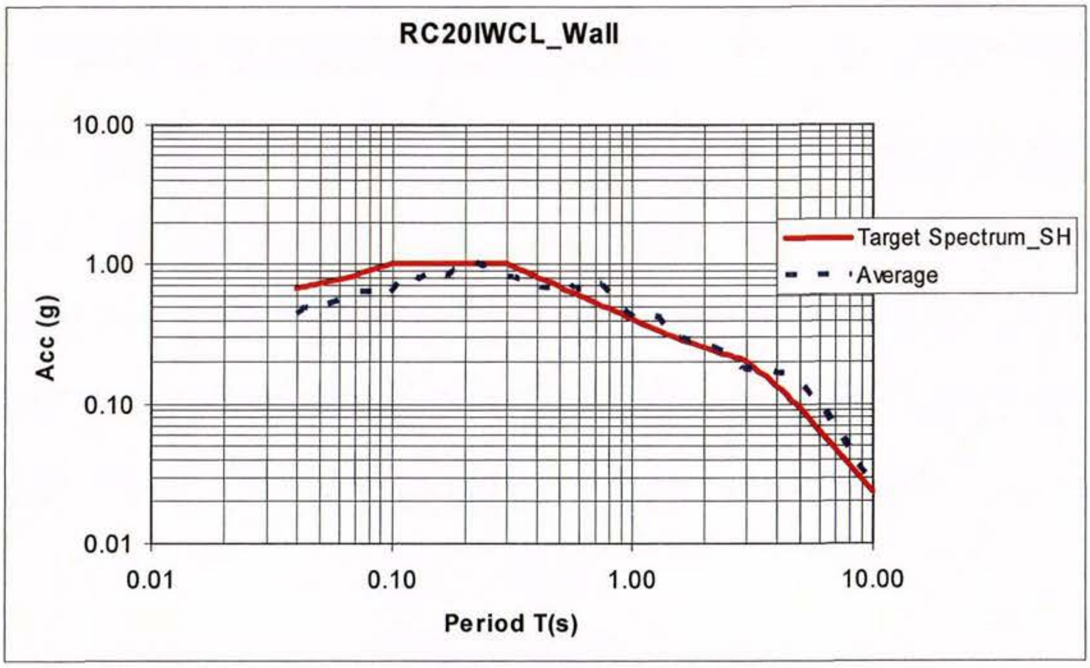
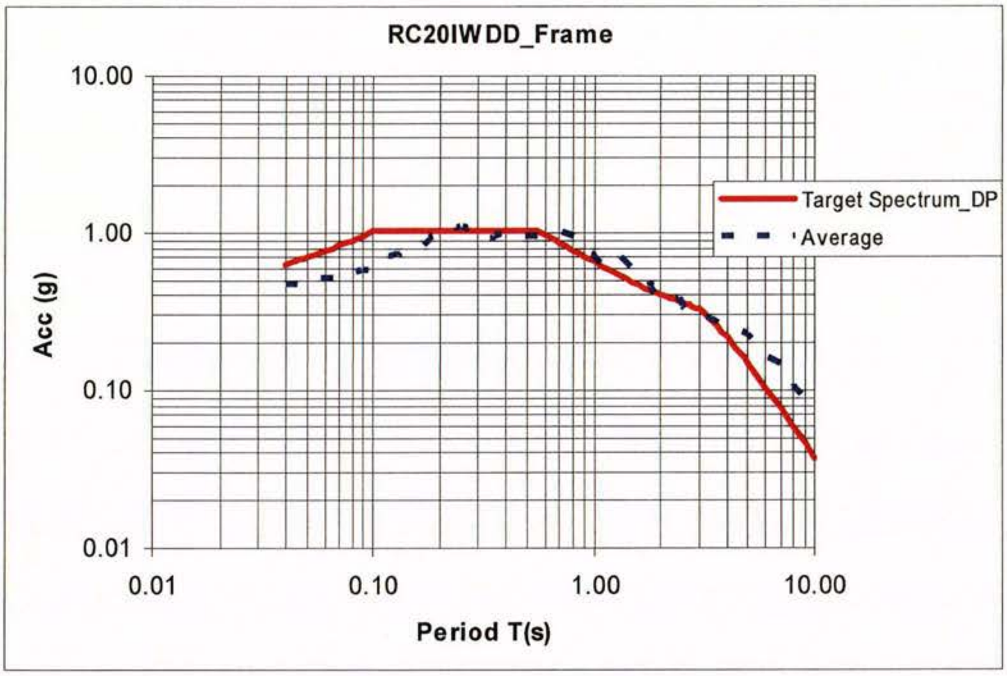


Figure 5d Comparison of target spectrum and the mean response spectrum from 7 records for RC20IWCL



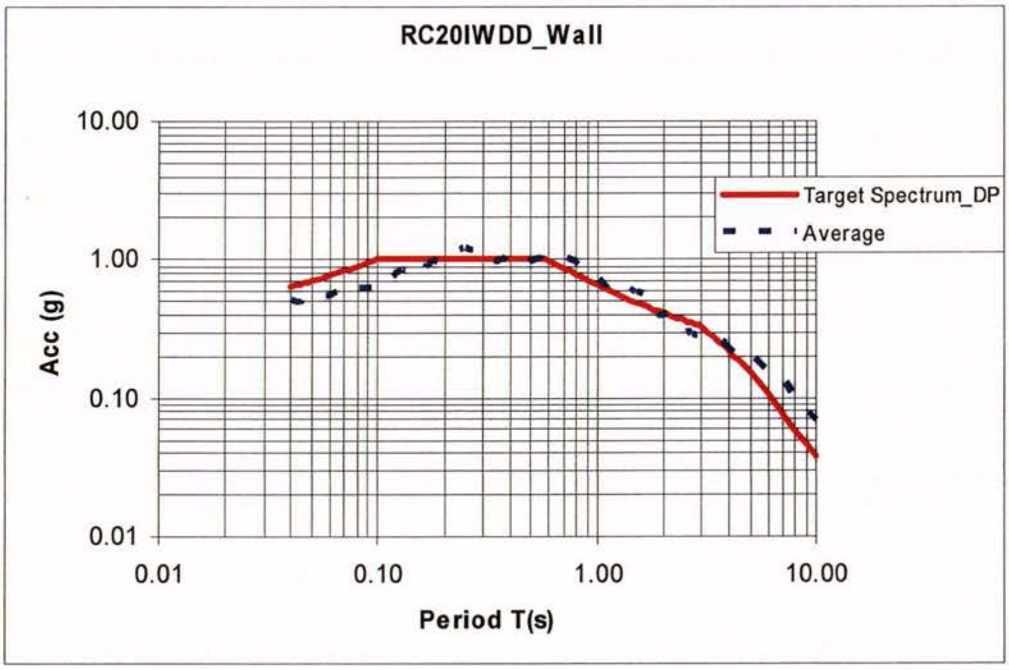


Figure 5e Comparison of target spectrum and the mean response spectrum from 7 records for RC20IWDD

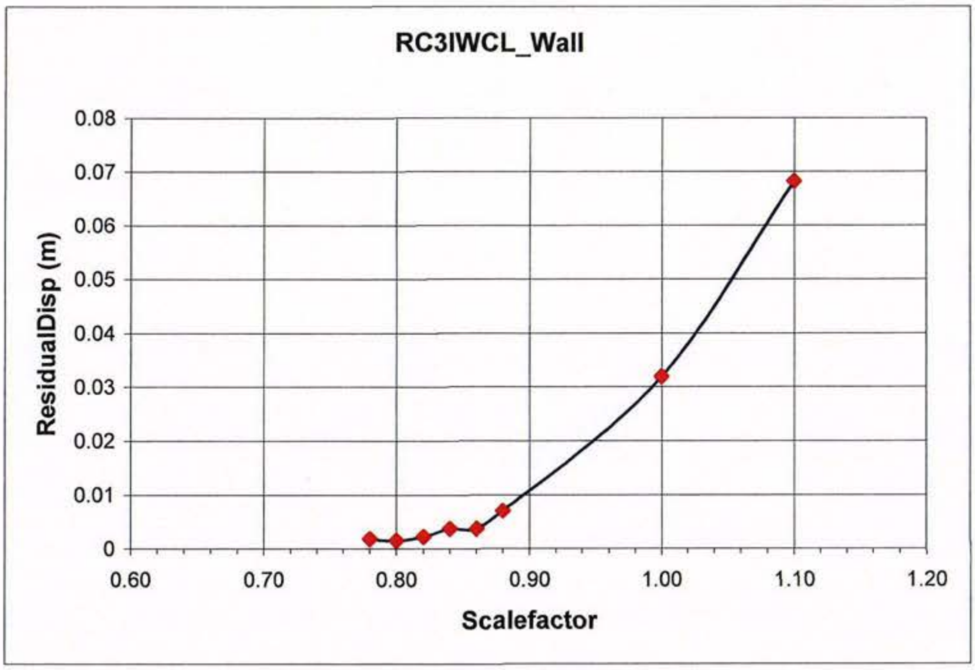


Figure 6 Nonlinear increase of residual displacements with scale factors for the RC3IWCL building excited by the Lucerne record with the principal component in the wall direction. This is indicative of the large drifts that may be estimated when k_2 exceeds 1.0 by a sufficient amount.

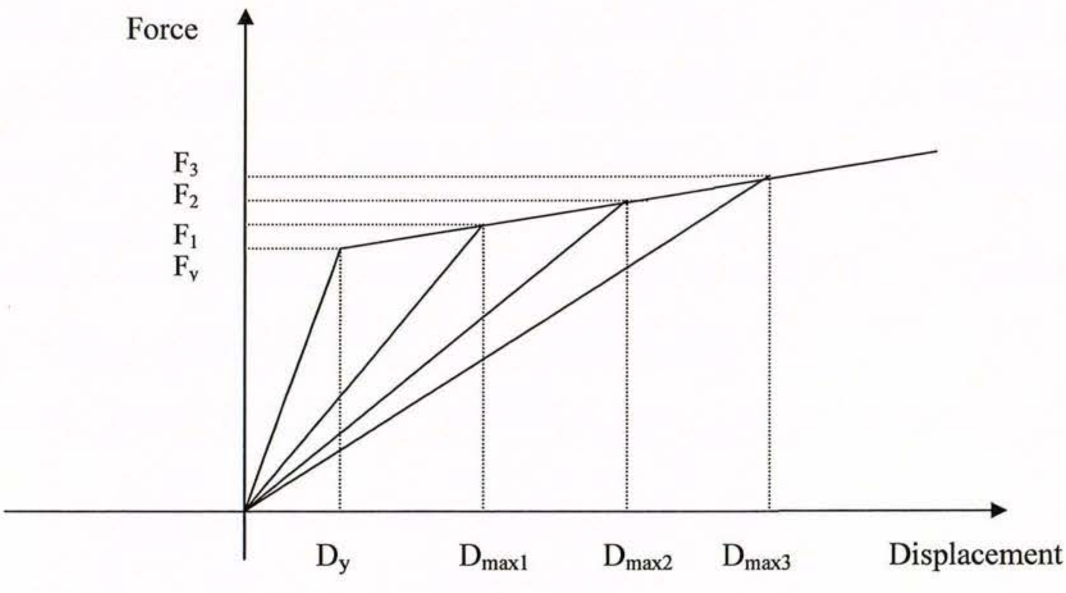
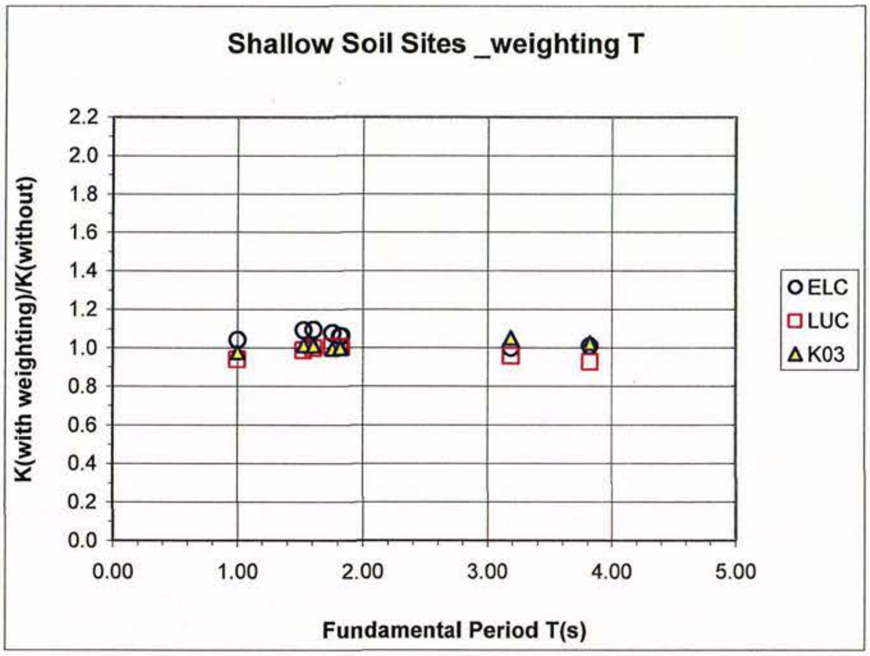


Figure 7 Sketch showing different ductility factors D_{maxi}/D_y and effective stiffnesses F_i/D_{maxi}



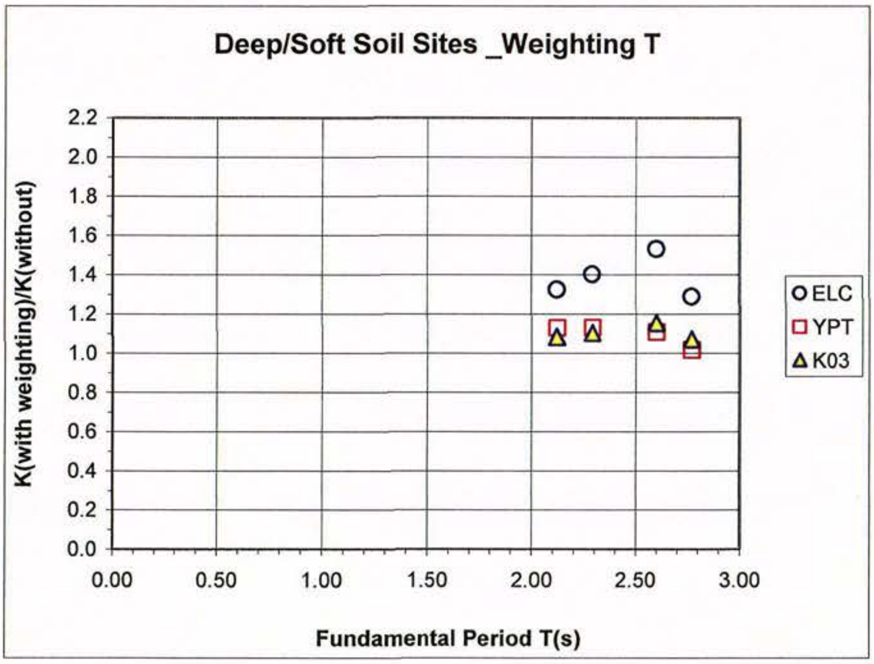
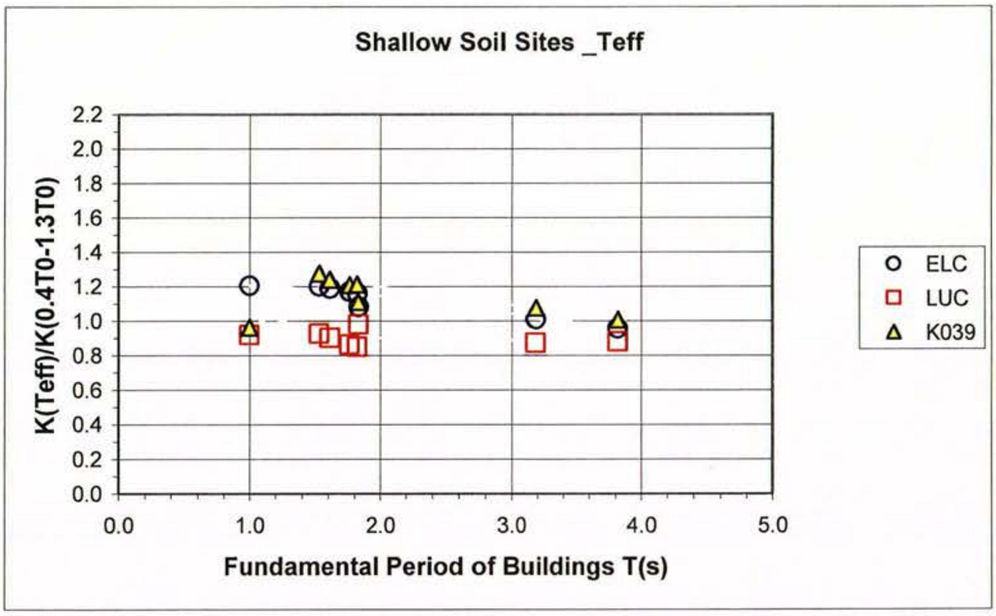


Figure 8a Ratios of the scale factors obtained when the square-errors are weighted by spectral period T to those obtained from the NZS1170.5 method without period weighting.



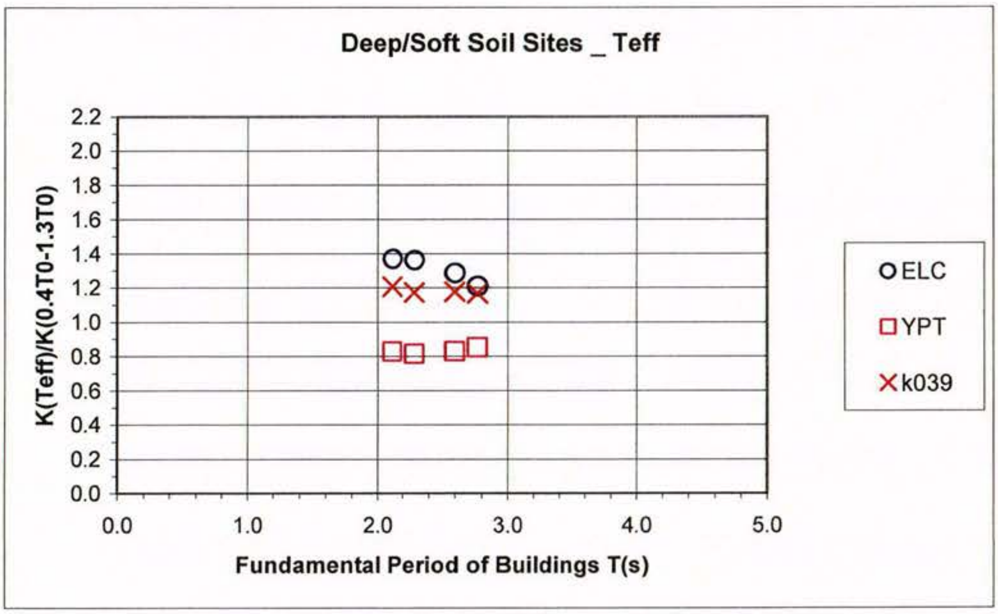
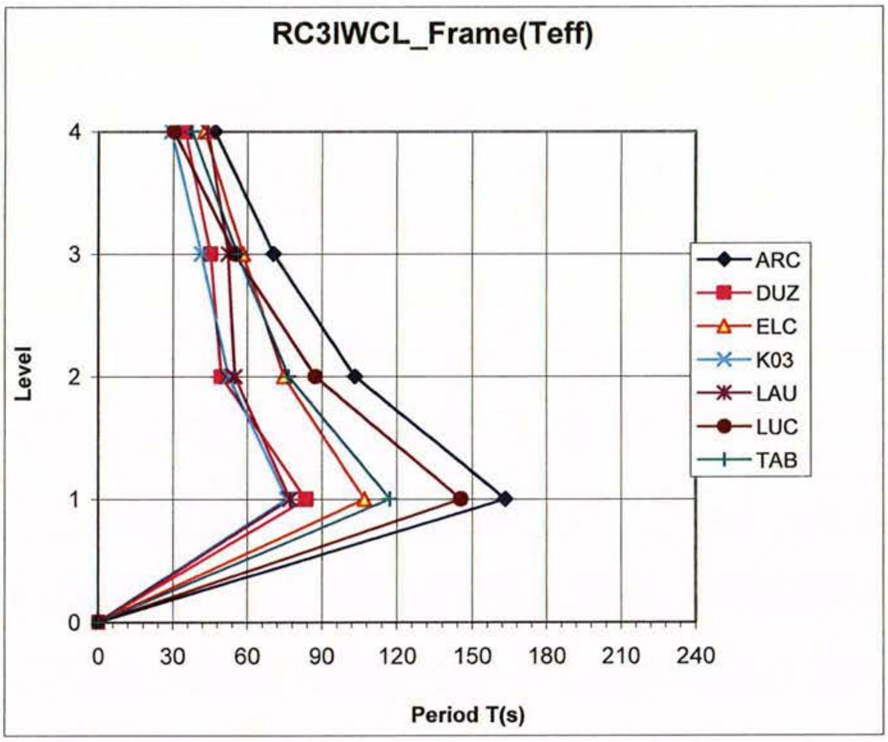


Figure 8b Ratios of the scale factors obtained when the upper period used for scaling the spectra is T_{eff} to those when it is T_0 as in the NZS1170.5 method. Note the desired behaviour of reduced scale factors for the forward-directivity records Lucerne (LUC) and Yarimca (YPT), and the generally increased factors for the non-FD records El Centro (ELC) and K039.



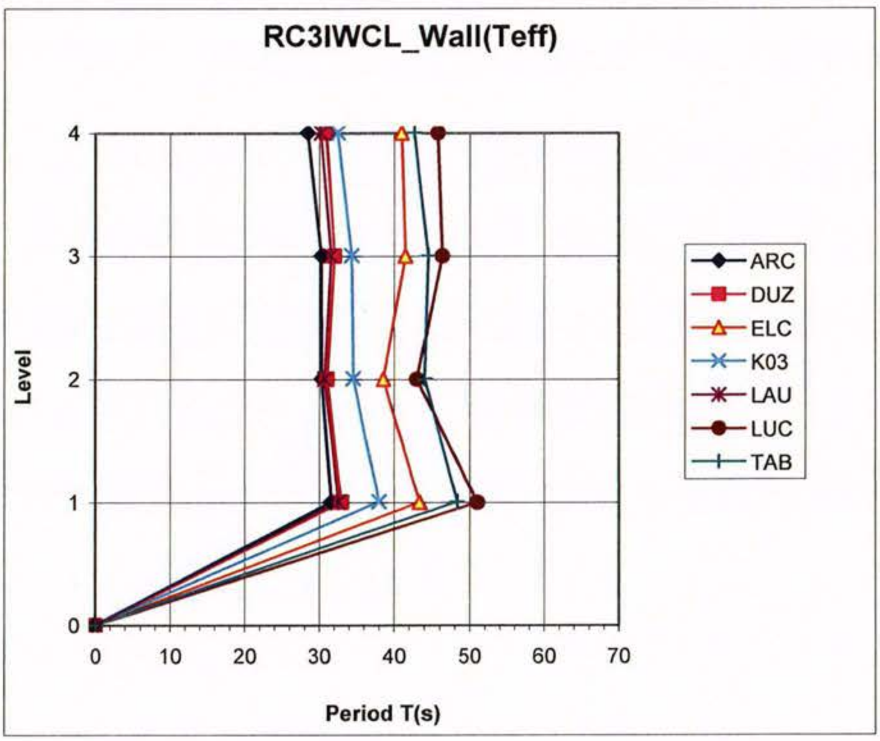
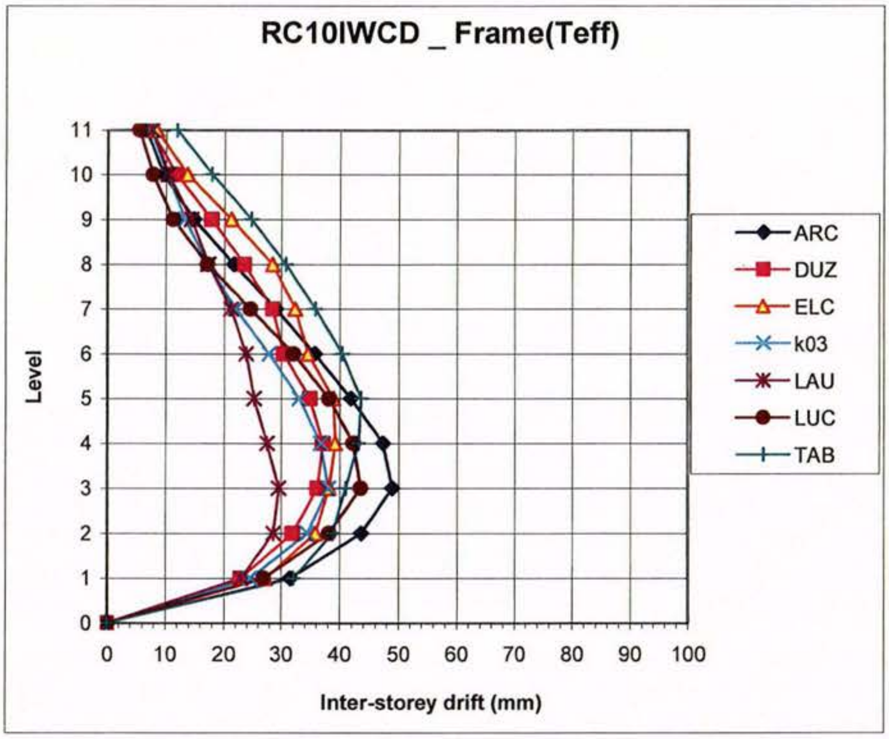


Figure 9a Inter-storey drifts from 7 records by using a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC3IWCL



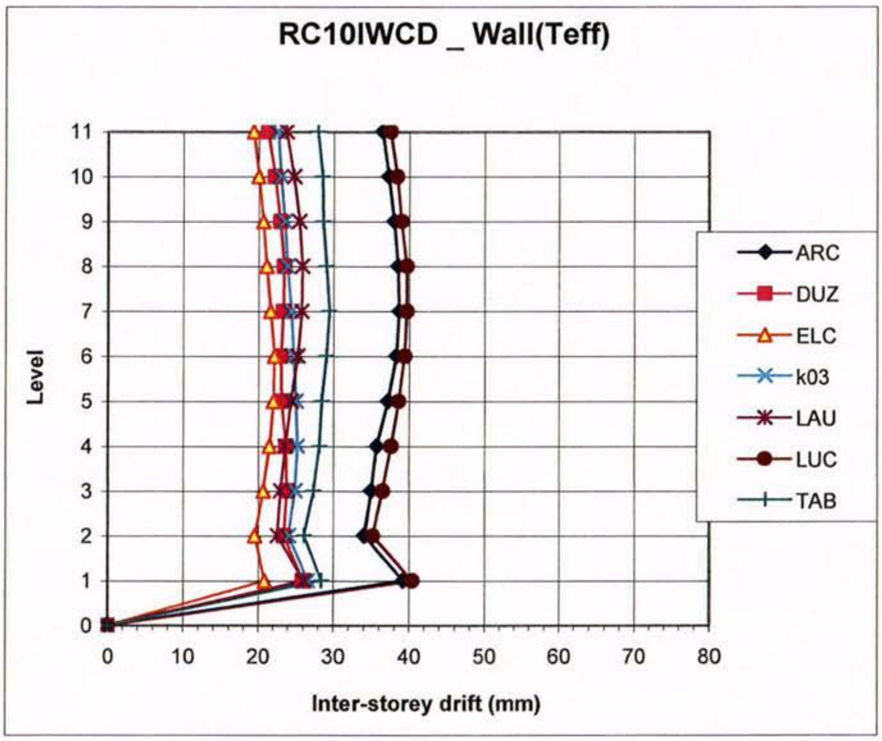
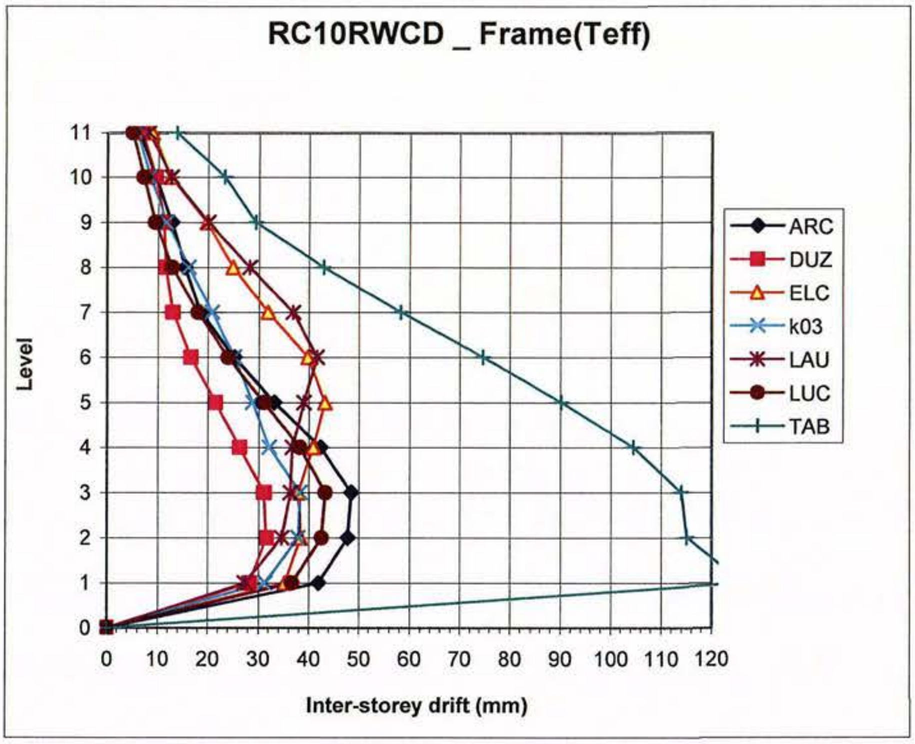


Figure 9b Inter-storey drifts from 7 records by using a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC10IWCD



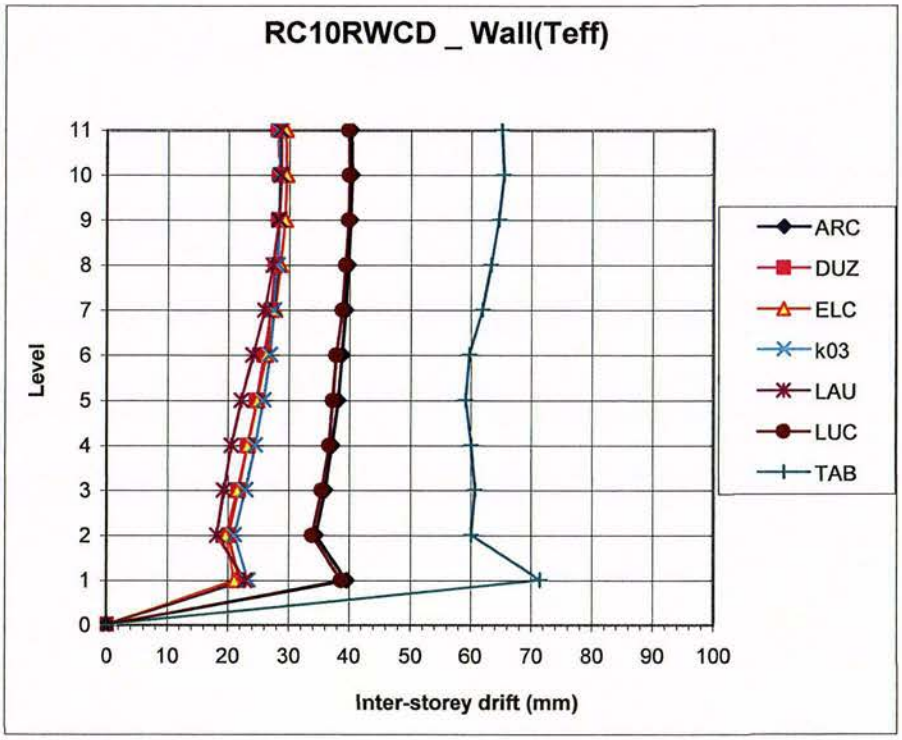
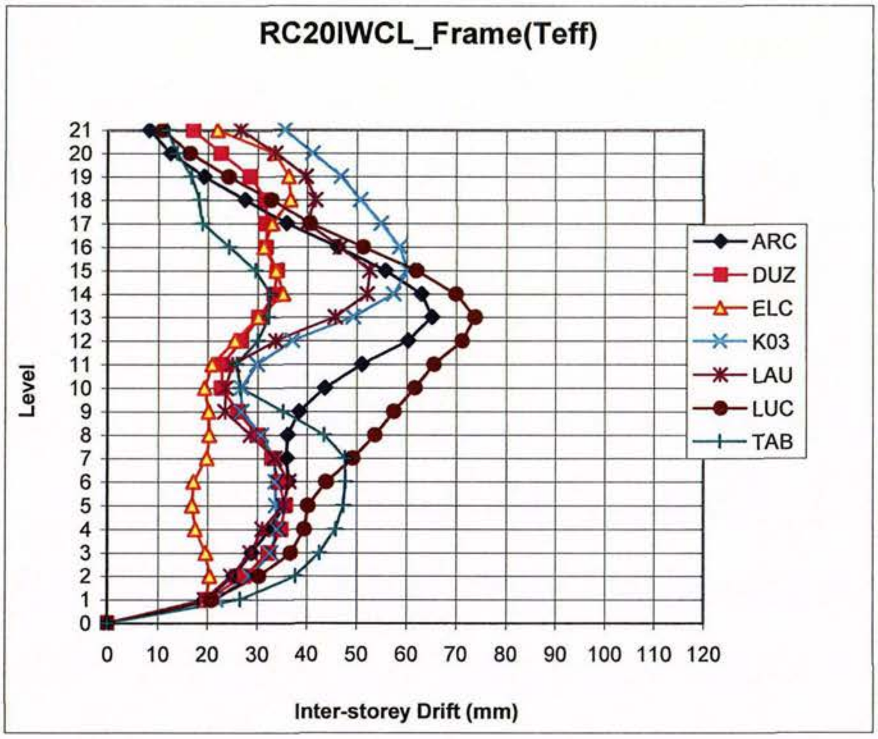


Figure 9c Inter-storey drifts from 7 records by using a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC10RWCD



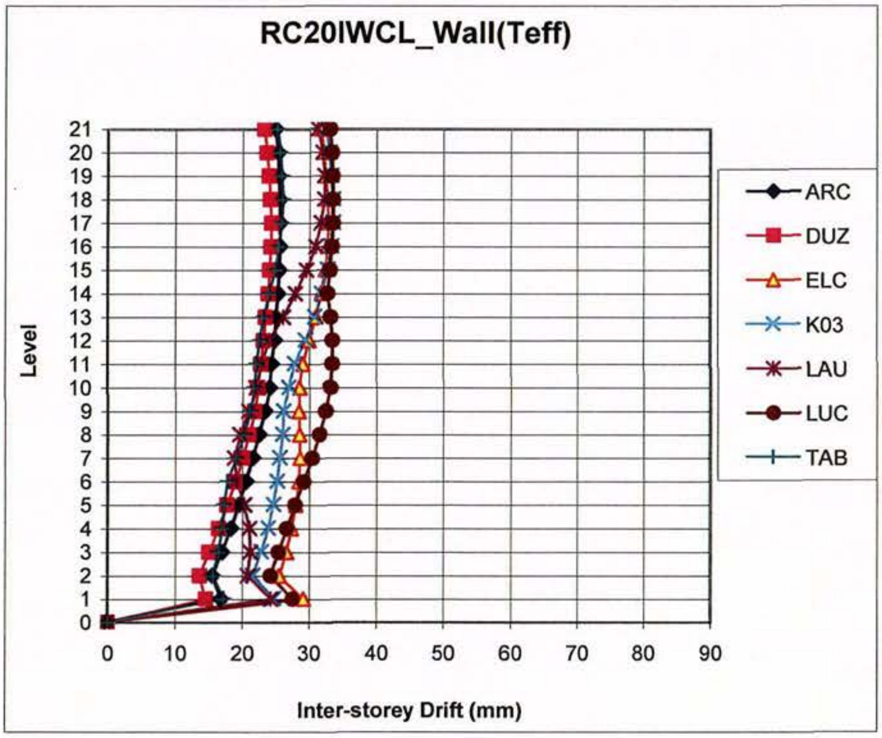
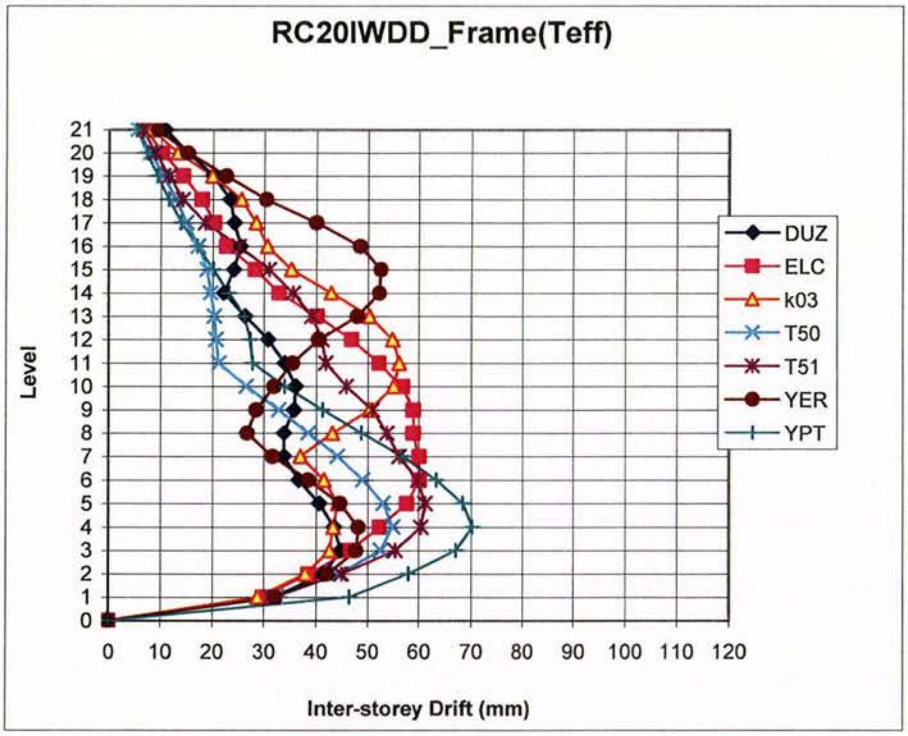


Figure 9d Inter-storey drifts from 7 records by using a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC20IWCL



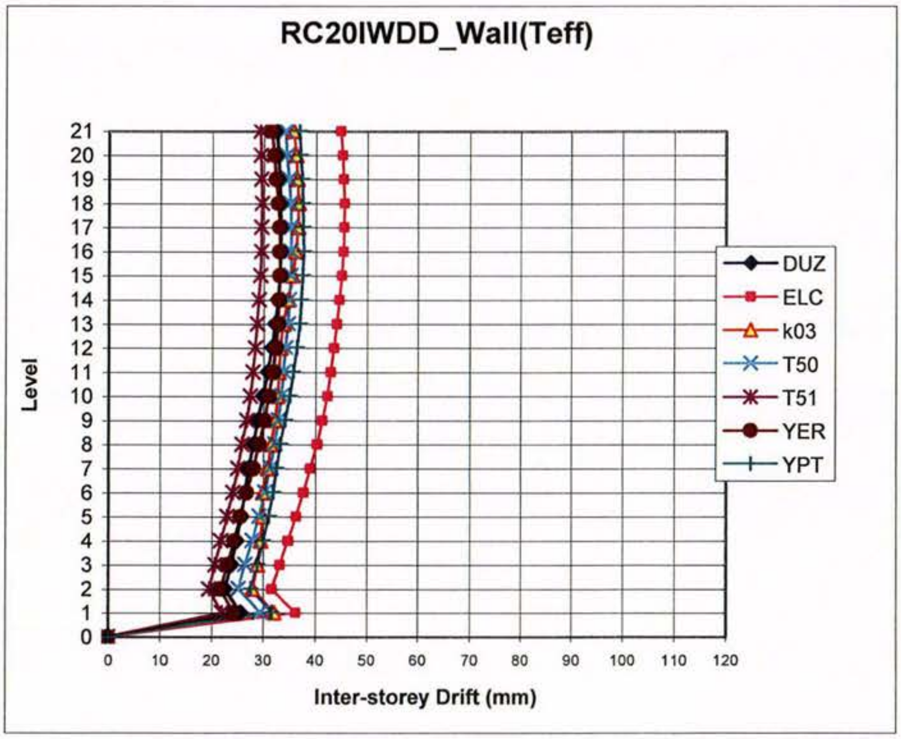
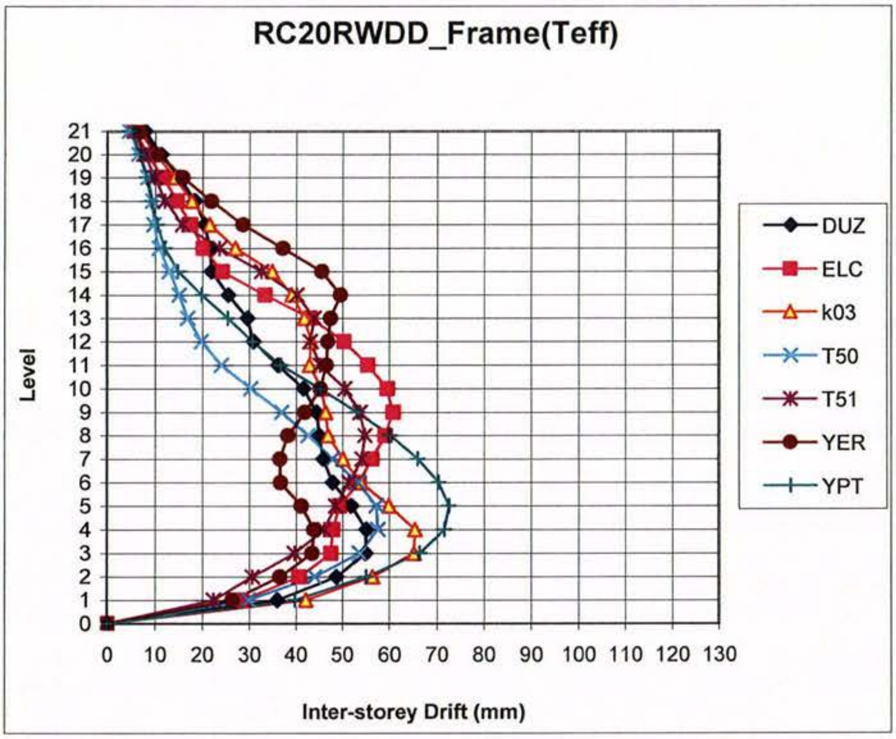


Figure 9e Inter-storey drifts from 7 records by using a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC20IWDD



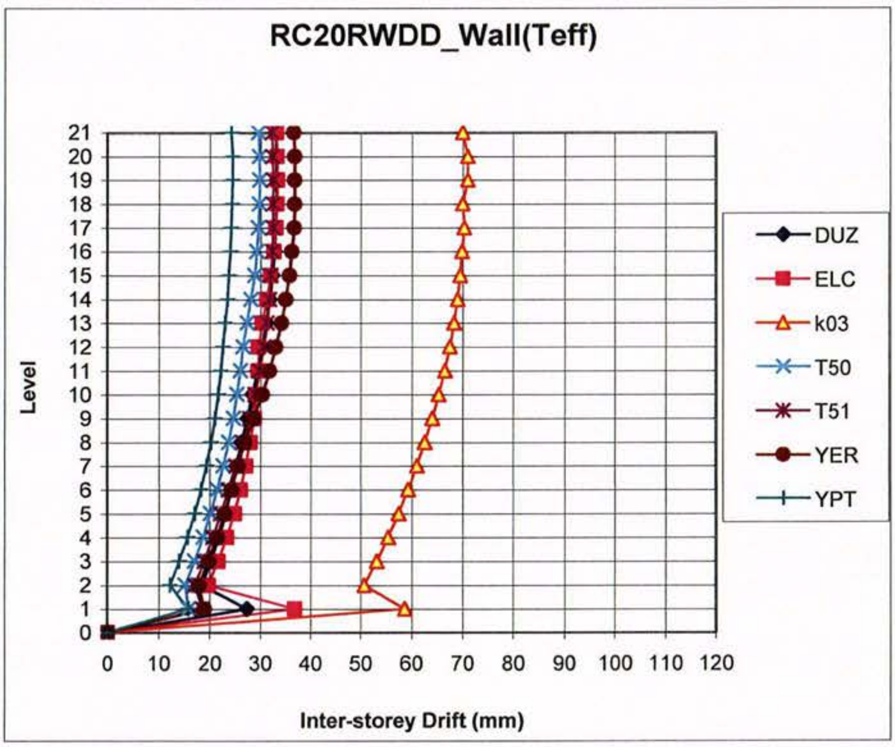
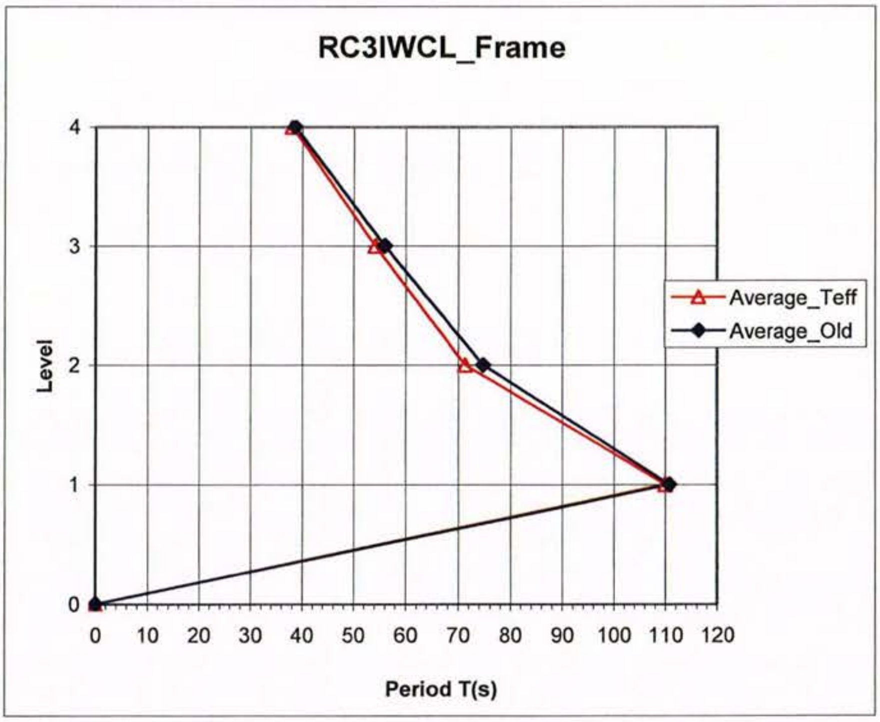


Figure 9f Inter-storey drifts from 7 records by using a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC20RWDD



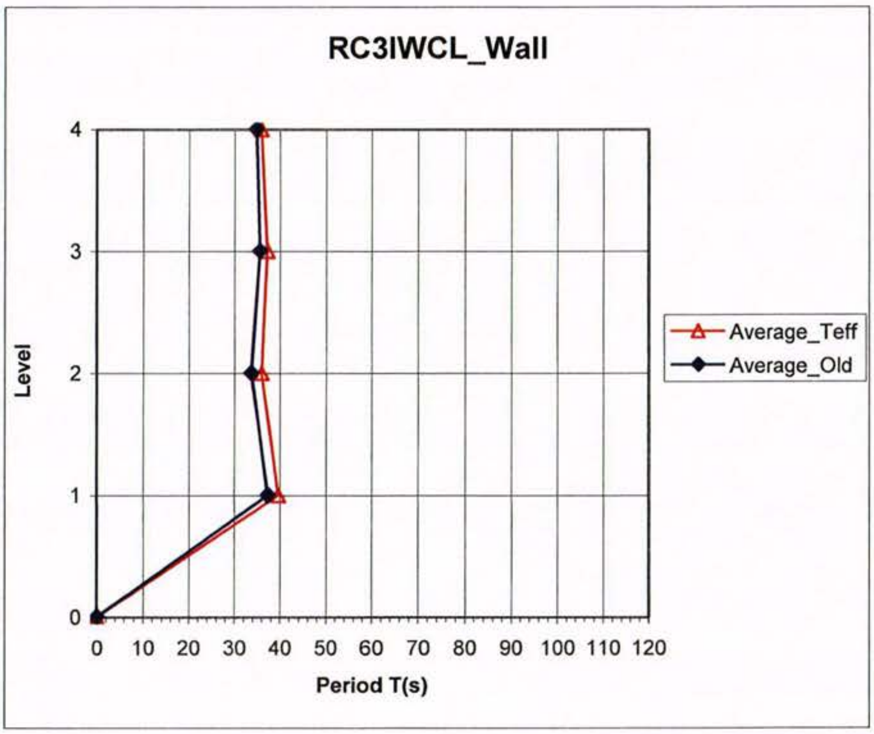
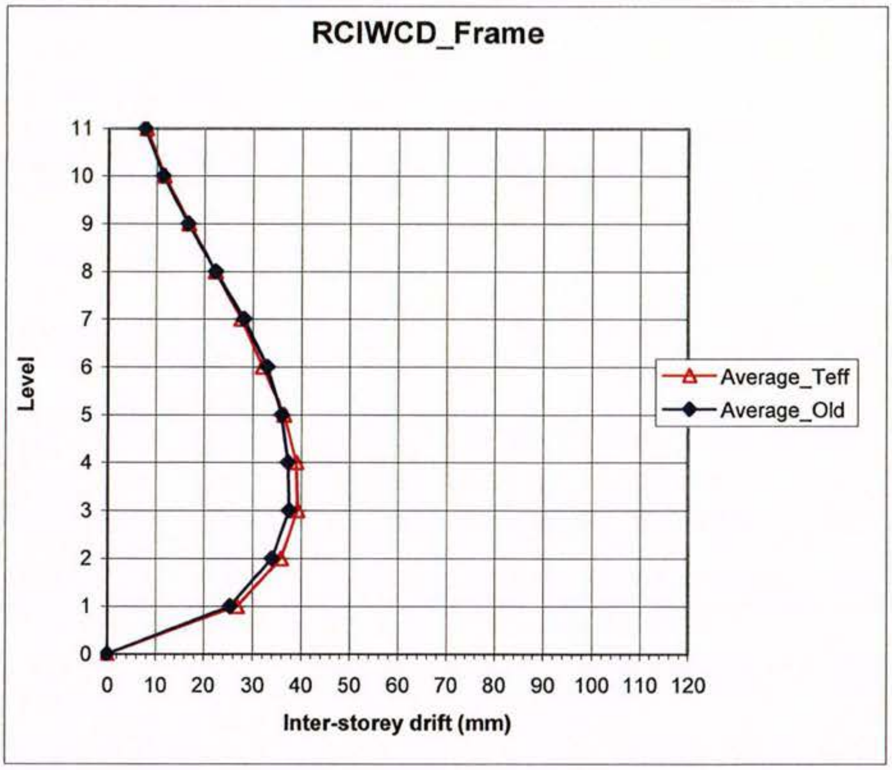


Figure 10a Comparison of mean inter-storey drifts from a scaling band of $0.4T_0$ to $1.3T_0$ and a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC3IWCL



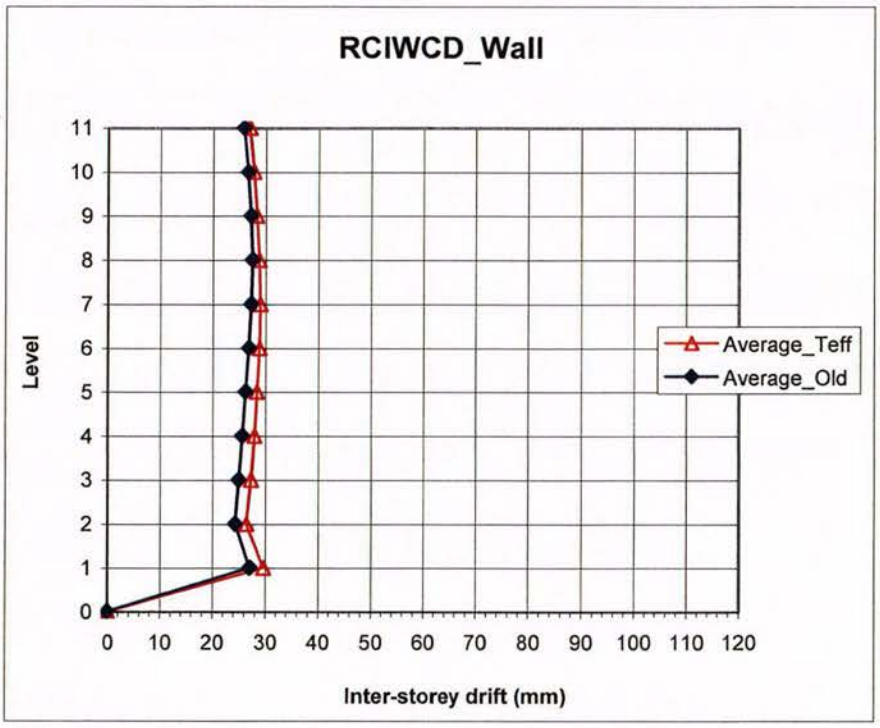
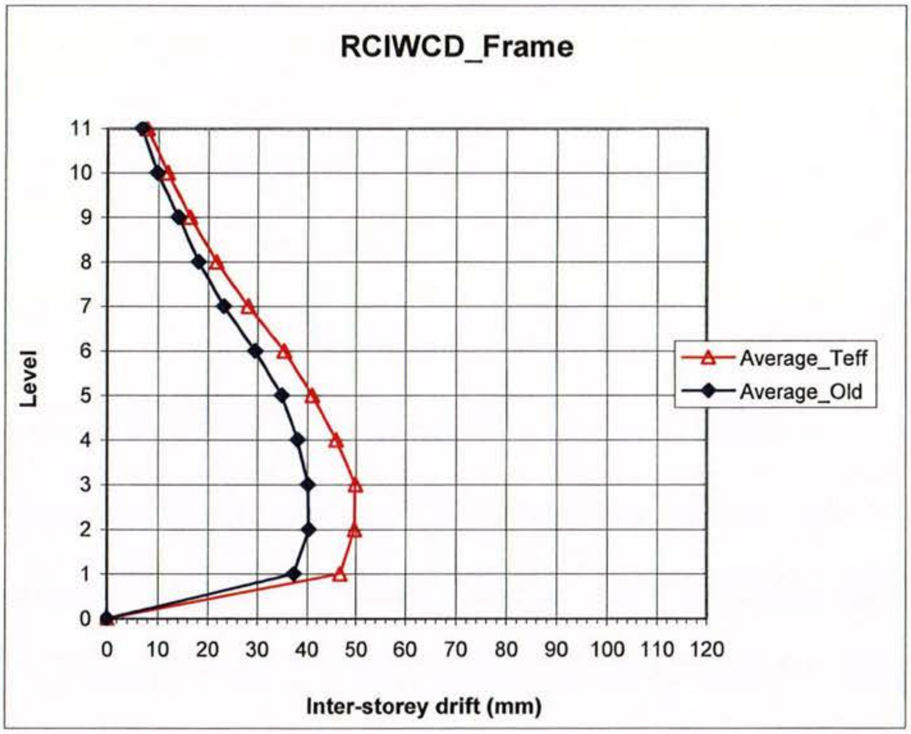


Figure 10b Comparison of mean inter-storey drifts from a scaling band of $0.4T_0$ to $1.3T_0$ and a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu T_0}$ for RC10IWCD



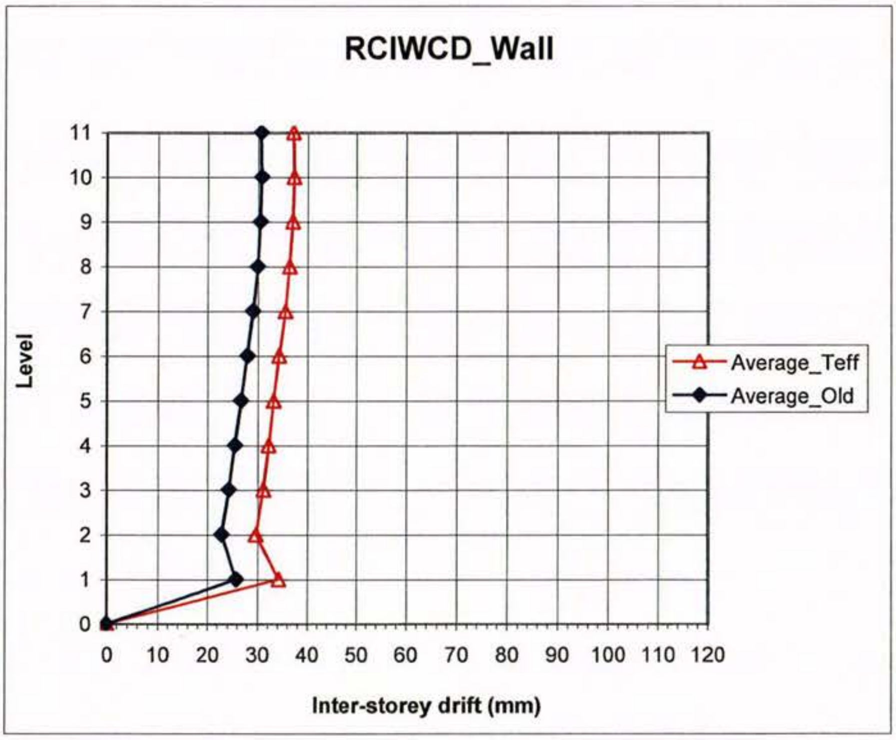
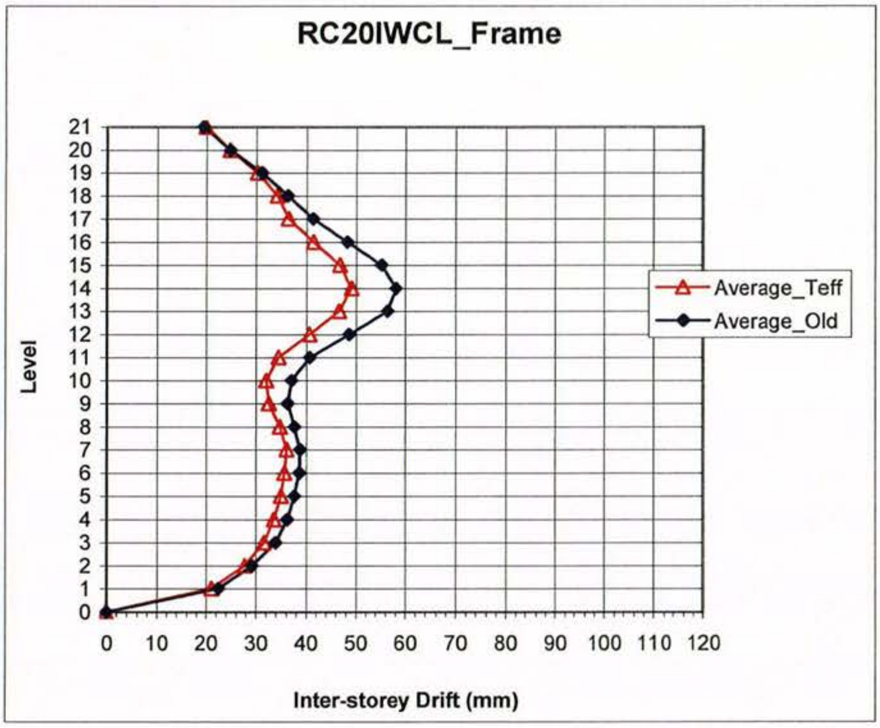


Figure 10c Comparison of mean inter-storey drifts from a scaling band of $0.4T_0$ to $1.3T_0$ and a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC10RWCD



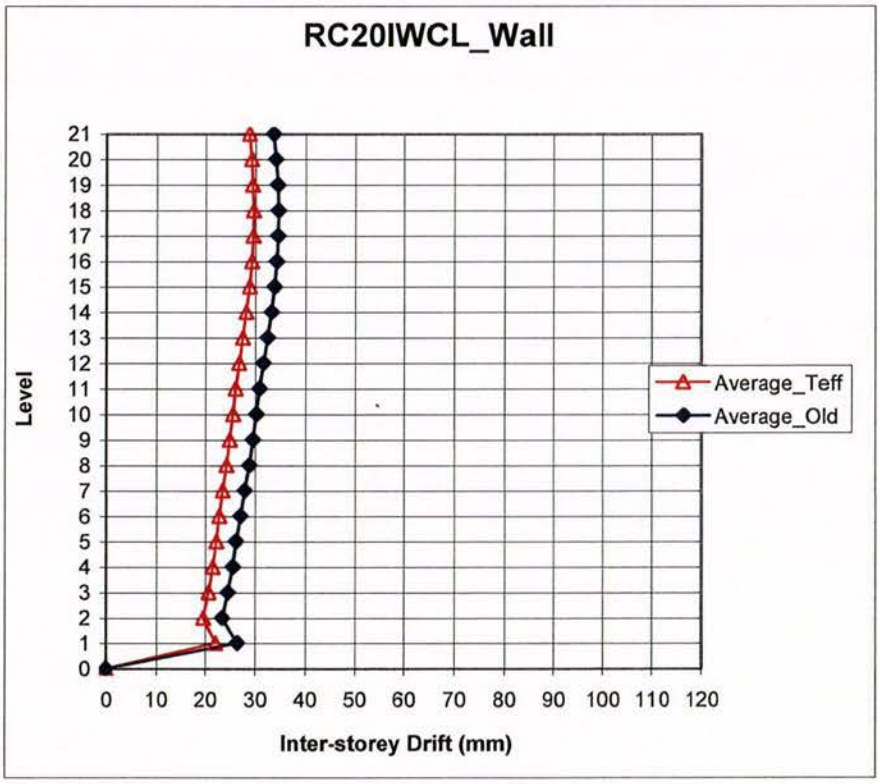
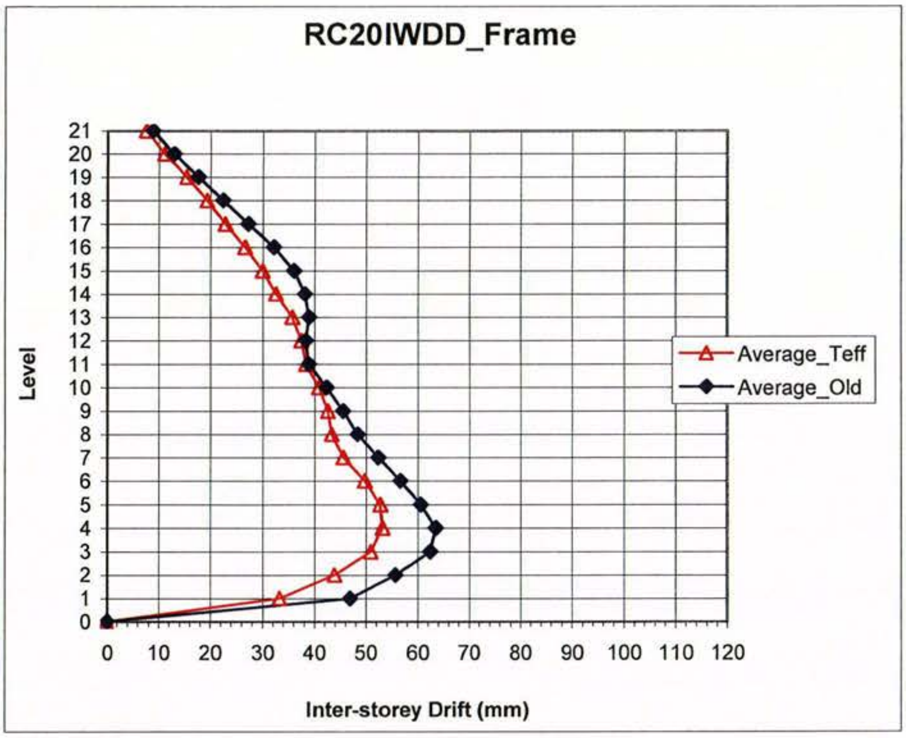


Figure 10d Comparison of mean inter-storey drifts from a scaling band of $0.4T_0$ to $1.3T_0$ and a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC20IWCL



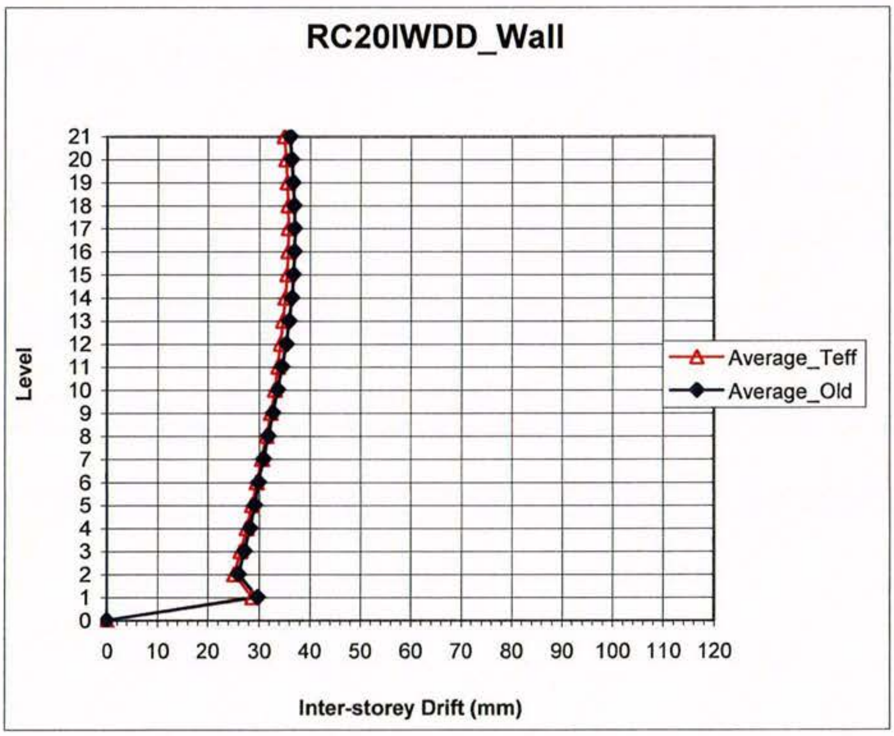
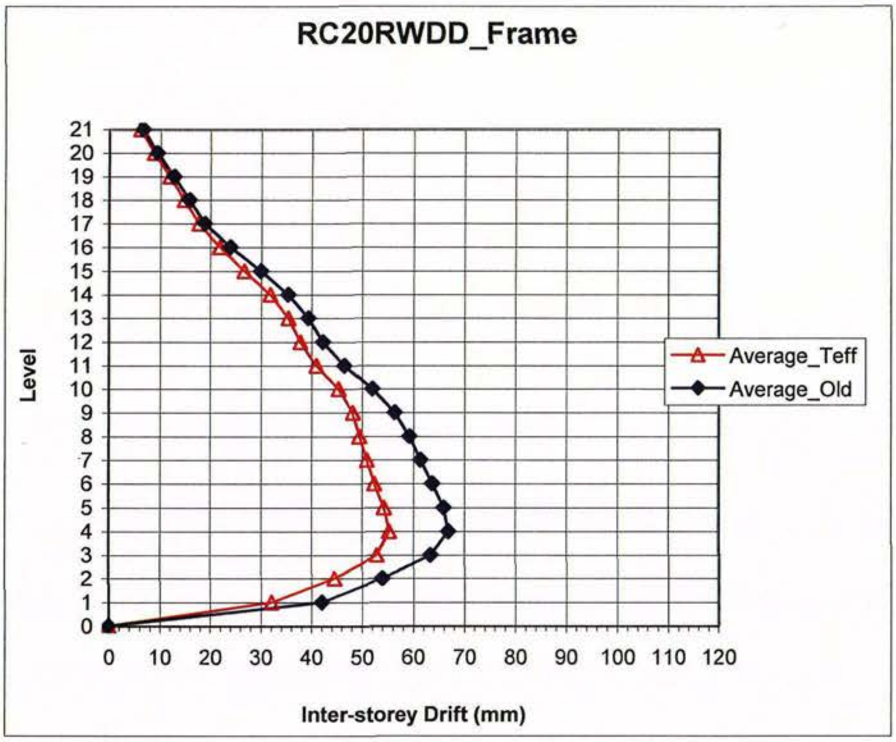


Figure 10e Comparison of mean inter-storey drifts from a scaling band of $0.4T_0$ to $1.3T_0$ and a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC20IWDD



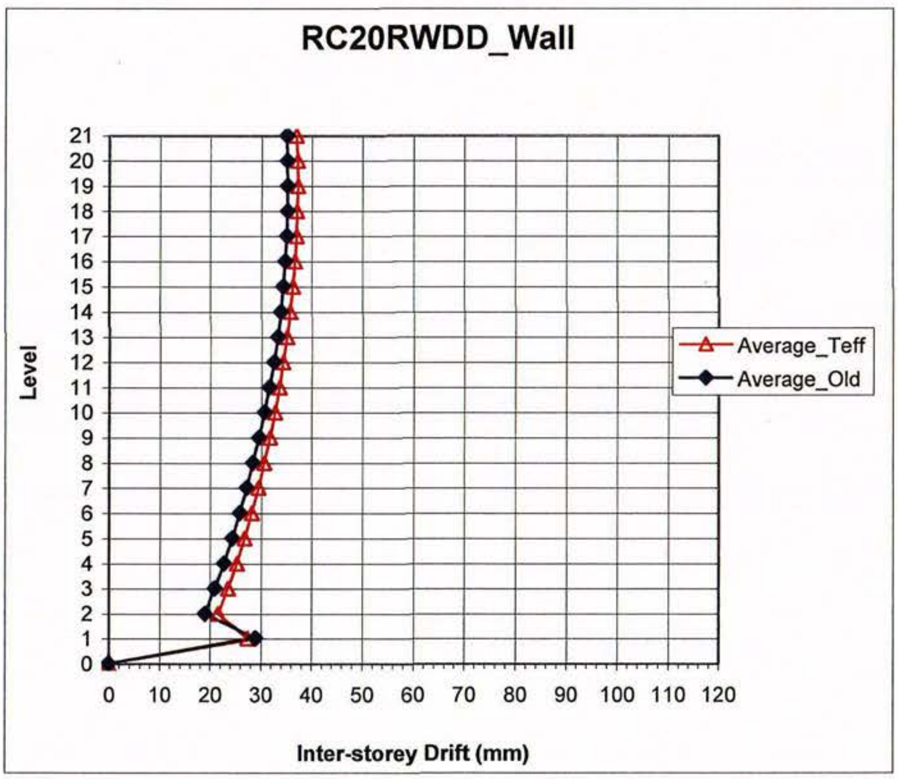


Figure 10f Comparison of mean inter-storey drifts from a scaling band of $0.4T_0$ to $1.3T_0$ and a scaling band of $0.4T_0$ to $T_{eff} = \sqrt{\mu}T_0$ for RC20RWDD

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Dunedin 9016
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road, Wairakei
Taupo 3377
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road, Gracefield
Lower Hutt 5010
PO Box 31312
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657