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Drift demand estimates for inelastic torsional response of half-scale seven-storey RC specimens

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ABSTRACT

Existing reinforced concrete buildings with irregularities are susceptible to torsional response and resulting localised damage or collapse under seismic excitation. Primary source of torsional response can be inherent stiffness irregularities due to asymmetric alignment of the structural elements, causing elastic torsional response. However, recent post-earthquake observations have identified the possibility of torsional response associated with inelastic response of structural elements during the earthquake (i.e. inelastic torsion). Due to the lack of experimental investigations to capture real inelastic torsional demands, it is questionable if existing seismic assessment guidelines can adequately estimate the displacement demand on buildings subjected to inelastic torsion. To address this need, this project first conducted shake-table tests of two seven-storey, half-scale specimens in NCREE Tainan laboratory to obtain inelastic torsional demands on three irregular systems: Stiffness, Damage and Ductility irregularities. The three irregular systems resulted in torsional response under unidirectional earthquake excitations and localised damage or collapse. This paper presents drift demands estimated for the tested irregular systems using the Simplified Lateral Mechanism Analysis, SLaMA, and discusses the applicability of the simple methods to structures susceptible to inelastic torsion. The assessment showed unconservative results in most cases for the system subjected to inelastic response. This indicates that the current simple

seismic assessment procedures may require modification to estimate the displacement demands due to inelastic torsional response.

1 INTRODUCTION

Reinforced concrete (RC) building structures have been rendered unusable after past earthquakes because of collapse or severe localized damage to structural elements. In some cases, post-earthquake investigations suggested that the localization of damage was caused by irregularities in the structural systems and the resulting torsional response. The irregularities predominantly come from unsymmetrical alignments of primary or secondary structural elements in plan. The resulting torsional eccentricity from stiffness irregularities is the most common parameter used in both new design standards and assessment guidelines among horizontal irregularities reported in FEMA P-2012 (2018). The concept of torsional strength irregularity – although only addressed in seismic assessment guidelines (i.e. ASCE, 2017 and MBIE et al., 2017) – is also important, especially when there is inelastic response. Past studies, such as Paulay (1998 and 2001), proposed theoretical approaches using both stiffness and strength eccentricities to estimate the effect of torsion in ductile systems in which nonlinear response is expected. Given that most building structures are designed to respond in their inelastic range under design level ground motions, it is prudent to consider torsional response of structures based on both stiffness and strength eccentricities.

The concepts of stiffness and strength eccentricities, however, are based on the original state of structure hence may not be sufficient to assess nonlinear torsion if structures are significantly damaged during seismic excitation. In addition, buildings with structural weaknesses are considered particularly susceptible to torsion. For instance, existing concrete buildings are more likely to be subjected to concentrated demands at soft or weak stories or at brittle elements such as non-ductile RC elements or masonry infill walls. Yet there is paucity of experimental data related to the effect of inelastic torsion on displacement demands in existing RC buildings.

The goal of this project is to fill this gap and to improve and calibrate methods in existing guidelines to estimate drift demands, including the effects of different forms of torsion. This study focuses on estimating displacement demands on the shake-table test specimens by the methods provided in seismic assessment guidelines. The test programme includes shake-table testing of two half-scale, 7-storey RC specimens (Specimen-1 and Specimen-2), with different sources of torsional irregularities, at the Tainan laboratory of National Center for Research on Earthquake Engineering (NCREE), Taiwan. Specimen-1 was designed to test torsional demands caused by stiffness eccentricity and “damage irregularity” while Specimen-2 was designed to investigate the effect of “ductility irregularity”. This paper presents the test programme and estimated displacement demands assessed by Simplified Lateral Mechanism Analysis (SLaMA) in accordance with the New Zealand Seismic Assessment Guidelines (MBIE et al., 2017). This study focuses on the drift demand estimates and does not evaluate the value %NBS.

2 SUMMARY OF SHAKE TABLE TESTS

In the interest of brevity, an overview of the shake table test programme is provided below. A detailed description of the shake table tests and results can be found in Suzuki et al (2021) or the datasets made available on DesignSafe-ci.org (Suzuki et al., 2020a and 2020b).

2.1 Test Specimens

The two test-structures, Specimen-1 and Specimen-2 were designed to study inelastic torsional response caused by different source of irregularities (illustrations shown in Table 1). The specimens were half-scale seven-storey structures as shown in Figure 1, made of three separate units (A, B, and C). In this study, only

Unit A – first two and a half storeys of each seven-storey structure – was newly constructed for each specimen. It was then connected with re-usable upper units (B and C) by boundary steel plates. Both specimens had a “soft” first storey with a height twice the height of the storeys above and RC shear walls in the short floor-plan direction (i.e. X-direction) in storeys 2 through 7. RC frames spanned one bay (3.5 m) along the short floor-plan direction and two bays (7 m) along the long floor-plan direction (Figure 1).

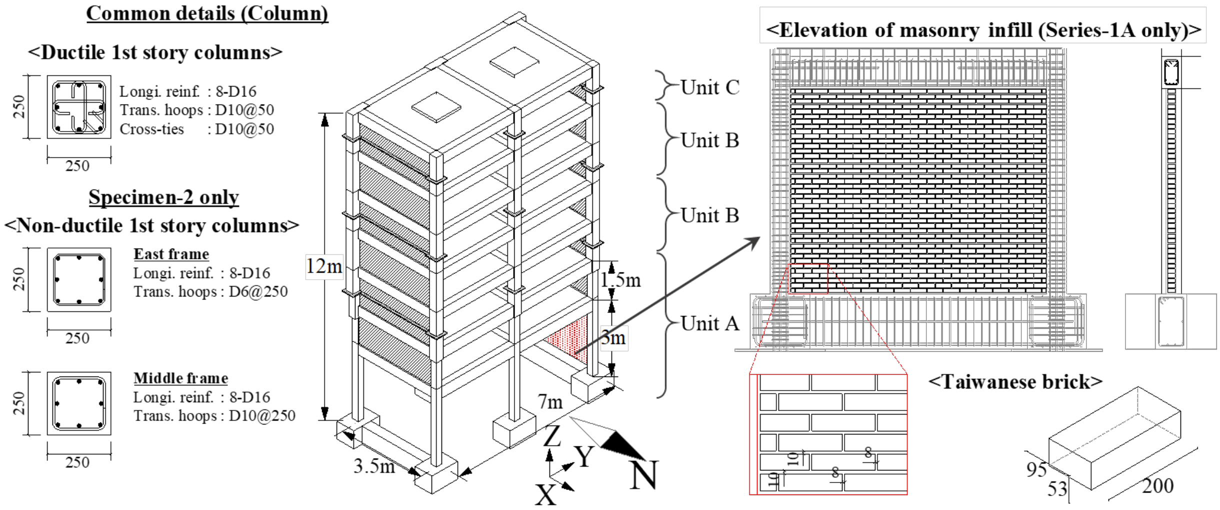
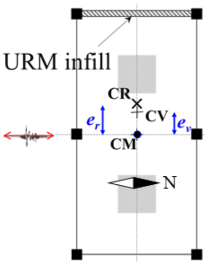
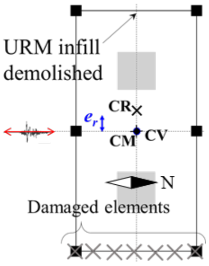
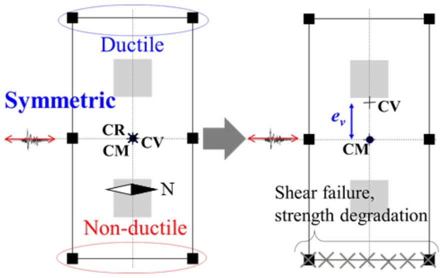


Figure 1 : Overview of the test specimen

Table 1: Summary of properties of shake-table specimens

Specimen	Specimen-1		Specimen-2
Test series name	Series-1A	Series-1B	Series-2
Source of torsional response	Stiffness irregularities	Damage irregularity	Ductility irregularity
Illustration of irregular systems			
Irregularity produced by	URM infill in West frame	Damage to East frame	Early strength degradation in East (non-ductile) frame

The columns at the first storey had a square cross-section measuring 250 mm x 250 mm and were reinforced with 8-D16 bars for a longitudinal reinforcement ratio of 2.6%. The first specimen was designed to explore the effect of: (i) torsional stiffness irregularity and (ii) damage irregularity. The columns in Specimen-1 included ‘ductile’ detailing including transverse reinforcement made of D10 hoops and crossties spaced at 50 mm to avoid brittle modes of failure. To create the stiffness eccentricity, an unreinforced masonry (URM) infill wall was installed in the West frame at the first storey. The first series of tests (referred to as Series-1A) were conducted on this specimen with the expectation that the shaking would cause more damage on the East frame (the side without infill wall). Series-1A tests resulted in damage to the columns in the East frame while the West frame was effectively undamaged. The infill wall was demolished after Series-1A resulting in a structure with “damage irregularity” for the next series of tests (referred to as ‘Series-1B’).

The second specimen was designed to explore the effect of ‘ductility’ irregularity. Unit A of Specimen-2 was made identical to that of Specimen-1 except for the transverse reinforcement detail of four of the first-storey columns. The columns on the East and the middle frames had D6 or D10 hoops at 250 mm, respectively (Figure 1). The asymmetric ductile detailing was selected to investigate the effect of “ductile irregularity”, in which torsion was expected because of asynchronous strength degradation during strong shaking. The sequence of tests on Specimen-2 was referred to as ‘Series-2’.

2.2 Input Ground Motion

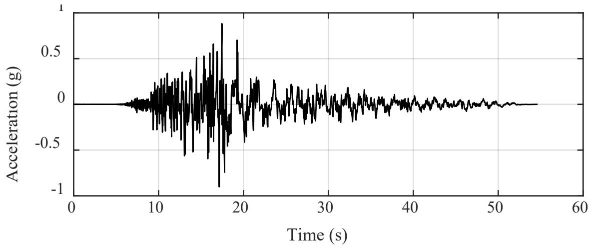


Figure 2 : ‘100%’ input acceleration.

The East-West component of the ground motion recorded at station CHY101 during 1999 Chi-Chi Earthquake, was selected for this testing programme. This record is not only considered to represent typical near-fault records in Taiwan, but Tarbali and Bradley (2014) also included this same motion in a list of appropriate ground motions for a ‘Wellington fault scenario’ for Wellington, New Zealand. The original record, from the PEER Ground motion database (PEER, 2012), was time scaled by a factor of 1/√2 (as the specimen is half-scale). The time-scaled record was also amplified in intensity by a factor of 2.65 to fit a 2500-year return period conditional mean spectrum (CMS) in Wellington CBD using the scaling method proposed in Baker (2011). The resulting record scaled in time and intensity is referred to as the ‘100%’ input for this testing programme (Figure 2) and has a peak ground acceleration and velocity of 0.90g and 1.22 m/s, respectively, although it is noted that the scaling in shake table tests did not exceed 60%. Each series of tests (Series 1A, 1B and 2) consisted of a total of four earthquake inputs as shown in Table 2. Response spectra of the table motions are presented in the next section for SLaMA assessment (Figure 3).

Table 2: Earthquake input sequence

#	Series-1A (with URM)		Series-1B (No URM)		Series-2 (Non-ductile)	
	Test name	**Scale**	**Test name**	**Scale**	**Test name**	**Scale**
1	1A-10%	10%	1B-10%	10%	S2-10%	10%
2	1A-20%	20%	1B-20%	20%	S2-20%	20%
3	1A-60%	60%	1B-40%	40%	S2-40%	40%
4	1A-60%-2	60%	1B-60%	60%	S2-60%	60%

3 DEMAND-ESTIMATE PROCEDURE

3.1 Analysis techniques and torsional assessment in the NZ Guidelines

New Zealand Assessment Guidelines describes linear and nonlinear assessment procedures as listed in Table 3. In linear analysis techniques, Equivalent Static Analysis (ESA), and Pseudo-nonlinear analysis are not suitable for torsional irregular structures, while Modal Response Spectrum Analysis (MRSA) can consider effects of elastic torsion by Method A: Elastic Torsion Responses in Appendix C2F, which is, however, suitable only for linear systems or systems subjected to limited ductility demands. MRSA often supplements nonlinear assessment procedure with accounting for effect of torsion or higher mode effects. The Guidelines, however, recommends the use of inelastic torsional assessment when used with nonlinear analysis techniques, because nonlinear response is expected in most of existing buildings under significant earthquake.

Analysis techniques for the nonlinear assessment procedure consists of Simplified Lateral Mechanism Analysis (SLaMA), Nonlinear Static Pushover Analysis (NLSPA), and Nonlinear Time-History Analysis (NLTHA). The SLaMA is an assessment method in the New Zealand Assessment Guideline recommended as a preliminary assessment tool to understand the structural mechanism before applying other advanced assessment procedures, or it can be used on its own to determine likely demands on the structure. The method is similar to the capacity spectrum method (ATC, 1996) but with system performance defined by the combination of the element performance and system mechanism assumptions; hence useful to understand structural systems and likely failure mechanisms.

Table 3 : Analysis techniques and limitation per Guidelines, including application for irregular systems

	Linear procedures	**Nonlinear procedures**
Analysis techniques	Equivalent static analysis (ESA) Modal response spectrum analysis (MRSA) Pseudo-nonlinear analysis	**SLaMA** NLSPA NLTHA
Limitations for irregular systems	ESA: No significant irregularity MRSA: elastic torsion can be considered in MRSA, but recommended to implement inelastic torsional assessment (e.g. **SLaMA**).	**SLaMA** & NLSPA: use Appendix C2F if irregularity presents NLTHA: no limitation
Torsional assessment (C2.5.8)	Amplify force and displacement demand by the factor γ or use amplification factor in ASCE 41-13	Undertake inelastic torsional assessment (Method B or Method C in Appendix C2F) OR Running multiple sensitivity analysis for accidental torsion OR Apply blanket torsional factor in NLSPA

Table 4 Torsional assessment methods in Appendix C2F of the Guidelines

Torsional Assessment Methods	**Method A (Elastic) Elastic Torsional Response**	**Method B (Inelastic) Inelastic Torsion Response with Ductile Systems in Both Directions**	**Method C (Inelastic) Absence of Strength Eccentricity**
Summary of the methods	MRSA in accordance with NZS 1170.5: 2004	Imposing force demand on orthogonal frames to the direction of consideration	Reducing system strength capacity by eliminating strength eccentricity
Criteria of using the method	Elastic systems or systems subjected to limited ductility demand	$\mu \geq 2$ in the considered direction	System with a strength eccentricity exceeding 2.5% of relevant dimension of the plan

In nonlinear assessment procedures, effects of torsion shall be considered either; i) undertaking inelastic torsional assessment, ii) running multiple sensitivity analysis to account for accidental torsion effects, or iii) apply blanket torsional factor (in NLSPA). Application of inelastic torsional assessment in New Zealand Seismic Assessment Guidelines is distinctive to other existing seismic assessment guidelines, and two inelastic assessment methods are provided; Method B: Inelastic Torsion Response with Ductile Systems in Both Directions, and Method C: Absence of Strength Eccentricity as shown in Table 4. These methods are derived from a series of inelastic torsional studies (e.g. Paulay, 1998, 2000 etc.): Method B accounts for additional force demand on orthogonal frames resisting to torsional force in torsional restraint (TR) systems, and Method C is to eliminate a strength eccentricity by reducing the strength capacity of elements responsible for the strength capacity of the system because force demand on these elements will not be able to reach those strength capacities in strength irregular systems.

This study tried to capture the effects of inelastic torsional assessment using Method C in SLaMA procedure when estimating displacement demand on Series-1A. Method-B was not able to impose additional torsional demand on the frames in the direction of interest (E-W direction) since the structures were not strength-irregular in the longitudinal (Y-) direction. Method C was not applicable to Series-1B and Series-2 which did not have any strength eccentricity to eliminate. These limitations in the application of inelastic torsional assessment indicates the needs for updated guidelines applicable to a wider range of existing buildings subjected to inelastic torsion.

In addition to applying Method C for Series-1A, this study evaluated change in displacement demand estimates with several variations in the critical parameters; stiffness reduction due to damage, and system yield displacement. The negative slope of the nonductile elements was not included since the displacement demand is taken at an effective period corresponding to the probable deformation capacity (before the strength degradation), hence a SLaMA assessment of Specimen 2 would ignore the ductility irregularity and consider this structure as symmetric. While this paper focuses on the assessment by SLaMA, discussion on the other assessment procedures in the MBIE et al. (2017) and ASCE 41 (2017), are shown in Suzuki (2021).

3.2 Overall procedure for displacement-based SLaMA assessment

This study followed the displacement-based SLaMA assessment procedure as described in Section C2 of the New Zealand Seismic Assessment Guidelines and summarised below.

The strength and deformation capacities of individual members were calculated using measured material properties in accordance with Section C5 in the Guidelines, except for the masonry infill which was based on masonry standards in Taiwan (MOI, 2008). The displacement profile was taken from Equations C2.4 and C2.5 in the Guidelines as the mechanism was assumed to be a column sway at first storey. In the test structure, the effective height is closest to the level of the fourth-floor slab, hence the displacement for the equivalent SDOF system corresponds to the displacement at that floor. The equivalent system performance curve was based on performances of individual members, the mechanism assumption above, and the critical parameters a) global yield displacement; b) stiffness degradation due to existing damage; c) use of inelastic torsional assessment (Method-C).

For assessing seismic demand, inherent damping of 0.02, instead of 0.05 as typically used in assessment, was used in this study to account for the fact that the specimens were bare RC structures. The influence of spectral shape on the outcome of SLaMA was also considered in this study. The target spectrum was determined by; a) recorded response spectra from table motion, and b) NZS 1170.5:2004 uniform hazard spectrum scaled to the intensity of table motion. The use of the two spectra was to capture the demand accounting for the effect of the unique characteristics of the input ground motion (in particular the hump for periods beyond 1.5 seconds), in comparison with that estimated using the NZS 1170.5 spectral shape. The reference ultimate limit state (ULS) NZS spectrum for Site Class D in Wellington CBD was scaled in accordance with NZS 1170.5:2004 (Standard New Zealand, 2004) to minimise the mean square error with the recorded table acceleration spectrum.

The scaled NZS spectra are presented in Figure 3 along with the ULS NZS spectrum and the 2% damped response spectra of the recorded acceleration from the shake-table tests. The recorded acceleration spectra are close to the scaled NZS spectra around the predominant period of the specimens, which ranged from 0.8 seconds to 1.3 seconds (Suzuki, 2021), with some small spikes around 1.0 second for low intensity motions. However, the earthquake response spectra have a large hump at around period range from 1.5 seconds to 3.0 seconds which resulted from the velocity pulse of the ground motion.

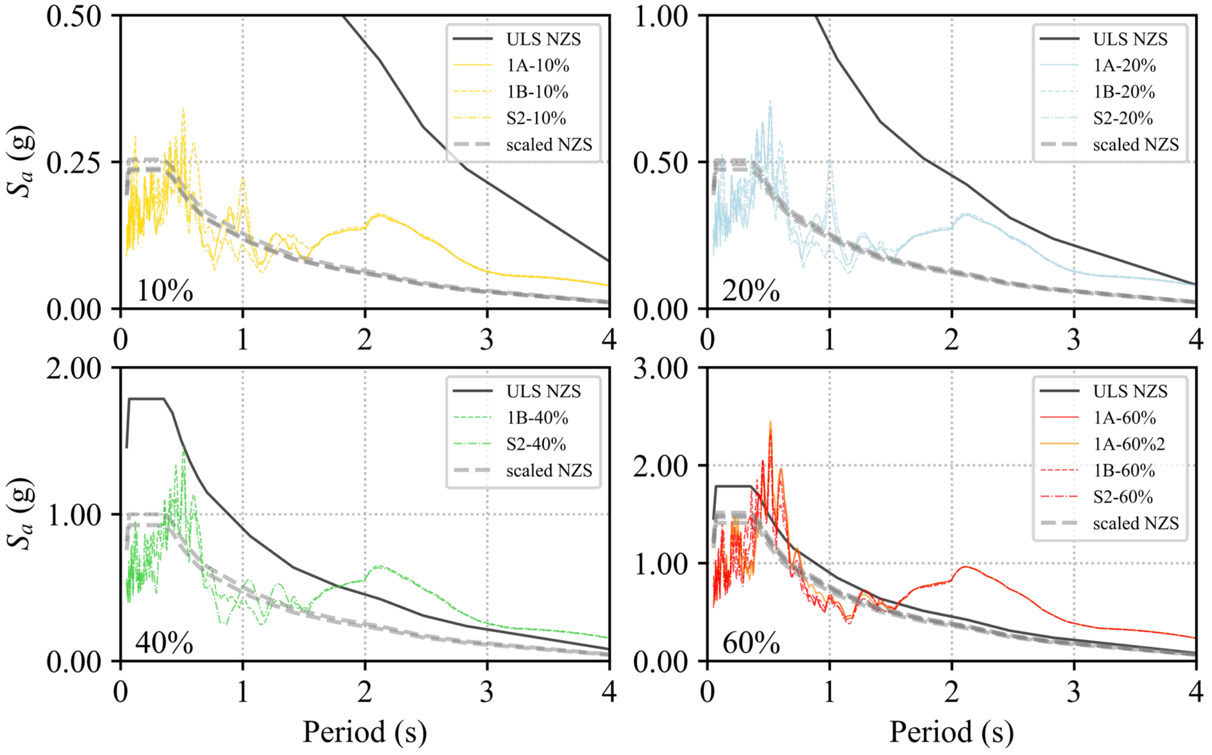


Figure 3 : ULS and scaled NZS1170.5 spectra and recoded acceleration spectra for SLaMA

The achievable equivalent viscous damping for the global system was evaluated based on a combination of hysteretic damping in each subsystem by using Eq. C2.11 in the Guideline; that is,

$$\xi_{sys} = \frac{\sum V_{base,i}\xi_i}{\sum V_{base,i}} \tag{1}$$

where ξ_{sys} and ξ_i is the equivalent viscous damping of the system and subsystem-i, respectively, and $V_{base,i}$ is the base shear of the subsystem-i (i.e. East, Middle and West frames of the specimens). The hysteretic damping of each subsystem was based on equations in Priestley et al. (2007), assuming Takeda-fat or Takeda-thin hysteresis for RC frame and RC frame with infill, respectively. Reduction factor K_ξ was then applied to the elastic target spectrum (i.e. 2% recorded acceleration spectrum or the scaled NZS spectrum) to obtain the acceleration-displacement response spectrum (referred to as ADRS) for the equivalent system damping. The equation below was modified from Eq. C3.1 in the Guidelines such that the reduction factor is 1.0 for a system damping of 0.02.

$$K_\xi = \left(\frac{0.04}{0.02+\xi_{sys}}\right)^{0.25} \tag{2}$$

The exponent of 0.25 within the equation above is as suggested for sites affected by near-fault velocity pulses (Priestley, 2003) instead of exponent of 0.5 in Eq. C3.1 in the Guidelines. Spectral displacement can be related to the spectral acceleration and the building period (see Eq. C3.2). The assessed displacement demand at effective height is determined using the period of the effective period, T_{eff}, based on the probable deformation capacity of the systems assessed for the assessment cases for SLaMA evaluation.

As noted previously, global performance curves were determined with variations in three parameters: a) global yield displacement; b) stiffness degradation due to existing damage; c) use of inelastic torsional assessment (Method C). Including two target spectra (recorded and scaled NZS) used to define the seismic demand, this study assessed 24 cases for Series-1A, and 9 cases for both Series-1B and Series-2, as summarized in Table 5.

Table 5 : Notation for cases considered in SLaMA evaluation

Cases for Series-1A	Cases for Series-1B	Cases for Series-2	NZS or recorded	Dy based on system or critical	Damage from previous EQ	Inelastic Torsional Assessment
1A-R-SU	**1B-R-SU**	**S2-R-SU**	Recorded	System	No	-
1A-R-CU	**-**	**-**	Recorded	Critical	No	-
1A-R-SUC	**-**	**-**	Recorded	System	No	Method C
1A-R-CUC	**-**	**-**	Recorded	Critical	No	Method C
1A-R-SD	**1B-R-SD**	**S2-R-SD**	Recorded	System	Yes	-
1A-R-CD	**1B-R-CD**	**S2-R-CD**	Recorded	Critical	Yes	-
1A-R-SDC	**-**	**-**	Recorded	System	Yes	Method C
1A-R-CDC	-	-	Recorded	Critical	Yes	Method C
1A-N-SU	**1B-N-SU**	**S2-N-SU**	NZS1170.5	System	No	-
1A-N-CU	**-**	**-**	NZS1170.5	Critical	No	-
1A-N-SUC	**-**	**-**	NZS1170.5	System	No	Method C
1A-N-CUC	**-**	**-**	NZS1170.5	Critical	No	Method C
1A-N-SD	**1B-N-SD**	**S2-N-SD**	NZS1170.5	System	Yes	-
1A-N-CD	**1B-N-CD**	**S2-N-CD**	NZS1170.5	Critical	Yes	-
1A-N-SDC	**-**	**-**	NZS1170.5	System	Yes	Method C
1A-N-CDC	**-**	**-**	NZS1170.5	Critical	Yes	Method C

Variation in assumed global yield displacement was considered to reflect the fact that the performance of stiffness irregular systems is dependent on the performance of critical (flexible) subsystem. The yield displacement in SLaMA procedure (i.e. Dy based on “System” in Table 5) is the global base shear divided by the elastic stiffness of the system, which results in small yield displacement when there is a very stiff element in one edge of the structure. This could result in huge discrepancy between the assessment and reality in terms of the period and equivalent damping. This study used above system yield displacement as well as the yield displacement determined by the critical (flexible) subsystem to see the effect of the underestimation of the global yield displacement.

This study also evaluated cases with or without stiffness degradation of damaged elements using a reduction factor on the effective stiffness of the damaged elements, as proposed in Marder et al (2020):

$$\lambda = 1/\mu \tag{3}$$

where μ is the ductility demand on damaged column due to the damaging earthquake determined from the experimental results to avoid any errors in estimated drift demand due to under/overestimation in the stiffness reduction.

This study assessed the use of Method C only for Series-1A, in which the masonry infill created the strength eccentricity in the system (i.e. $0.27L$ where L is a longitudinal dimension of the plan). As illustrated in Figure 4, per Method C, elimination of the strength eccentricity can be achieved by subtracting the strength capacity of the masonry infill (= 457 kN) from the strength capacity of the subsystem in the West (V_3 in the figure). Consequently, the strength capacity of the system without strength eccentricity corresponds to that in the symmetric system without the masonry wall.

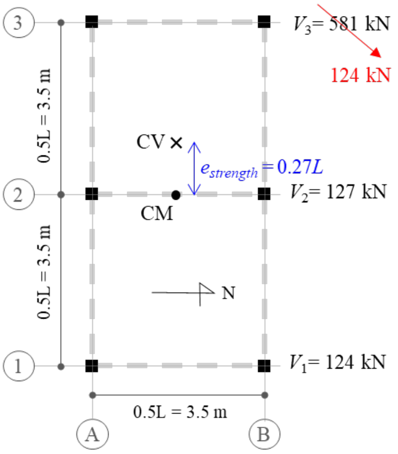


Figure 4 : Strength capacity reduction for Series-1A in accordance with Method C

4 DRIFT DEMAND ESTIMATES

4.1 Simplified Lateral Mechanism Analysis (SLaMA)

Figure 5 presents an example of the plots for the performance curve and ADRS for the damping defined by probable deformation capacity (Cases 1A-N-SU and 1B-N-SU). In the figure, the black bilinear curves represent the system performance, and the dashed red line is ADRS. The grey dashed lines indicate the response at the effective period (i.e. straight line from origin to the probable displacement capacity). The intersection of the grey T_{eff} line and the ADRS shall provide with the displacement demand for each test. The resulting displacement demands for all of the assessed cases are presented in Figure 6, along with the displacement demands at the effective height (4th floor) in the experiment (“Dexp East” and “Dexp West”).

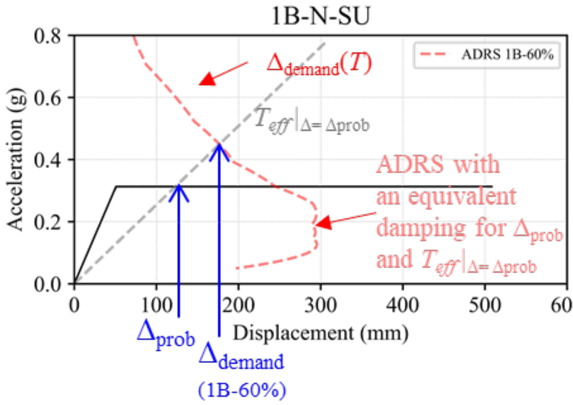


Figure 5 : Example plots of a capacity curve for an equivalent SDOF system obtained by SLaMA with ADRS for the case 1B-N-SU.

In the assessment results for Series-1A, applying Method C significantly increased the estimated displacement demand regardless of the earthquake intensity, target spectrum or other parameters affecting the system performance curve. Although the estimated demand without Method C was much less than the experimental results, Method C was able to show good estimates for 1A-60%, which suggests that the use of Method C in SLaMA is useful for the system with strength irregular systems. The stiffness reduction due to damage slightly increased the estimated demand in Series-1A. The effect was not as sensitive as to the Method C application; however, the combination of the critical yield displacement, stiffness reduction and Method C (i.e. cases -CDC) was able to increase displacement demand estimates in the second 60% test (1A-

60%2). Yet, further considerations may be required for better estimation since estimated demands were overall unconservative for 1A-60%2.

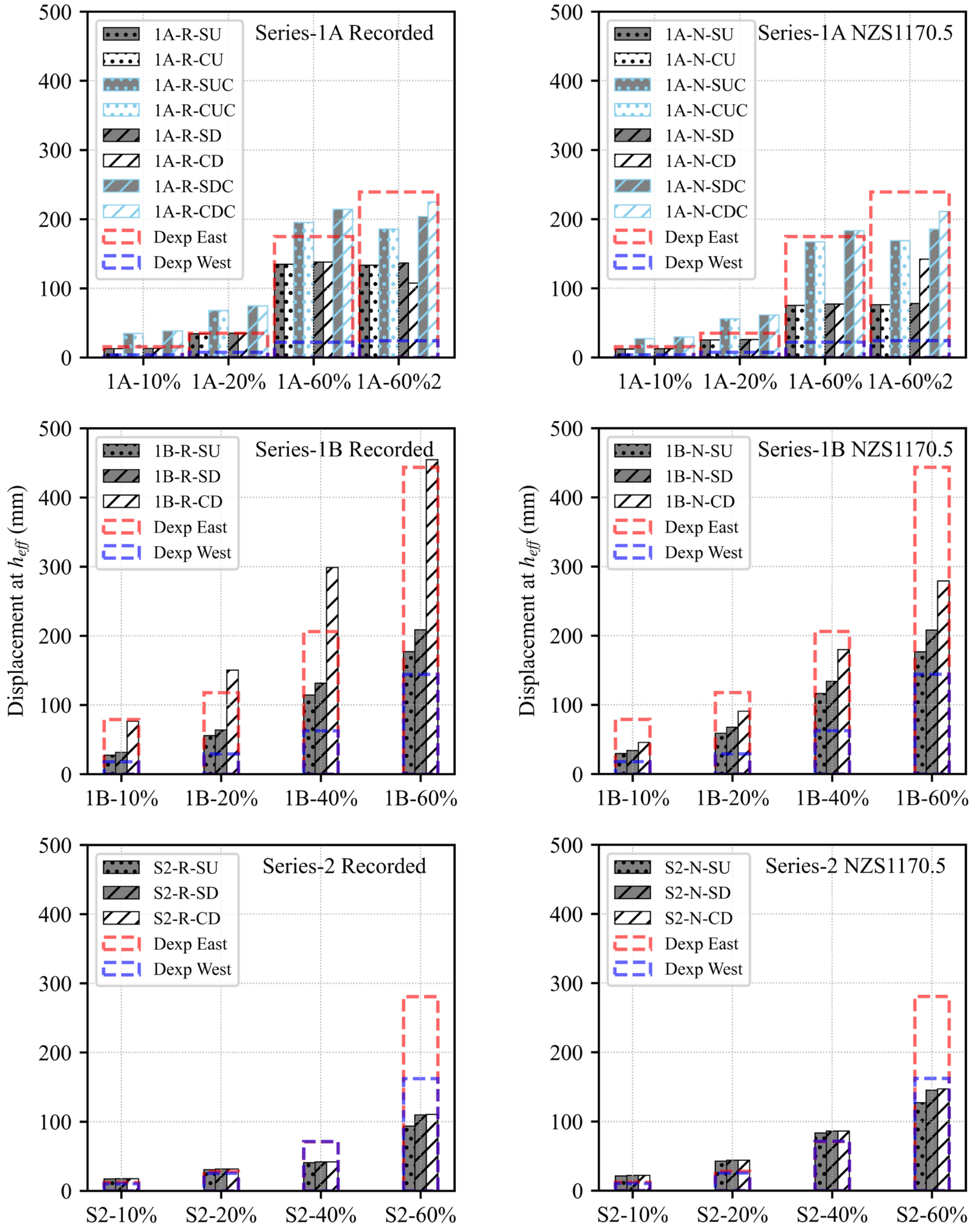


Figure 6 : Displacement demand at h_{eff} obtained from SLaMA. The bars with light blue lines show the cases with Method C applied, grey shaded bars are the cases with system yield displacement whereas unshaded bars indicate cases with critical yield displacements. The different hatches or dots represent the cases with or without stiffness reduction due to existing damage, respectively.

The assessment for damage irregularity (Series-1B) overall underestimated the demands in the critical side (i.e. East) except for the case with stiffness reduction and critical yield displacement (1B-R-CD). The cases with both stiffness reduction and critical yield displacement (i.e. cases "CD") increased the estimated demand, and 1B-R-CD (i.e. the case with critical yield displacement and stiffness reduction and recorded spectrum as a target) could capture the observed demand in the experiment. The result suggests that it is essential to include the effect of damage and considering the response in the critical side.

SLaMA estimated the displacement demands well for symmetric responses in S2-10%, S2-20% and S2-40%, except that S2-R-SU, S2-R-SD and S2-R-CD underestimated the demand in S2-40%. As Figure 3 shows uneven spectral shape at around period 1.0 second, the estimation was sensitive to the effective period. The estimated demands for S2-60%, which resulted in torsional response and collapse of the specimen due to ductility irregularity, were all far smaller than the observed demand in the critical (non-ductile, East) edge. The underestimation was not unexpected as SLaMA does not consider any effect of torsion due to ductility irregularity. The estimated results were close to the observed response in the ductile edge (i.e West), expect for the cases affected by the shape of the recorded acceleration spectrum. This indicates that the system with ductility irregularity is subjected to larger demand than the symmetric system and hence modification of SLaMA to account for the additional demands due to asymmetric strength degradation may be required.

5 CONCLUSIONS

This paper presented the application of SLaMA in the New Zealand Seismic Assessment Guidelines to shake table specimens subjected to different forms of inelastic torsion. The assessment included some variations in defining the system performance and target earthquake demand. The primary outcomes from the study are:

- Applying Method C to the stiffness irregular system of Series-1A resulted in significant increase in the estimated displacement demands, which was effective for estimating the inelastic response for largest inputs (i.e. 1A-60%)
- Taking the critical yield displacement, rather than the system yield displacement, only affected the estimated results when the stiffness reduction due to damage was included.
- The damage irregular system (Series-1B) had better demand estimates when both stiffness reduction due to damage and the critical yield displacement were used.
- The shape of the target spectrum, specifically the hump at longer periods, had a significant impact on the estimated displacements. This suggests the need to carefully consider the potential shape of the spectrum in seismic assessment.
- SLaMA was not able to capture the displacement demand amplification due to ductility irregularity. Modification of SLaMA procedures to account for the additional demands due to asymmetric strength degradation may be required.

Although this paper focused on the simplest assessment method of the New Zealand Seismic Assessment Guidelines, Suzuki (2021) also discusses the results from other assessment procedures, such as nonlinear static or nonlinear dynamic procedures in accordance with both New Zealand Guidelines and ASCE 41-17.

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