
Accounting for post-yield stiffness and strength within the equivalent static analysis method

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ABSTRACT

Structural systems often exhibit significant post-yield stiffness and strength gain, yet current New Zealand force-based seismic design procedures do not explicitly account for these effects. This paper examines how post-yield behaviour influences displacement and strength demands, drawing on insights from displacement-based design (DBD) to inform improvements to the equivalent static method in NZS 1170.5. A generalised expression for the mechanism force-reduction factor, R_{mech} , is developed using secant-stiffness concepts and a work-based combination of subsystem ductilities. A large numerical investigation is undertaken to evaluate R_{mech} across a wide range of structural configurations. Results show that the post-yield stiffness ratio, together with the design ductility, can provide a good indication of R_{mech} . A simplified expression for practical design use is proposed, enabling initial-period-based methods to better reflect realistic mechanism formation and post-yield stiffness and strength development. The findings highlight a pathway for incorporating post-yield behaviour into future revisions of NZS 1170.5.

1 INTRODUCTION

Building structures may exhibit significant post-yield stiffness when subject to lateral loading. This can be seen in the pushover curves shown in Figure 1, where steel moment resisting frame (SMRF) structures examined by Dong et al. (2025) exhibited considerably higher post-yield stiffness and strength gain relative to cantilever RC wall structures. Such large differences between structural systems are not unexpected and relate to the way that inelasticity develops in the structure up until a full plastic mechanism forms. A cantilever reinforced concrete (RC) wall, for example, is designed to form a single plastic hinge at its base. Once this hinge forms, additional lateral displacement is accommodated primarily through inelastic deformations at the hinge, and only modest increases in lateral resistance occur due to strain-hardening, with a typical post-yield stiffness ratio (representing the ratio of post-yield stiffness to initial stiffness) of 5% (Priestley et al. 2007). In contrast, moment resisting frame systems often exhibit substantial post yield stiffness and strength gain. This is because multiple plastic hinges must form across several beams and

columns before a full collapse mechanism is realised, leading to progressive strength increases as yielding spreads. Owing to the sequential nature of hinge formation, the system exhibits high post-yield stiffness even though individual plastic hinges in the steel frames may be well characterised with a post-yield stiffness ratio of 5%. Even within RC wall buildings, the apparent post-yield stiffness of the system can vary markedly between buildings. In buildings containing multiple walls of different lengths, longer walls may yield at relatively small displacements, while shorter, stiffer walls remain elastic until larger drift demands develop. As these shorter walls attract more load, the lateral resistance appears to increase significantly, producing a substantial post-yield strength gain despite each individual wall being characterised by a 5% post-yield stiffness ratio.

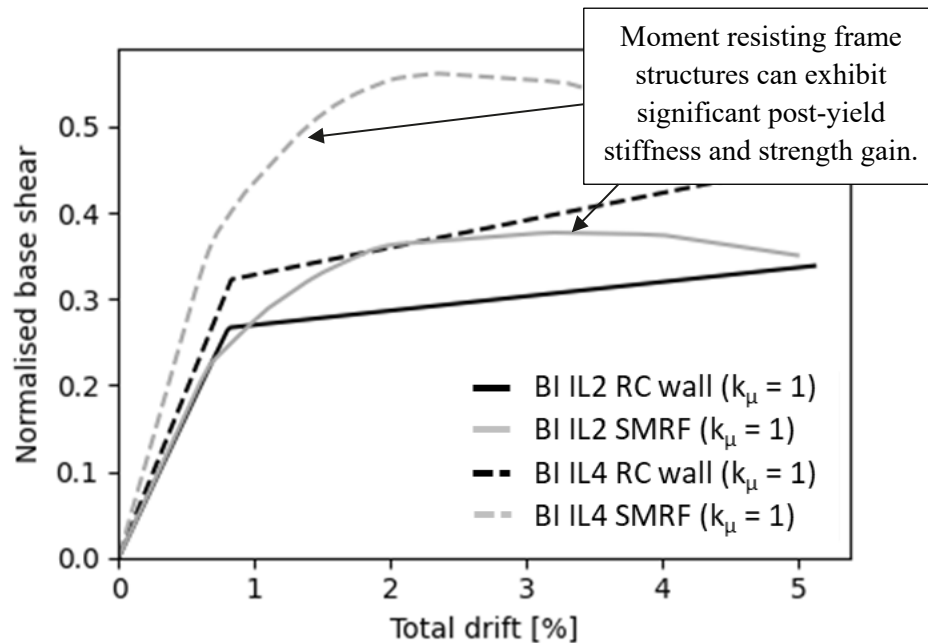


Figure 1: Pushover curves from Dong et al. (2025) that illustrate differences in post-yield stiffness between steel moment-resisting frame (SMRF) structures and reinforced concrete (RC) wall structures.

1.1 What impact should the post-yield stiffness and strength have on peak displacement demands?

Intuitively, one expects that a system that has larger post-yield stiffness and strength is likely to experience less displacement in an earthquake. However, the equal-displacement rule, widely used in force-based design methods in current codes, states that the peak displacement demand on a system responding non-linearly will be equal to the spectral displacement demand at the initial period of the building. Thus, the equal-displacement rule implies that the post-yield stiffness and strength of a building have no effect on the peak inelastic displacement demand. However, a large number of studies have demonstrated that the post-yield stiffness ratio can affect inelastic displacement demands. For instance, research by Nassar & Krawinkler (1991) led to formulation of a force-reduction factor that was a function of post-yield stiffness ratio, but it does not appear to have been implemented in codes. Ruiz-García & Miranda (2003) also found that post-yield stiffness affected maximum inelastic displacement demands but the impact was sensitive to building period (and hence, spectral shape) and it was not incorporated into their proposed expressions for force-reduction factors. A number of researchers also highlighted that increased post-yield stiffness reduced residual displacements (e.g. Borzi et al. 2001; Pettinga et al. 2007). However, none of these studies appears to have arrived at a direct, practical means of accounting for post-yield stiffness ratio within common-code seismic design methods, such as the equivalent static method in NZS1170.5 (2004). That said, a number of international codes have introduced provisions to try and account for post-yield stiffness and strength gain, as discussed next.

1.2 How do design codes allow for post-yield stiffness and strength gain?

The New Zealand seismic design standard NZS1170.5 (2004) does not explicitly account for variations in post yield stiffness ratio or post yield strength gain when determining the required design strength of a structure. Internationally, some seismic codes have taken steps to incorporate the effect of post-yield strength gain into design strength calculations. For instance, the Canadian seismic code (NBCC, 2015) defines a factor R_{mech} that considers the increased resistance that arises from mobilising the full capacity of the structure such that a collapse mechanism is formed. However, according to Mitchell et al. (2003), the overstrength arising from the hierarchy of yielding reduces with increasing number of storeys and is less than 10% for buildings 3-storeys or taller.

In Europe, Eurocode 8 (CEN, 2004) includes provisions that adjust the required design yield strength based on the expected post-yield resistance increase. This is done via an α_u/α_l behaviour factor that includes simplified consideration of post-yield strength development due to both strain hardening and mobilisation of a full plastic mechanism for the structure. The factor α_u/α_l varies from 1.0, for buildings with two uncoupled walls in each direction, to a maximum of 1.3 for multi-bay, multi-storey MRF structures or dual systems.

Such provisions highlight a potential opportunity to revise NZS 1170.5, as the influence of post yield behaviour on design strength is not directly considered at present.

2 ACCOUNTING FOR POST-YIELD STIFFNESS IN DISPLACEMENT-BASED DESIGN AND ASSESSMENT

In contrast to force-based design methods, the Direct displacement-based design (DBD) approach of Priestley et al. (2007) inherently accounts for post-yield strength gain as part of the design and assessment process. This is achieved by using the secant stiffness to peak response and computing a system ductility and inelastic spectrum scaling factor with account for sequential plastic hinge formation of different lateral force resisting elements within the system. This can be seen with reference to the idealised lateral force-displacement response shown in Figure 2 for a system realised with two lateral force resisting elements (e.g. two cantilever RC walls) working together to resist the seismic load.

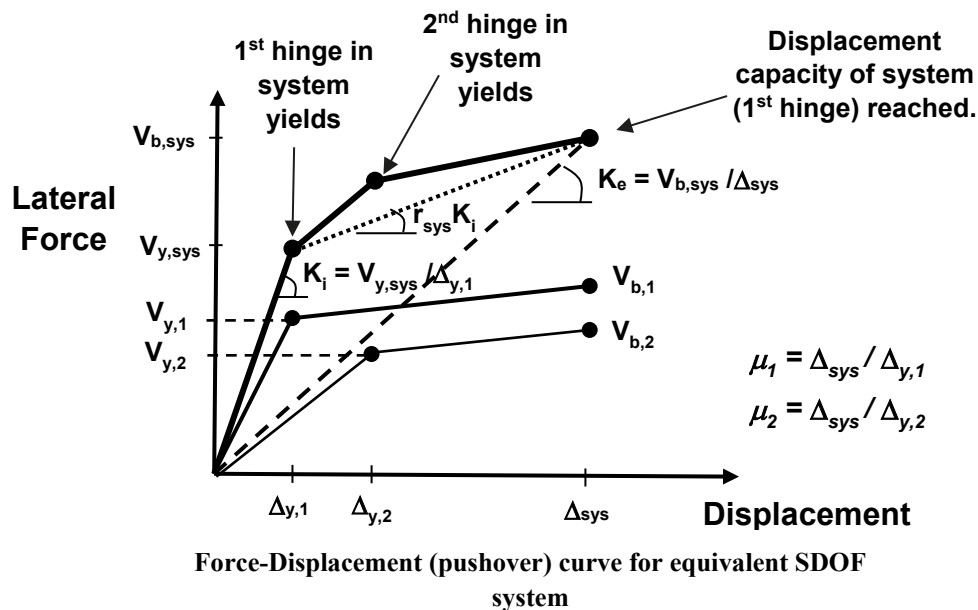


Figure 2: Force-displacement (pushover) curve for a structural system, identifying contributions of two plastic hinges to the system stiffness and strength.

The system shown in Figure 2 has a displacement capacity of Δ_{sys} , that implies ductility demands on the lateral sub-systems of μ_1 and μ_2 , as shown in Figure 2. At the attainment of Δ_{sys} , the total base shear resistance is $V_{b,sys}$, equal to the sum of the base shear resistances $V_{b,1}$ and $V_{b,2}$, offered by lateral sub-systems 1 and 2 respectively (refer to Figure 2).

To quantify the intensity of ground shaking that the system in Figure 2 could sustain, the displacement-based assessment procedure could first quantify the effective period, T_e , of the system as:

$$T_e = 2\pi \sqrt{\frac{m_e}{K_e}} \quad (1)$$

where m_e is the effective mass of the structure and K_e is the effective stiffness (shown in Figure 2). Observe, from Figure 2, that the effective stiffness inherently considers the post-yield stiffness and base shear resistance of the system.

In addition to the effective period, an inelastic spectrum scaling factor is required. As shown by Pennucci et al. (2011), amongst others, this depends on the hysteretic properties of the system. There are various expressions in the literature that can be used to scale the elastic spectrum to given an inelastic spectrum associated with the effective period of a structure, including the following from Pennucci et al. (2011) for structures characterised by Takeda-Thin hysteretic properties (e.g. well detailed RC wall structures):

$$\eta_{sys} = \left(\frac{\pi \mu_{sys}}{8.94 \mu_{sys} - 5.8} \right)^{0.5} \quad (2)$$

where μ_{sys} is the system ductility, approximated using a work-based approach to combine the relative ductility contributions from the different sub-systems, as per Equation 3.

$$\mu_{sys} = \frac{\mu_1 \Delta_1 V_{b,1} + \mu_2 \Delta_2 V_{b,2}}{\Delta_1 V_{b,1} + \mu_2 \Delta_2} \quad (3)$$

The work-based approach highlighted in Equation 3 has been successfully tested as part of Direct DBD for a range of mixed-systems (Sullivan et al. 2006, Garcia et al. 2010, Maley et al. 2010), with the most comprehensive numerical investigation by Maley (2011) finding that it tends to provide slightly conservative design solutions.

Typically, displacement compatibility will imply that sub-systems in a structure will displace together, such that $\Delta_1 = \Delta_2$ in Equation 3 and thus, in such cases the system ductility expression simplifies to:

$$\mu_{sys} = \frac{\mu_1 V_{b,1} + \mu_2 V_{b,2}}{V_{b,sys}} \quad (4)$$

where the symbols are defined in Figure 2.

Once the inelastic spectrum scaling factor has been obtained, the spectral displacement capacity, $S_d(T_e)$, at the effective period of the system can be obtained as follows:

$$S_d(T_e) = \frac{\Delta_{sys}}{\eta_{sys}} \quad (5)$$

where Δ_{sys} is the equivalent single-degree of freedom (SDOF) system displacement capacity (refer Figure 2) and η_{sys} is taken from Equation 2.

This discussion shows that secant-stiffness based design and assessment methods, such as Direct DBD, can relatively simply account for the effect of post-yield stiffness and strength gain. The paper now investigates how the Direct DBD approach could be used to inform suitable R_{mech} values for use within an initial-period based seismic design method, such as the equivalent static method.

3 ACCOUNTING FOR POST-YIELD STIFFNESS IN THE EQUIVALENT STATIC METHOD

The procedure used in Direct DBD can be developed to assess the likely impact of post-yield stiffness and strength gain on the spectral displacement capacity of a system at its effective period, T_e . Subsequently, by assuming a relationship between demands at the effective and initial periods of vibration (e.g. that they both lie in the constant velocity portion of the design spectrum), the equivalent spectral acceleration capacity at the initial period of the structure can be found. Via this approach, Equation 6 has been formulated to quantify the force reduction factor, R_{mech} , to account for the manner with which a mechanism develops in a system.

$$R_{mech} = \frac{S_a(T_1)_{cap,sys}}{S_a(T_1)_{cap,r=0.05}} = \frac{\eta_{r=0.05} \sqrt{\frac{\mu}{1+r(\mu-1)}}}{\eta_{sys} \sqrt{\frac{\mu_{sys}}{1+r_{sys}(\mu_{sys}-1)}}} \quad (6)$$

where $S_a(T_1)_{cap,sys}$, is the spectral acceleration capacity of a lateral force resisting system with multiple hinges and an effective post-yield stiffness ratio, r_{sys} (given by Equation 7), system ductility capacity, μ_{sys} , (given by Equation 10), and inelastic spectrum scaling factor, η_{sys} (from Equation 2), and; $S_a(T_1)_{cap,r=0.05}$, is the spectral acceleration capacity of a system with the same initial period and with a post-yield stiffness ratio, r , of 0.05, ductility capacity, μ , and inelastic spectrum scaling factor, $\eta_{r=0.05}$, (obtained by substituting $\mu = \mu_{sys}$ into Equation 2).

$$r_{sys} = \frac{\left(\frac{V_{b,sys}}{V_{y,sys}} - 1\right)}{\mu - 1} \quad (7)$$

where μ is the ductility capacity of the structure (assumed to be associated with yield of the first plastic hinge or sub-system), $V_{b,sys}$ is the base shear force that develops in the structure (shown in Figure 2) when displaced laterally to the peak displacement and $V_{y,sys}$ is the base shear force (also shown in Figure 2) in the structure when the first plastic hinge forms. It can also be shown that the ratio of the peak to yield base shear forces can be computed as follows:

$$\frac{V_{b,sys}}{V_{y,sys}} = \frac{\left[1 + r_1(\mu - 1) + \frac{V_{y,2}}{V_{y,1}} \left(1 + r_2 \left(\mu \frac{\Delta_{y1}}{\Delta_{y2}} - 1\right)\right)\right]}{1 + \frac{V_{y,2} \Delta_{y1}}{V_{y,1} \Delta_{y2}}} \quad (8)$$

Where r_1 and r_2 are the post-yield stiffness ratios (typically assumed to equal 0.05) of individual lateral force resisting systems 1 and 2 respectively, and $V_{y,2}/V_{y,1}$ and $\Delta_{y,2}/\Delta_{y,1}$ are ratios of the base shear yield force and yield displacements respectively (see Figure 2), of the individual lateral force resisting systems.

A system inelastic spectrum scaling factor is required for Equation 6 and can be computed via Equation 2 for structures characterised by Takeda Thin hysteresis. To do this, the system ductility, μ_{sys} , can be computed as a function of the ductility capacity of the critical sub-system, μ_1 , and the stiffness, strength and yield displacement ratios of the individual systems from:

$$\mu_{sys} = \frac{(1 + r_1(\mu_1 - 1)) \mu_1 \left(1 + \frac{\Delta_{y1} V_{y,2}}{\Delta_{y2} V_{y,1}} \left(\frac{1 + r_2 \left(\mu_1 \frac{\Delta_{y1}}{\Delta_{y2}} - 1\right)}{1 + r_1(\mu_1 - 1)}\right)\right)}{1 + r_1(\mu_1 - 1) + \frac{V_{y,2}}{V_{y,1}} \left(1 + r_2 \left(\mu_1 \frac{\Delta_{y1}}{\Delta_{y2}} - 1\right)\right)} \quad (9)$$

where the symbols have been defined earlier (see also Figure 2).

3.1 Simplified expression for the mechanism force reduction factor, R_{mech}

There are a number of factors that are likely to affect the mechanism force reduction factor, as can be appreciated from Equation 6 and the approximations made to derive it. A numerical investigation is undertaken here to arrive at a more simplified expression for the mechanism force-reduction factor, suitable for use in the equivalent static method, modal response spectrum or initial-period based pushover seismic assessment. More specifically, the R_{mech} values obtained from Equation 6 are computed for a number of structural systems (with idealised pushover curves similar to that shown in Figure 2) with $V_{y,2}/V_{y,1}$ ratios ranging from 0.25 to 4, $\Delta_{y,2}/\Delta_{y,1}$ ratios ranging from 1.5 to 5, and ductility capacities ranging from 2 to 5. A full list of system characteristics and results obtained are reported in Table 1.

The results of the numerical study were then post-processed to establish a relationship between post-yield stiffness or strength and the R_{mech} factor. Figure 3(a) shows that the post-yield stiffness ratio for the system provides a reasonable indication for the R_{mech} factor if the system ductility is known. Figure 3(b) suggests that R_{mech} could be estimated directly as a function of the post-yield strength ratio but upon closer inspection, it is noted that for low ductility levels, the values for R_{mech} plateau. As such, Figure 3a includes R_{mech} values obtained from the following simplified expression for R_{mech} :

$$R_{mech} = 1 + 0.35\mu(r_{sys} - 0.05) \quad (10)$$

Where the base shear values were illustrated earlier in Figure 2.

For future code implementation within the equivalent static method, it is apparent that the designer is not likely to know the post-yield stiffness ratio for their structure. To overcome this, code writers could identify systems that are characterised with higher post-yield stiffness ratios (such as steel MRF structures) and those with lower values (such as RC wall structures). Together with good estimates of the design ductility demand, the designer could then compute R_{mech} via an equation, such as Equation 10, but modified according to the hysteretic properties of the structural system. Note that the resulting values for R_{mech} are likely to range from 1.0 to 1.4, which coincidentally aligns well with current recommendations in Eurocode 8.

The values provided in this paper should be considered as preliminary and the expressions should be tested and refined further as part of future research. This is principally because the numerical study conducted here only considered a single hysteretic model and assumed that the building period lies within the constant-velocity portion of the response spectrum. Furthermore, it would be desirable to use the results of non-linear response history analysis of a large set of structures, with different periods, hysteretic properties and ground motion characteristics to better validate the approach.

4 CONCLUSIONS

This paper has demonstrated that post-yield stiffness and strength gain can have a significant influence on the seismic performance of structural systems, yet these effects are not explicitly considered in the equivalent static method of NZS 1170.5. By drawing on the principles of Direct Displacement-Based Design, a generalised formulation for the mechanism force-reduction factor, R_{mech} , was developed. This factor seeks to quantify the influence of sequential hinge formation and post-yield stiffness on the capacity of a structure to resist earthquake shaking.

A numerical investigation showed that the post-yield stiffness ratio of a structural system, together with the displacement ductility, can provide a good predictor for R_{mech} . Based on these findings, a simplified expression for R_{mech} was proposed. Recognising that some systems are likely to be characterised by higher post-yield stiffness ratios than others, code writers could use the expression to define values for R_{mech} according to structural system and design ductility. This would appear to offer a practical means of incorporating post-yield behaviour into initial-period-based design and assessment procedures.

Table 4: System characteristics used to quantify R_{mech} values from Equation 6 numerically.

Ductility Limit	$\Delta y_2/\Delta y_1$	V_{y2}/V_{y1}	μ_{sys}	η_{sys}	$V_{sys}/V_{y,sys}$	r_{sys}	η_{single}	$R_{mech} = \frac{S_{a,sys}}{S_{a,single}}$
2	1.5	0.25	1.87	0.73	1.118	0.12	0.72	1.04
2	2	0.25	1.81	0.74	1.156	0.16	0.72	1.06
2	1.5	0.5	1.78	0.74	1.169	0.17	0.72	1.07
2	2	0.5	1.68	0.76	1.240	0.24	0.72	1.09
2	1.5	1	1.67	0.76	1.240	0.24	0.72	1.09
2	2	1	1.51	0.78	1.367	0.37	0.72	1.12
2	1.5	1.5	1.61	0.77	1.288	0.29	0.72	1.11
2	2	1.5	1.41	0.81	1.457	0.46	0.72	1.13
2	1.5	2	1.56	0.78	1.321	0.32	0.72	1.12
2	2	2	1.34	0.82	1.525	0.53	0.72	1.13
3	1.5	0.25	2.81	0.68	1.168	0.08	0.67	1.05
3	2	0.25	2.72	0.68	1.206	0.10	0.67	1.07
3	3	0.25	2.63	0.68	1.246	0.12	0.67	1.09
3	1.5	0.5	2.68	0.68	1.219	0.11	0.67	1.08
3	2	0.5	2.52	0.69	1.290	0.15	0.67	1.12
3	3	0.5	2.38	0.70	1.371	0.19	0.67	1.16
3	1.5	1	2.51	0.69	1.290	0.15	0.67	1.12
3	2	1	2.28	0.70	1.417	0.21	0.67	1.18
3	3	1	2.05	0.72	1.575	0.29	0.67	1.23
3	1.5	1.5	2.41	0.69	1.338	0.17	0.67	1.14
3	2	1.5	2.13	0.71	1.507	0.25	0.67	1.21
3	3	1.5	1.85	0.74	1.733	0.37	0.67	1.27
3	1.5	2	2.34	0.70	1.371	0.19	0.67	1.16
3	2	2	2.02	0.72	1.575	0.29	0.67	1.23
3	3	2	1.71	0.75	1.860	0.43	0.67	1.28
3	1.5	3	2.26	0.70	1.417	0.21	0.67	1.18
3	2	3	1.90	0.73	1.670	0.34	0.67	1.25
3	3	3	1.54	0.78	2.050	0.53	0.67	1.30
4	1.5	1	3.35	0.66	1.340	0.11	0.65	1.12
4	2	1	3.05	0.67	1.467	0.16	0.65	1.19
4	3	1	2.75	0.68	1.625	0.21	0.65	1.25
4	4	1	2.60	0.68	1.720	0.24	0.65	1.29
4	1.5	1.5	3.22	0.66	1.388	0.13	0.65	1.15
4	2	1.5	2.84	0.67	1.557	0.19	0.65	1.23
4	3	1.5	2.48	0.69	1.783	0.26	0.65	1.31
4	4	1.5	2.30	0.70	1.927	0.31	0.65	1.35
4	1.5	2	3.13	0.67	1.421	0.14	0.65	1.17
4	2	2	2.71	0.68	1.625	0.21	0.65	1.26
4	3	2	2.30	0.70	1.910	0.30	0.65	1.34
4	4	2	2.10	0.71	2.100	0.37	0.65	1.38
4	1.5	3	3.02	0.67	1.467	0.16	0.65	1.19
4	2	3	2.53	0.69	1.720	0.24	0.65	1.29
4	3	3	2.06	0.72	2.100	0.37	0.65	1.38
4	4	3	1.83	0.74	2.371	0.46	0.65	1.42
4	1.5	4	2.95	0.67	1.495	0.17	0.65	1.20
4	2	4	2.43	0.69	1.783	0.26	0.65	1.31
4	3	4	1.92	0.73	2.236	0.41	0.65	1.41
4	4	4	1.67	0.76	2.575	0.53	0.65	1.43
5	1.5	0.25	4.69	0.64	1.268	0.07	0.64	1.05
5	2	0.25	4.54	0.64	1.306	0.08	0.64	1.07
5	3	0.25	4.41	0.64	1.346	0.09	0.64	1.10
5	4	0.25	4.35	0.64	1.368	0.09	0.64	1.11
5	5	0.25	4.31	0.64	1.381	0.10	0.64	1.11
5	1.5	0.5	4.47	0.64	1.319	0.08	0.64	1.08
5	2	0.5	4.23	0.64	1.390	0.10	0.64	1.12
5	3	0.5	4.00	0.65	1.471	0.12	0.64	1.17
5	4	0.5	3.89	0.65	1.517	0.13	0.64	1.19
5	5	0.5	3.82	0.65	1.545	0.14	0.64	1.20
5	1.5	1	4.20	0.64	1.390	0.10	0.64	1.12
5	2	1	3.82	0.65	1.517	0.13	0.64	1.19
5	3	1	3.46	0.66	1.675	0.17	0.64	1.26
5	4	1	3.28	0.66	1.770	0.19	0.64	1.30
5	5	1	3.18	0.66	1.833	0.21	0.64	1.32
5	1.5	1.5	4.03	0.65	1.438	0.11	0.64	1.15
5	2	1.5	3.57	0.66	1.607	0.15	0.64	1.24
5	3	1.5	3.12	0.67	1.833	0.21	0.64	1.32
5	4	1.5	2.91	0.67	1.977	0.24	0.64	1.37
5	5	1.5	2.78	0.68	2.077	0.27	0.64	1.40
5	1.5	2	3.92	0.65	1.471	0.12	0.64	1.17
5	2	2	3.40	0.66	1.675	0.17	0.64	1.27
5	3	2	2.89	0.67	1.960	0.24	0.64	1.37
5	4	2	2.65	0.68	2.150	0.29	0.64	1.42
5	5	2	2.50	0.69	2.286	0.32	0.64	1.45

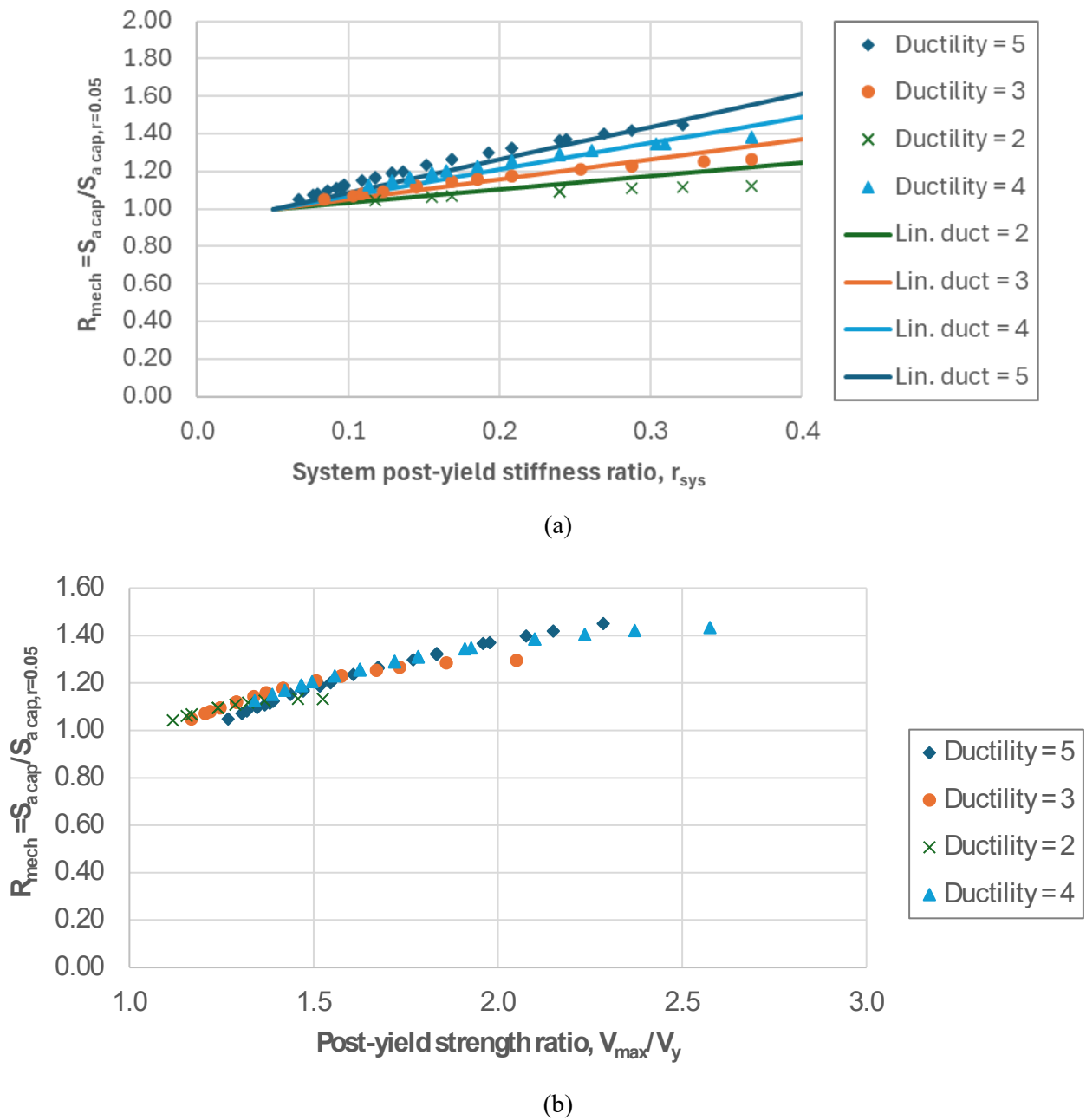


Figure 3: Mechanism force reduction factor, R_{mech} , obtained numerically via a displacement-based assessment procedure (via Equation 6) as a function of (a) system post-yield stiffness ratio, and (b) system post-yield strength ratio.

Further research is recommended to validate the refine the proposed expression across a broader range of structural typologies, hysteretic models, and ground motion characteristics. Nonetheless, the results presented here highlight a clear opportunity to enhance the accuracy and consistency of force-based seismic design in New Zealand by explicitly recognising the beneficial effects of post-yield stiffness and strength gain.

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