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Investigation of vertical reinforcement termination in lightly reinforced concrete walls

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ABSTRACT

Reinforced concrete (RC) structural walls are effective lateral force-resisting components commonly implemented in tall buildings. Recent studies have investigated the impact of minimum vertical reinforcement limits on the ductility at the plastic hinge region of RC walls and resulted in revisions to design standard requirements in both New Zealand and the United States. These studies focused on cantilever walls with the single plastic hinge at the wall base, whereas tall buildings exhibit more distributed plasticity demands up the wall height. In addition, the termination rules for the vertical reinforcement in the plastic hinge region were not considered during previous tests and modelling.

The main objective of this research is to investigate the seismic performance of RC walls in tall buildings, considering the influence of the vertical reinforcement contents up the full wall height. Push-over analyses were conducted on a 20-storey tall RC wall prototype, to investigate the sensitivity of the termination height of the vertical reinforcement in the plastic hinge. Based on the model results, current capacity design rules reviewed in NZS 3101:2006 may be insufficient to ensure that yielding is confined to the plastic hinge region. Preliminary recommendations are made regarding the termination height of additional vertical reinforcement within the plastic hinge.

1 INTRODUCTION

Reinforced concrete (RC) structural walls are effective lateral force-resisting components that are commonly implemented in tall buildings. Recent studies (Lu, Gultom, Ma, & Henry, 2018) (Lu & Henry, 2018) have investigated the impact of minimum vertical reinforcement limits on the ductility at the plastic hinge region of RC walls and resulted in revisions to design standard requirements in both New Zealand (NZS 3101:2006-A3, 2017) and the United States (ACI Committee 318, 2019). These studies focused on cantilever walls with the single plastic hinge at the wall base, whereas tall buildings exhibit more distributed plasticity demands up the wall height. In addition, the termination rules for the vertical reinforcement in the plastic hinge region were not considered during previous tests and modelling.

In order to investigate the seismic performance of lightly reinforced concrete wall in tall buildings, Push-over analyses were conducted on a 20-storey wall prototype to investigate the influence of the additional reinforcement height up to the wall height. A fibre model for tall, lightly reinforced concrete walls was developed that implemented regularisation techniques to accurately capture strain localisation and wall failure (Deng & Henry, 2020a),(Deng & Henry, 2020b). The modelling techniques were validated against the experimental tests with a range of vertical reinforcement contents to confirm the full range of wall sections can be accurately modelled. The model developed was then used to conduct parametric analyses to investigate the effect of vertical reinforcement termination on the Push-over response of lightly reinforced walls with a range of design parameters.

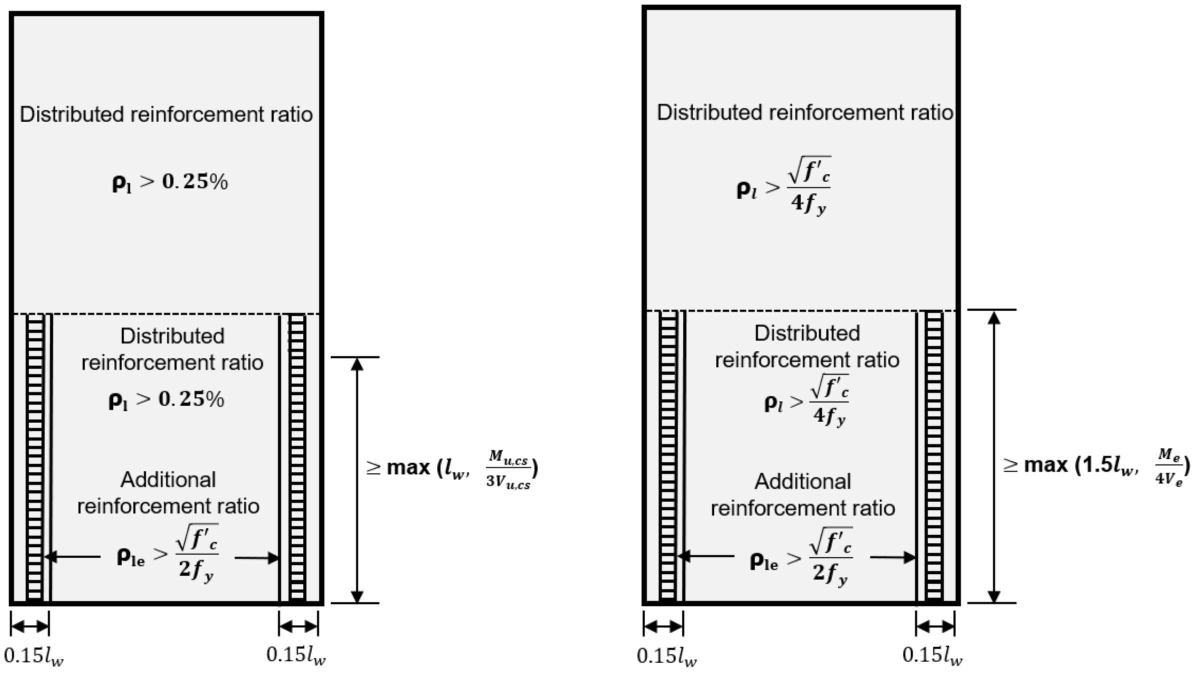
2 MINIMUM VERTICAL REINFORCEMENT REQUIREMENTS

The minimum longitudinal reinforcement requirements for the full height of tall walls in the United States (ACI Committee 318, 2019) and New Zealand standards (NZS 3101:2006-A3, 2017) were compared and are summarized in Table 1. The comparison illustrated that both ACI 318-19 and NZS 3101:2006-A3 stipulate the same amount of additional reinforcement lumped within the plastic hinge height is equal to $\sqrt{f_c'}/2f_y$, which depends on the concrete and reinforcement strength. For the distributed reinforcement in the central web region within the plastic hinge and full section outside the plastic hinge height, the ACI 318-19 defines a ratio of 0.25% while NZS 3101:2006 still considers the reinforcement and concrete strength, requiring a ratio of $\sqrt{f_c'}/4f_y$. In terms of the additional reinforcement height, ACI 318-19 requires a length equal to the larger of l_w and $M_u/3V_u$, as shown in Figure 1 (a). While in NZS 3101:2006-A3 the additional reinforcement must extend over the ductile detailing length or higher if required by capacity design:

- **Ductile detailing length:** Equal to the larger of $1.5\mathrm{L_w}$ and $\mathrm{M_{max}}/4\mathrm{V_{max}}$, where $\mathrm{L_w}$ was the wall length and $\mathrm{M_{max}}/\mathrm{V_{max}}$ was the moment to shear ratio at the critical section, as shown in Figure 1 (b).
- **Capacity design requirement:** The flexural capacity envelope must exceed the design envelop when an overstrength flexural capacity develops at the wall base, as shown in Figure 2. The capacity is based on the nominal flexural strength $\mathrm{M_n}$.

Table 1: Comparison of minimum vertical reinforcements for RC walls

Standards	**Plastic hinge**			**Outside plastic hinge**
	Additional reinforcement ratio	**Distributed reinforcement ratio**	**Additional reinforcement height**	**Distributed reinforcement ratio**
ACI 318-19	$\geq \frac{\sqrt{f_c'}}{2f_y}$	≥ 0.25 %	$\max\left(l_w, \frac{M_u}{3V_u}\right)$	≥ 0.25 %
NZS 3101-A3	$\geq \frac{\sqrt{f_c'}}{2f_y}$	$\geq \frac{\sqrt{f_c'}}{4f_y}$	**Detailing** $\max\left(1.5l_w, \frac{M_u}{4V_u}\right)$ **Capacity design** Moment capacity greater than demand	$\geq \frac{\sqrt{f_c'}}{4f_y}$



(a) ACI 318-19 (b) NZS 3101:2006-A3

Figure 1: Comparison of the wall detailing requirement between the United States and New Zealand

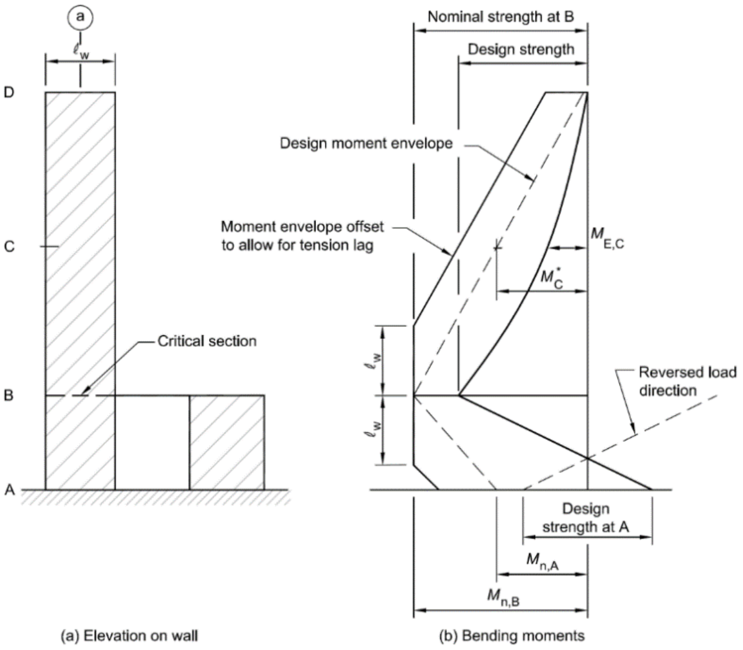
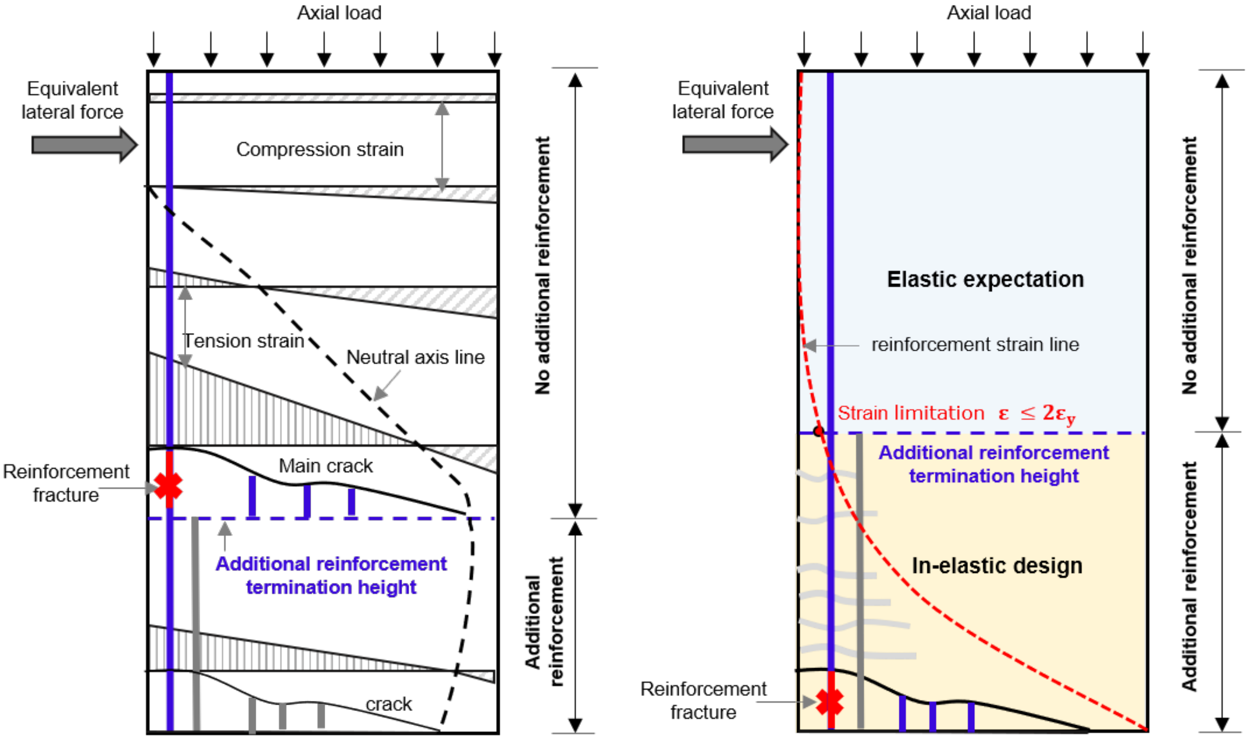


Figure 2: Capacity design bending moment envelop for a structural wall (NZS 3101:2006-A3, 2017)

Considering the seismic performance of tall walls, the lesson learned from the past Chuetsu-oki and Chile earthquakes showed that insufficient strength in the upper storeys probably resulted in damage occurring at the mid-height outside the intended plastic hinge region at the wall base (ABS Consulting, 2008) (Wallace et al., 2012). It highlighted the importance of reinforcement termination height to prevent premature reinforcement failure occurring outside the ductile hinge region, as shown in Figure 3 (a). To estimate the expected elastic performance beyond the plastic hinge height, Los Angeles Tall Buildings Structural Design

Council (2020) set the acceptance criteria that reinforcement strain limit for walls with no confinement at $2\varepsilon_y$, where the ε_y is the reinforcement yield strain, as shown in Figure 3 (b).



(a) Unexpected failure (b) Assumed failure

Figure 3: Failure mode for the single plastic hinge designed tall walls

3 PARAMETRIC ANALYSIS

3.1 Wall description

All the wall models in the parametric study had identical dimensions with a length of 8.2 m, thickness of 0.3 m, storey height of 3.4 m, and total height of 68 m. The wall model was based on the web region of an existing 20-storey archetypical core wall model (Panagiotou et al., 2009). The tall walls were designed in accordance with the minimum reinforcement limits required by ACI 318-19 (ACI Committee 318, 2019). For the section within the plastic hinge region, the minimum required end zone longitudinal reinforcement ratio was 0.78% ($\sqrt{f_c'}/2f_y$), leading to two layers of 11 × D12.7 (#4) bars (diameter = 12.7mm) placed at 100 mm within the end region with the reinforcement ratio of 0.79%. The distributed minimum longitudinal reinforcement ratio was 0.25% in the central web region, resulting in two layers of 32 × D9.5 (#3) bars (diameter = 9.5 mm) placed at 200 mm centres over the wall length, as shown in Figure 4. For the section outside the plastic hinge region, the required distributed minimum longitudinal reinforcement ratio was 0.25%, resulting two layers of 44 × D9.5 (#3) bars (diameter = 9.5 mm) placed at 200 mm centring over the wall length, as shown in Figure 5.

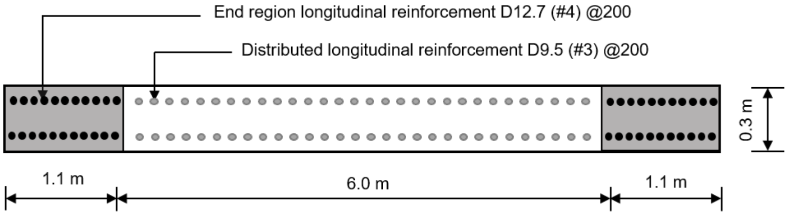


Figure 4: Section of the plastic hinge region

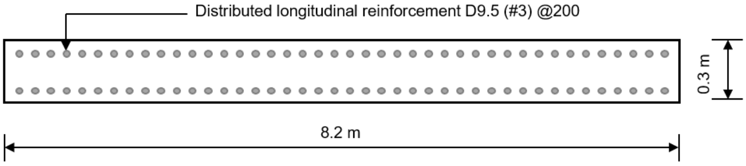


Figure 5: Section of outside the plastic hinge

The imposed axial load was assumed as 0.4% $f_c'A_g$ for each storey leading to 8% $f_c'A_g$ acting at the base. The tall wall models were loaded in plane, using an inverted triangular lateral load pattern up the entire wall height, as depicted in Figure 6. The walls were modelled with a specific concrete strength of 43 MPa and calculated tensile strength of 3.6 MPa. The models used Grade 60 reinforcing bar properties with 420 MPa for yield stress and 620 MPa for ultimate stress, as recommended in A615/A615M-18 (A615/A615M−18, 2018). The onset of reinforcement yielding and fracture were respectively defined as the tensile strain of 0.21% and 12%. The first reinforcement fracture was defined as the drift capacity.

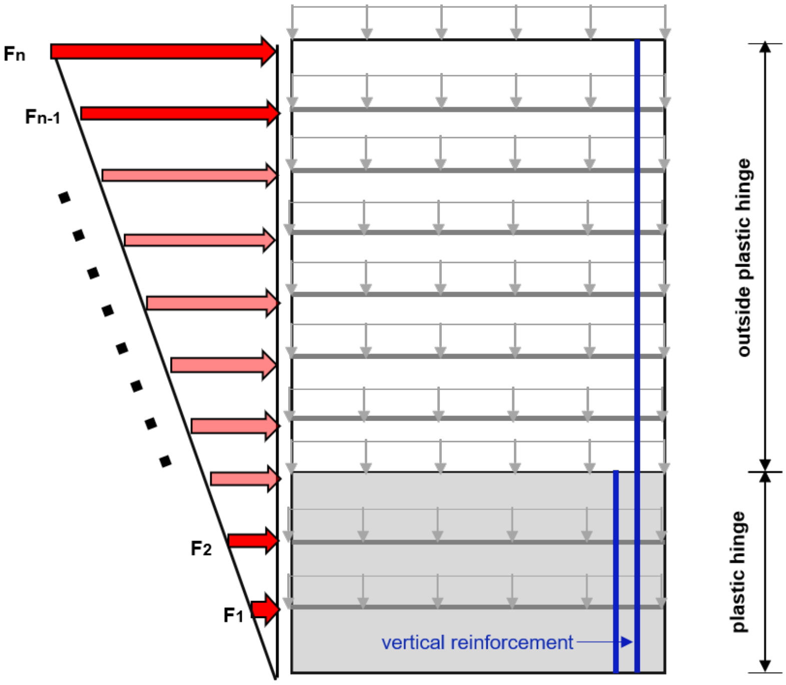


Figure 6: Loading protocol for the tall wall models

Table 2: Details for additional reinforcement height comparison

Wall No.	Base axial load ratio (%)	Wall height (Storey)	Wall length (m)	Wall thickness (m)	Additional reinforcement height (Storey)	Reinforcement ratio in the lower storey			Reinforcement ratio in the upper storey (%)	f_y (MPa)	f_u (MPa)	f_u/f_y
						End (%)	Web (%)	Total (%)				
Rein-AR2	8.0	20	8.2	0.3	2	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR3	8.0	20	8.2	0.3	3	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR4	8.0	20	8.2	0.3	4	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR5	8.0	20	8.2	0.3	5	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR6	8.0	20	8.2	0.3	6	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR7	8.0	20	8.2	0.3	7	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR8	8.0	20	8.2	0.3	8	0.76	0.25	0.40	0.25	420	620	1.47
Rein-AR20	8.0	20	8.2	0.3	20	0.76	0.25	0.40	0.50	420	620	1.47

AR = additional reinforcement height

3.2 Wall performance

The calculated moment drift response for all of the wall models is shown in Figure 7. The model results showed a similar performance in both the strength and deformation. The can be summarized that the increased termination height resulted in a slight increase of strength, but a slight reduction of deformation, except Rein-AR2 did not follow this trend. Due to the plastic hinge contribution to the deformation capacity, the reinforcement strain profile was used to describe the yield hinges distribution up to full height. Figure 9 (b) and Figure 16 (b) represented the outmost reinforcement strain profile at the maximum drift. It was found walls with 2 to 7 storeys of additional reinforcement probably formed the dual plastic hinges as the yield occurred at the reinforcement termination height. The indication of a secondary plastic hinge at reinforcement discontinuity was illustrated in Figure 8. Based on the energy dissipation theory, the total energy dissipated by the deformation is equal to the area from two split hinges region under the strain profile, as proposed in Equation (1). Equation (2) and Equation (3) represented the estimation for the energy released by each plastic hinge along the reinforced bar. Considering the almost same amount of energy dissipation at the base hinge for model walls with 4 to 8 storey additional reinforcement height (from Rein-AR4 to Rein-AR8), the larger strain at the termination location, represented the more energy dissipation at the second plastic hinge which resulted in larger deformation capacity. For walls of Rein-AR2 and Rein-AR3 with unexpected failure at additional reinforcement termination height, the released energy at the first plastic hinge was critical to determine the deformation capacity, which means the larger reinforcement strain at wall base led to the higher ductility. The least energy dissipation in total plastic hinges caused the lowest deformation capacity for Rein-AR2.

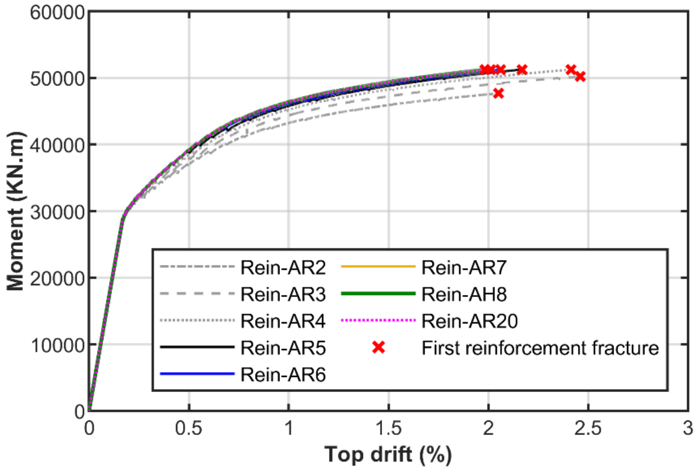


Figure 7: The comparison of the base moment-drift response

$$E_{tot,Eng} = E_{1st,Enghin} + E_{2nd,Enghin} \tag{1}$$

Where $E_{1st,Enghin}$ and $E_{2nd,Enghin}$ are the amount of energy dissipation for the first and secondary plastic hinge and $E_{tot,Eng}$ is the total amount of energy dissipation.

$$\mathrm{E}_{1\mathrm{st,Enghin}} = \frac{1}{2} \times \mathrm{h}_{\mathrm{add,rein}} \times \varepsilon_{\mathrm{s,base}} \times \mathrm{E}_{\mathrm{s}} \times \mathrm{A}_{\mathrm{s}} \tag{2}$$

$$\mathrm{E}_{2\mathrm{nd,Enghin}} = \frac{1}{2} \times \mathrm{h}_{2\mathrm{nd,yd}} \times \varepsilon_{\mathrm{s,ter}} \times \mathrm{E}_{\mathrm{s}} \times \mathrm{A}_{\mathrm{s}} \tag{3}$$

Where $h_{add,rein}$ is the additional reinforcement height, $h_{2nd,yd}$ is the extending reinforcement yielding height at the secondary plastic hinge, $\varepsilon_{s,base}$ and $\varepsilon_{s,ter}$ are the reinforcement strain at the base and additional reinforcement termination height, E_s is Young's modulus, and A_s is the section area for the reinforcing bar.

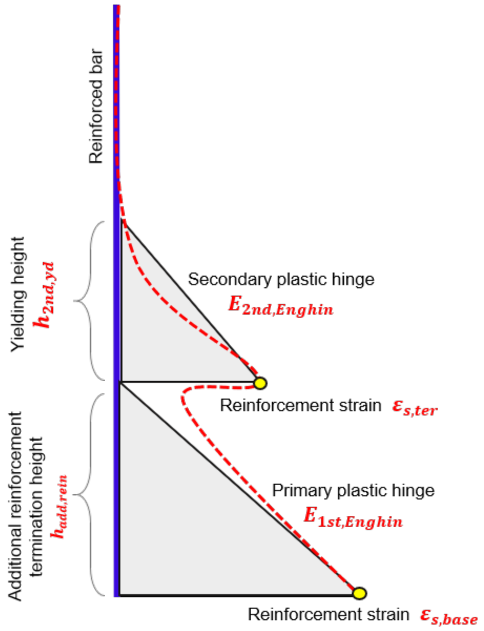
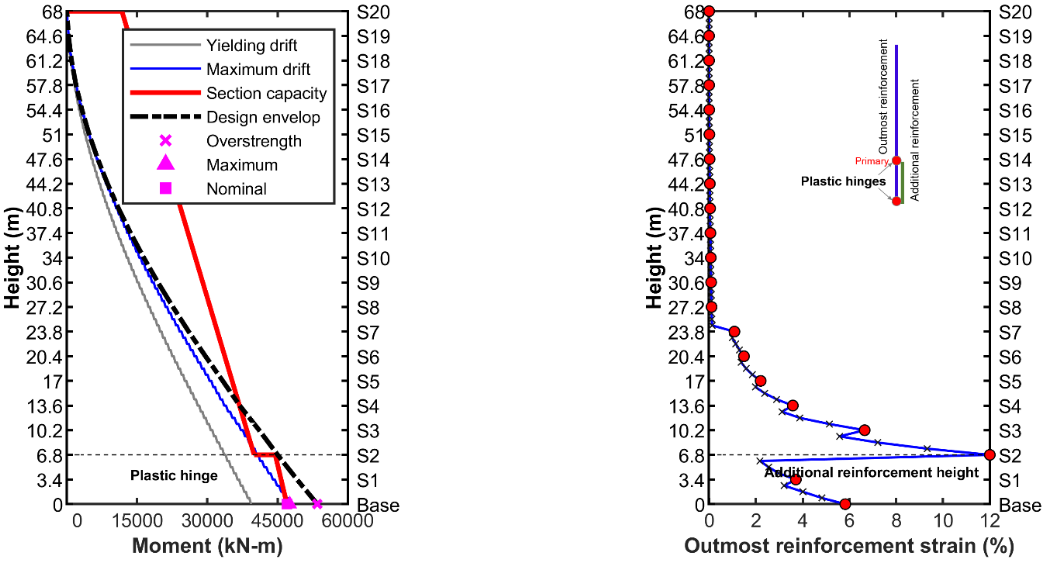


Figure 8: Illustration of the reinforcement with the dual plastic hinge

The moment profile presenting the relationship between capacity and demand is shown in Figure 9 (a) to Figure 16 (a). The demand profile for the first yielding and fractured reinforcement at the base was recorded to represent the response of the elastic design target and ultimate inelastic phrases. The capacity profile was determined by the nominal moment at the critical section, including the wall base, termination height of reinforcement and the wall top. The maximum design load envelop was determined by the overstrength capacity moment at the base that was proportional to upper storeys according to the height. The model results showed the walls with equal to or higher than 4-storey of additional reinforcement can satisfy the capacity design requirement that the section capacity is greater than the required by maximum design load demand (NZS 3101:2006-A3, 2017). However, The acceptance criteria for reinforcement strain limit indicated the insufficient additional reinforcement height probably resulted in the dual plastic hinges not conforming to the expected elastic response for the region outside the plastic hinge. For example, wall Rein-AR4 with 4-storey additional reinforcement was sufficient to meet the capacity design requirement, but strains of up to 7.8% were still observed at the termination point. It was worth noting the greater nominal moment capacity than the required maximum demand was not sufficient to prevent the section yielding.

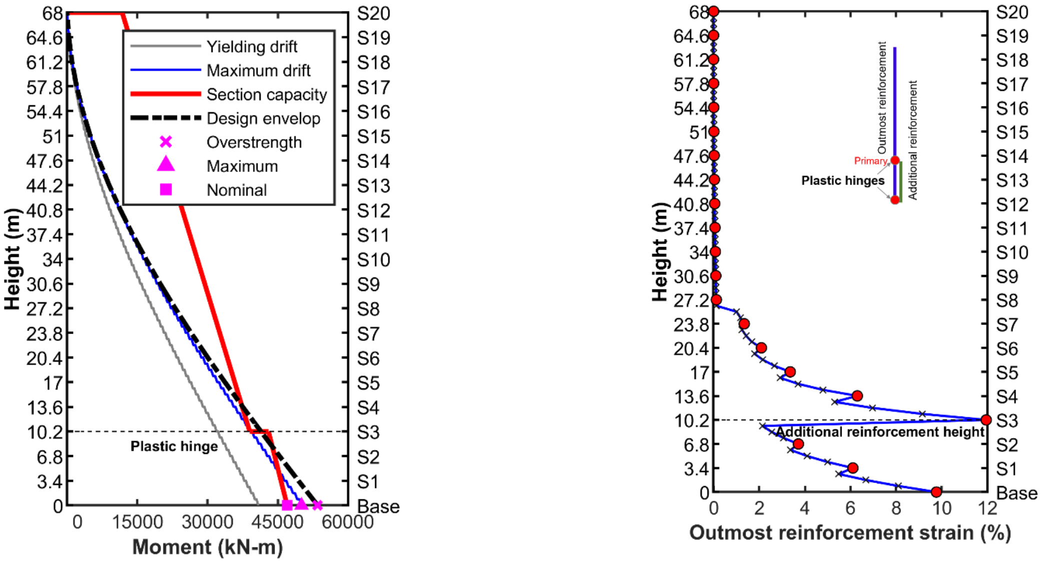
The relationship between the additional reinforcement height and strain response at termination was concluded in Figure 17. The result showed that until 8-storey additional reinforcement height can comply with the reinforcement strain limitation for the upper portion that was higher than the required 4-storey and 5-storey additional reinforcement in NZS 3101:2006-A3 and ACI 318-19. It implicated that the vertical reinforcement termination height stipulated in current standards was probably not sufficient to satisfy the elastic assumption for the region outside the plastic hinge.



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

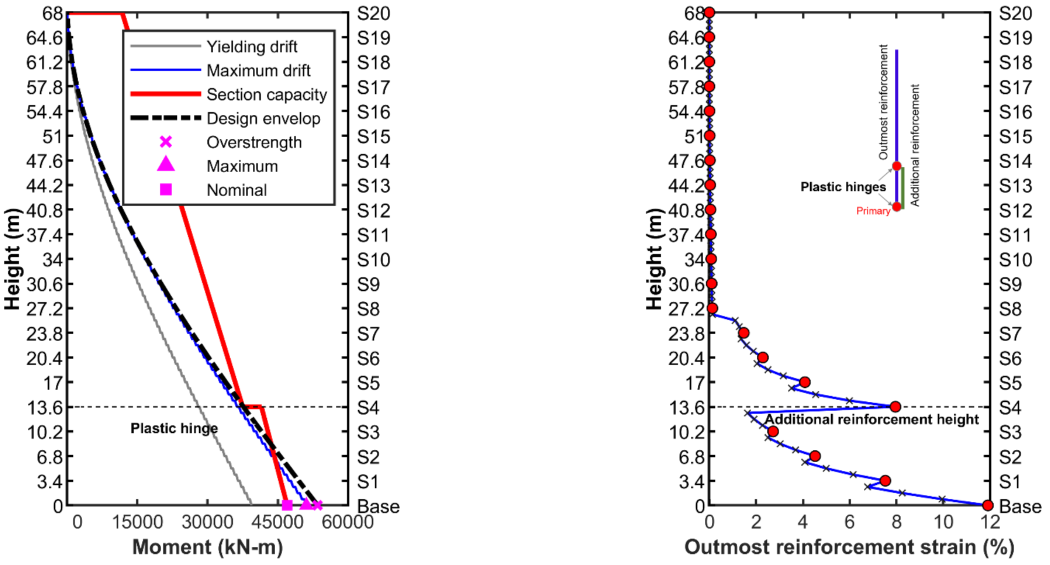
Figure 9: Rein-AR2 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

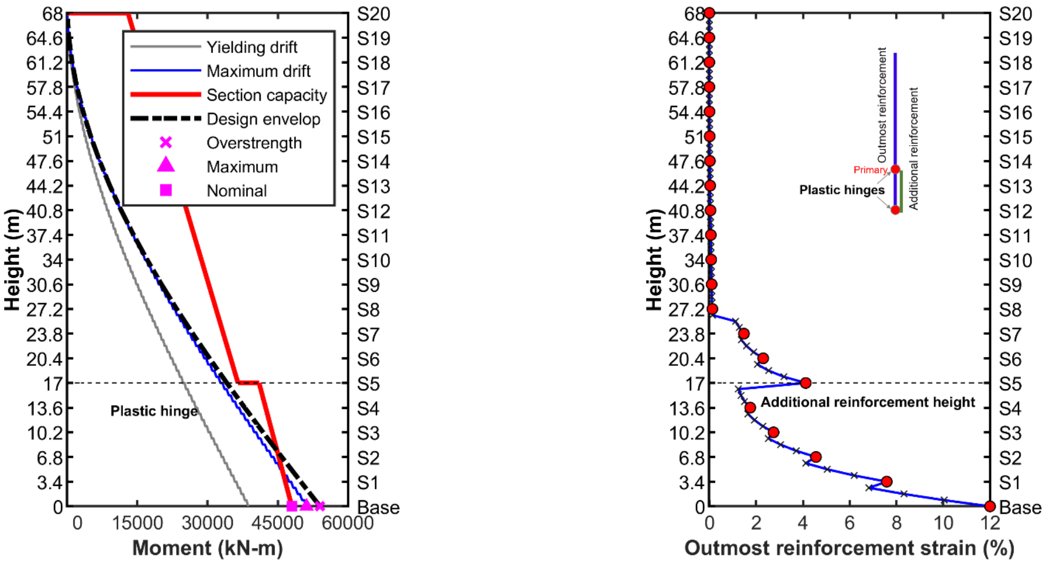
Figure 10: Rein-AR3 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

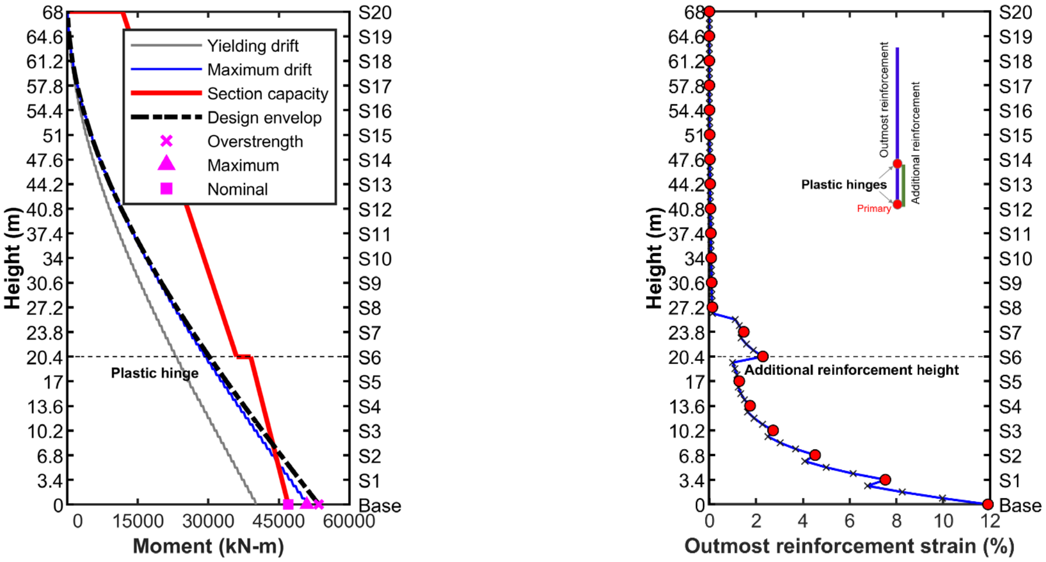
Figure 11: Rein-AR4 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

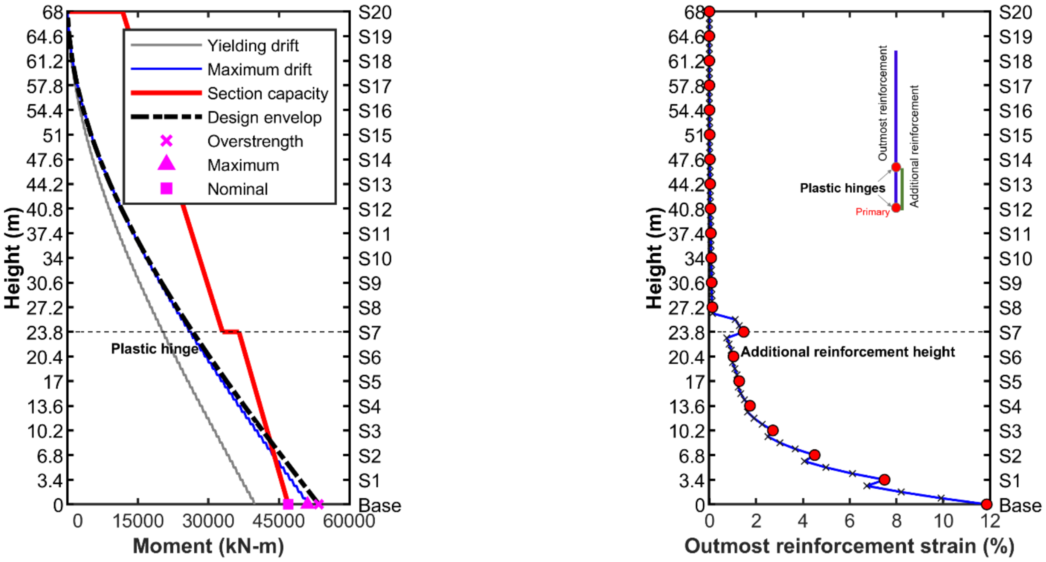
Figure 12: Rein-AR5 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

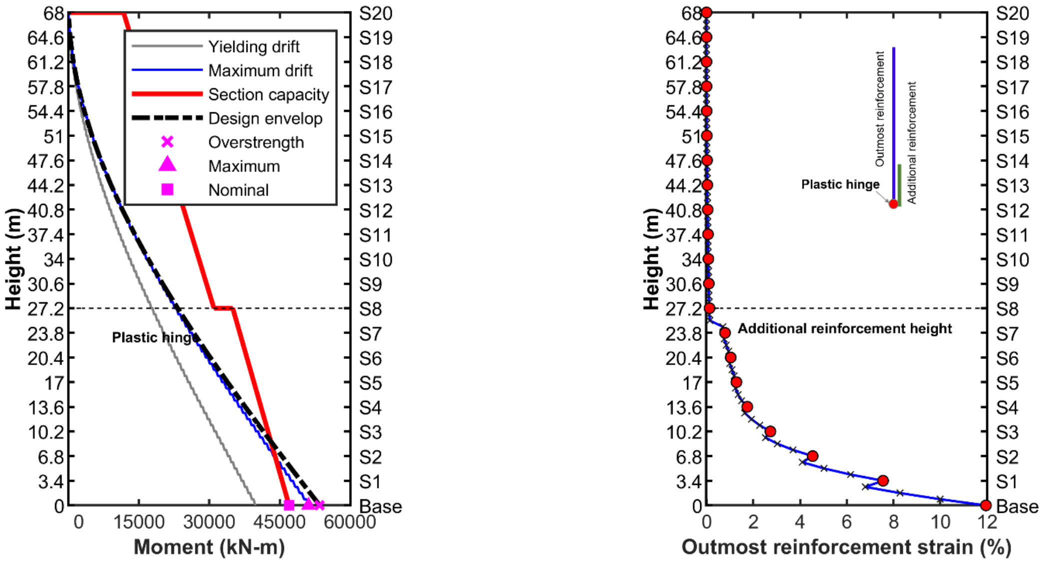
Figure 13: Rein-AR6 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

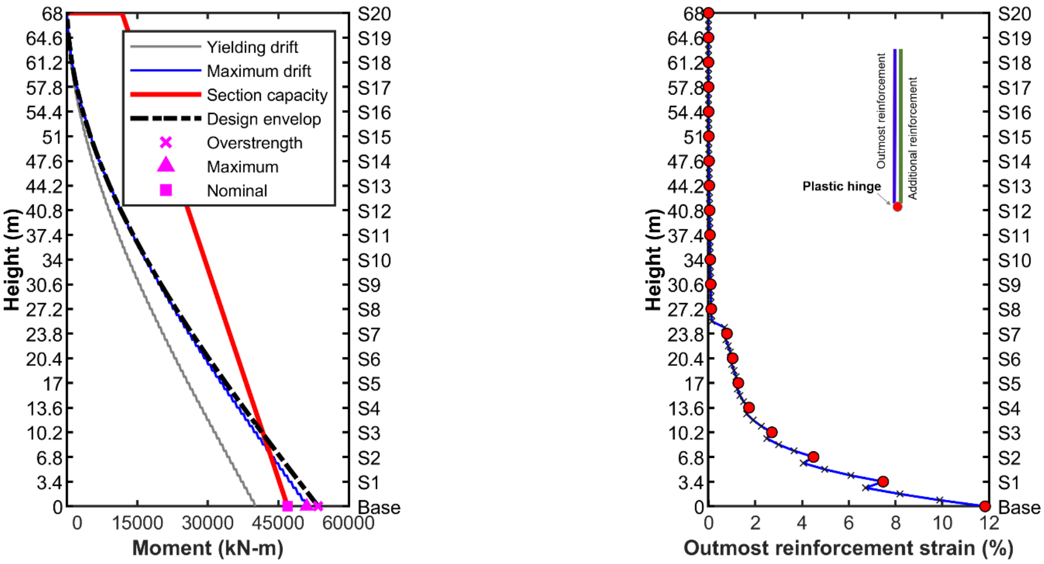
Figure 14: Rein-AR7 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

Figure 15: Rein-AR8 wall height performance



(a) Moment demand and capacity profile

(b) Outmost reinforcement strain profile at maximum drift

Figure 16: Rein-AR20 wall height performance

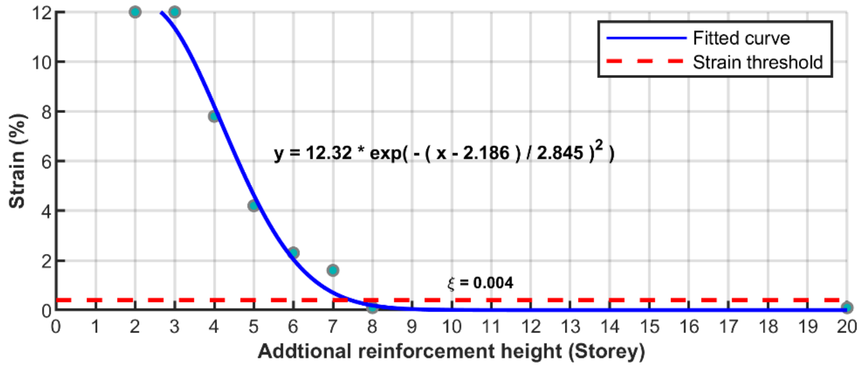


Figure 17: Outmost reinforcement strain at additional reinforcement termination height

4 CONCLUSIONS

The sensitivity of the termination height for additional vertical reinforcement was investigated for the lightly reinforced concrete tall walls designed with the minimum reinforcement requirement in ACI 318-19 (ACI Committee 318, 2019). Preliminary finding from the numerical study are summarized as follows:

- The walls designed with the insufficient additional reinforcement height probably formed a second plastic hinge at the termination height that not conforming to the assumed single plastic hinge design in ACI 318-19 and NZS 3101:2006.
- The greater nominal moment capacity than the required moment demand was not sufficient to prevent the section yielding.
- The minimum additional vertical reinforcement height required in both ACI 318-19 and NZS 3101:2006 appears insufficient to ensure that reinforcement strains are limited at the termination height.

5 ACKNOWLEDGEMENTS

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