Review of Confinement Requirements for the Seismic Design of Rectangular RC Walls in Australia

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Abstract

The majority of low, mid and high-rise buildings in Australia are RC wall buildings, which rely on walls or building cores as the primary lateral load resisting system. The seismic design approach in Australia, like many regions of lower seismicity, typically consists of undertaking a force-based equivalent static or pseudo dynamic analysis method, where inelastic behaviour of the building is indirectly accounted for using force-reduction factors. The force-reduction factors are used to reduce the seismic design actions the structure is designed for under the premise that the earthquake forces acting on the structure are predominantly resisted by inelastic responding elements in the structural system (i.e. strength is being traded for ductility). The Australian standard for concrete structures, AS 3600 provides prescriptive detailing requirements, which if adhered to, should allow a structure to have the required amount of inelastic capacity assumed in the design. This paper will initially provide a summary of the boundary element detailing requirements (i.e. confinement steel) in the new 2018 edition of AS 3600. This is followed by a parametric study that was undertaken to assess the effectiveness of confinement reinforcement in RC walls typical of Australian construction practices. The results of the parametric study are then discussed with reference to a series of AS 3600 compliant boundary element reference examples that were developed. The paper concludes with a general discussion on the role of boundary elements and the effectiveness of confinement steel in the context of limited ductile and moderately ductile wall design.

Keywords: reinforced concrete walls, RC walls, confinement of RC walls.

1 Introduction

The majority of low, mid and high-rise buildings in Australia are RC wall buildings, which rely on walls or building cores as the primary lateral load resisting system (Menegon et al. 2017). The seismic design approach in Australia, like many regions of lower seismicity, typically consists of undertaking a force-based equivalent static or pseudo dynamic analysis method, where inelastic behaviour of the building is indirectly accounted for using force-reduction factors. The force-reduction factors are used to reduce the seismic design actions the structure is designed for under the premise that the earthquake forces acting on the structure are predominantly resisted by inelastic responding elements in the structural system. This indirect method for accounting for inelastic behaviour means force-based analysis procedures are largely perceived as elastic design approaches within the design community.

The Australian Concrete Standard, AS 3600 (Standards Australia 2018), specifies a series of ductility classifications (e.g. non-ductile, limited ductile or moderately ductile) that have associated design requirements and varying levels of detailing, which if adhered to, should allow a structure to have a given amount of inelastic capacity. Each of these ductility classifications has a respective force-reduction factor (i.e. R_f) that varies from 1.3 to 4.5 (refer Table 1). This paper will summarise and review current boundary element detailing requirements required by AS 3600 for RC wall sections. The paper presents the results of a parametric study into the effectiveness of the confinement rules in AS 3600 for rectangular walls. The paper concludes with a discussion on alternative methods for assessing whether confinement should be provided in RC walls. The scope of this study is to provide a review and assessment of the specific confinement rules outlined in AS 3600. The authors note that considerable research has been performed in relation to the role of confinement in RC walls and how it effects the ductility and seismic performance (e.g. Wallace and Moehle (1992), Wallace (1994), Kwan and He (2001), Park et al. (2007), Su and Wong (2007), Kuang and Ho (2008) or Welt et al. (2017)). However, this paper focuses on the confinement rules in AS 3600, of which little research has been undertaken.

Table 1: Ductility classes for RC walls in AS 3600.

Ductility class	$\boldsymbol{\mu}$	$\boldsymbol{s_p}$	$\boldsymbol{R_f}$	**Notes**
Non-ductile	1.0	0.77	1.3	No specific seismic detailing of the structure is required.
Limited ductile	2.0	0.77	2.6	The structure is detailed in accordance with Section 14.6 of AS 3600.
Moderately ductile	3.0	0.67	4.5	The structure is detailed in accordance with Section 14.7 of AS 3600.
Fully ductile	4.0	0.67	6.0	The structure is designed and detailed in accordance with New Zealand Standards*.

* when the ductility factor is greater than 3.0 (i.e. $\mu > 3.0$) the structure should be designed in accordance with NZS 1170.5 (Standards New Zealand 2004), NZS 3101 (Standards New Zealand 2006) and the AS 1170.4 (Standards Australia 2007) Hazard Map. Ductility Class E reinforcement, in accordance with AS/NZS 4671 (Standards Australia and Standards New Zealand 2001) must also be specified.

2 Boundary Element Confinement Rules to AS 3600:2018

The Australian concrete structures standard, AS 3600, recently underwent a major revision, which was approved by the committee (i.e. BD-002) and published in 2018. Significant changes to the seismic design and detailing requirements were made in the 2018 edition of the standard. This included the development and inclusion of a new standalone seismic design chapter, namely *Section 14 Design for Earthquake Actions*. Many of the new detailing requirements for RC walls in Section 14 of AS 3600 are summarised and discussed in Menegon et al. (2018b). The confinement rules for RC walls is one of the most significant updates from the 2009 edition of the code. The 2018 version of the code essentially requires the plastic hinge region/s of RC walls in buildings with ductility classifications of limited ductile or moderately ductile to have confinement reinforcement (e.g. closed ligatures or cross-ties). The one major exception however, is low-rise buildings with a limited ductile classification and a total number of stories equal to four or fewer above their 'structural base'. In these buildings, the confinement requirements can be satisfied by providing either 2-N16 vertical bars with an N12 'U' bar or 4-N12 vertical bars with R10 closed ligatures, as shown in Figure 1, where an N12 bar denotes a 12 mm nominal diameter grade D500N bar to AS/NZS 4671 (Standards Australia and Standards New Zealand 2001).

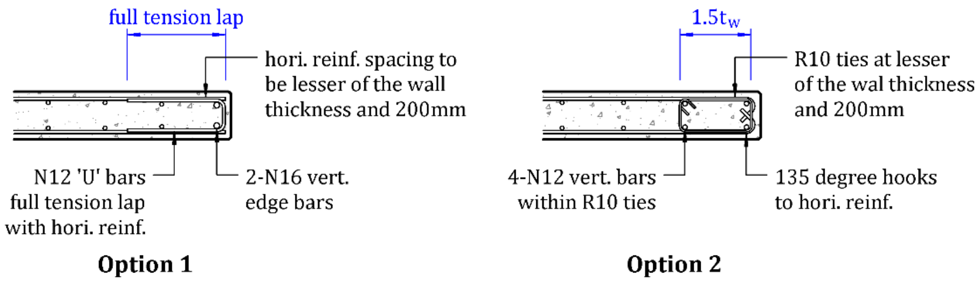


Figure 1: End region detailing for limited ductile walls in RC buildings with not more than four storeys.

It is not clear as to what the 'structural base' of the wall refers to, however a valid interpretation could be: the foundation in low-rise buildings without basements (e.g. ground level); or the storey where the maximum bending moment is resolved in low-rise buildings with basement excavations. This is further illustrated in Figure 2.

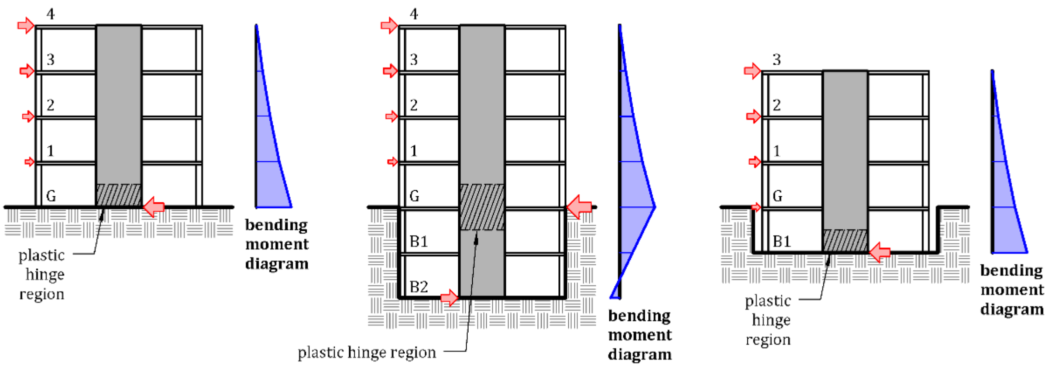


Figure 2: Four-storey limit for simplified limited ductile detailing requirements.

For limited ductile walls (in buildings greater than four storeys), AS 3600 requires any region of the wall with a compressive stress greater than $0.15f_c'$ to have the vertical bars restrained in accordance with Clause 10.7.4. This essentially means every vertical bar, or every second vertical bar if the spacing is 150 mm or less centre-to-centre, has to be restrained with a cross-tie or closed ligature. Further, AS 3600 also requires any region of the wall with a compressive stress greater than $0.2f_c'$ to comply with Clause 14.5.4, which is the confinement requirements for columns in intermediate moment resisting frames.

For moderately ductile walls (in all buildings), AS 3600 requires any region of the wall with a compressive stress to comply with Clause 14.5.4. These requirements for limited ductile and moderately ductile walls are shown in Figure 3.

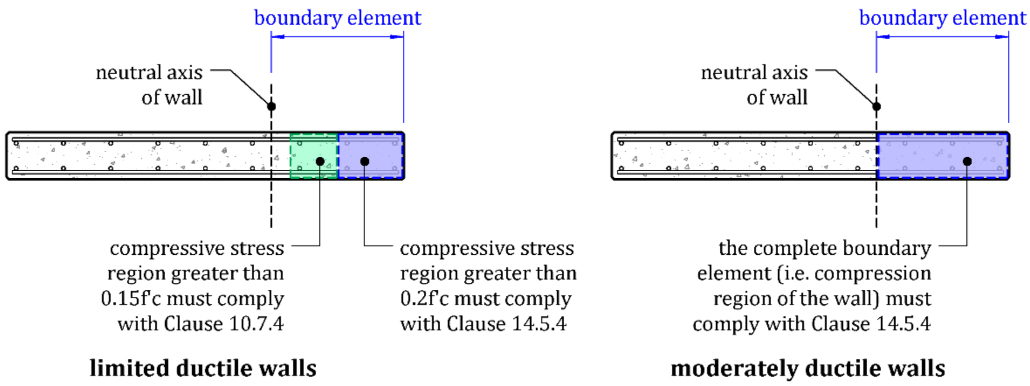


Figure 3: AS 3600 compression regions in limited and moderately ductile walls.

Lastly, if concrete strengths greater than 65 MPa are adopted, confinement to the core wall must be provided in accordance with Clause 14.5.4, regardless of the compressive stress on the wall.

Clause 14.5.4 of AS 3600 outlines the detailing requirements for columns in intermediate moment resisting frames. The following requirements must be met for a wall to comply with Clause 14.5.4:

1. Over a distance of $2L_w$ from the base of the wall, or plastic hinge region, the confinement must consist of closed ligatures only and the first ligature must be a minimum of 50 mm from the face of foundation or support.
2. In regions where the compressive stress is greater than $0.2f_c'$ or the concrete strength is greater than 65 MPa each vertical bar must be restrained by a closed ligature.
3. In regions where the compressive stress is greater than $0.2f_c'$ a minimum effective lateral confining pressure equal to $0.01f_c'$ must be provided to the core of the wall.
4. The area of cross ties or closed ligatures must not be less than $0.5t_w s/f_{sy.f}$, where s is the spacing and $f_{sy.f}$ is the yield stress of the cross ties or closed ligatures.
5. The spacing of cross ties or closed ligatures must not be greater than the lesser of the following:
    a. 8 times the diameter of the smallest vertical bar enclosed.
    b. 24 times the dimeter of the ligature or cross-tie.
    c. Half the thickness of the wall.
    d. One quarter the length of the wall.
    e. 300 mm.

AS 3600 states that the compressive stresses used to assess whether the $0.15f_c'$ or $0.2f_c'$ limits are exceeded "shall be calculated using the design action effects for the strength limit state, a linear-elastic strength model and the gross cross-section properties of the wall". This effectively implies that the stresses should be calculated using the classic engineering statics formula: $\sigma = P/A \pm M/Z$, where $\sigma =$ stress, $P =$ the axial load applied to the wall, $A =$ the gross cross-sectional area of the wall, $M =$ the bending moment applied to the wall from the lateral earthquake actions and $Z =$ the gross section modulus of the wall (i.e. $Z = t_w L_w^2/6$ for a rectangular wall). It should be noted that these compressive stresses are "used as an index value and does not necessarily describe the actual state of stress that may develop at the critical section under the influence of the actual inertia forces for the anticipated earthquake intensity" (American Concrete Institute 2014).

The stress-based method for determining whether boundary elements are required was essentially adopted from the 1995 edition of the American Concrete Code, ACI 318. ACI 318 has since adopted a more precise *displacement-based* design inspired method for determining whether confined boundary elements are required. However, the stress-based method was retained in the 2014 edition of ACI 318 because it is straightforward and easy to use in a design environment, in addition to the fact that it is "conservative for assessing required transverse reinforcement at wall boundaries for many walls" (American Concrete Institute 2014).

3 Parametric Study into the Effectiveness of Boundary Element Confinement

Confinement in RC walls can increase the curvature ductility (i.e. sectional ductility) of an element by providing lateral confinement pressure to the core of the wall, which allows the compressive region of the section to be subjected to larger maximum compressive strains, compared to a typical unconfined cross-section.

A parametric study was performed on rectangular RC wall cross-sections to assess what effect the increasing levels of effective lateral confinement pressures have on the curvature ductility. The parametric study was performed using a non-linear fibre element analysis program developed by authors called WHAM (Menegon et al. 2018a; Menegon et al. 2019b), which can calculate the non-linear moment-curvature response of RC cross-sections. The program can be downloaded free-of-charge from Menegon (2019). The program uses the Mander, Priestley and Park (1988) non-linear stress-strain material model for confined and unconfined concrete.

The parametric study initially included six different variables, which were: wall lengths of 2,000, 3,500 and 5,000 mm; wall thicknesses of 200 and 300 mm; concrete grades N40 and N50 (i.e. 'normal' grade concrete with a characteristic compressive strength of 40 and 50 MPa, respectively), which have mean in-situ compressive strengths (i.e. f_{cmi}) of 42.8 and 53.2 MPa as per AS 3600; axial load ratios of 0.00, 0.04, 0.08, 0.12, 0.16 and 0.20 (where axial load ratio is taken as $N^*/(A_g f_{cmi})$); and vertical reinforcement ratios of approximately 1.1% and 2.1%. This resulted in 144 different wall cross-section combinations. A typical wall cross-section is shown in Figure 4. Each different wall cross-section was analysed with a 'baseline' effective lateral confinement pressure of 0.3 MPa and then subsequently re-analysed with increasing effective lateral confinement pressures of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 MPa. The baseline cross-section was analysed with an effective lateral confinement pressure of 0.3 MPa since it was shown using experimental validations by Menegon (2018) that walls typical of Australian construction practices, which have horizontal reinforcement at spacings approximately equal to the wall thickness and fully developed/lapped 'U' bars at the ends of the wall, have approximately this nominal level of effective confinement.

A bilinear approximation of each non-linear moment-curvature response was determined (as illustrated in Figure 4), which allowed the cross-sections curvature ductility to be calculated, i.e. $\mu_\phi = \phi_u / \phi_y$. The bilinear approximation was determined by taking a line from the origin through the point of first yield, which was taken as the point when yielding of the extreme tensile reinforcing bar occurs or when a compressive strain of 0.2% is reached, whichever occurs first. A horizontal line to the ultimate point was then assumed. The ultimate point was taken as per the recommendations of Priestley, Calvi and Kowalsky (2007) / Sullivan, Priestley and Calvi (2012) for the 'no collapse' performance objective. This results in a maximum tensile reinforcement strain of 4.5% for grade D500N reinforcement (i.e. $\varepsilon_{su} = 0.9 \times 0.05 = 0.045$) and Equation 1 for the maximum compressive strain of concrete. Grade D500N is deformed ribbed reinforcement with a characteristic yield strength of 500 MPa, as per AS/NZS 4671 (Standards Australia and Standards New Zealand 2001).

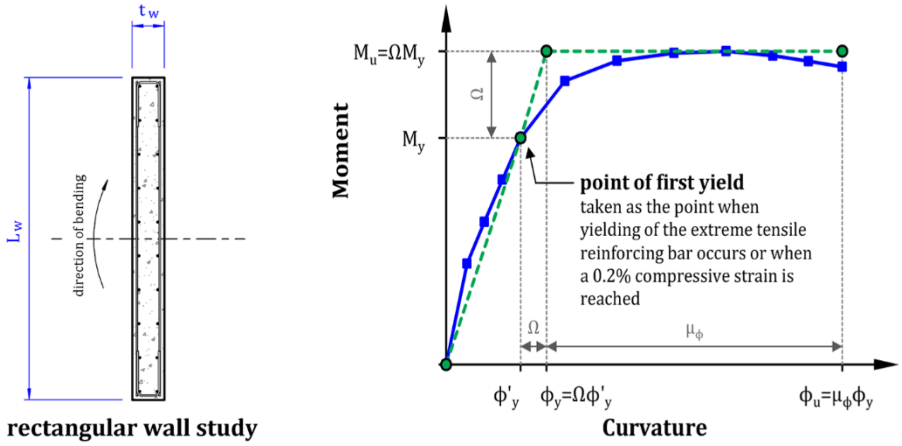


Figure 4: Parametric study specimen and bilinear approximation.

$$\varepsilon_{cu} = 1.5 \times \left(\min \left[0.004 + \frac{1.4 \rho_v f_{sy.f} \varepsilon_{su.f}}{f'_{cc}} \;\; ; \;\; 0.02 \right] \right) \qquad \ldots 1$$

Where: ρ_v = volumetric ratio of confinement steel

$f_{sy.f}$ = yield stress of confinement steel

$\varepsilon_{su.f}$ = ultimate strain of confinement steel

f'_{cc} = confined concrete strength

The confined concrete strength (i.e. f'_{cc}) in Equation 1 was determined using the Mander et al. (1988) model (refer Equations 2 to 4 below), since this concrete model is adopted in WHAM.

$$f'_{cc} = K f'_c \qquad \ldots 2$$

$$K = 2.254 \sqrt{1 + \frac{7.94 f_L}{f'_c}} - \frac{2 f_L}{f'_c} - 1.254 \qquad \ldots 3$$

$$f_L = 0.5 k_e \rho_v f_{sy.f} \qquad \ldots 4$$

Where: f_L = effective lateral confinement pressure

k_e = confinement effective coefficient

= 0.5 for walls (Priestley et al. 2007)

By combining Equations 1 through 4, Equation 5 can be derived, which provides the ultimate confined concrete compressive strain as a function of the effective lateral confinement pressure. This is advantageous since the effective lateral confinement pressure is a primary variable for the parametric study. The ultimate compressive strains determined using Equation 5 for the different concrete grades assumed in the parametric study are summarised in Table 2.

$$\varepsilon_{cu} = \min \left[0.006 + \frac{0.42}{f'_c\left(2.254\sqrt{\frac{1}{f_L^2}+\frac{7.94}{f'_c f_L}}-\frac{2}{f'_c}-\frac{1.254}{f_L}\right)} \; ; \; 0.03 \right] \quad \ldots 5$$

To assess the effectiveness of boundary element confinement, the increase in curvature ductility was determined as a ratio of the curvature ductility of the 'confined' cross-section (μ'_ϕ) where the lateral confinement pressure was $\geq$ 0.5 MPa, divided by the curvature ductility of the 'baseline' cross-section (μ_ϕ), i.e. μ'_ϕ/μ_ϕ.

Table 2: Ultimate compressive strain limits.

Concrete grade	**Effective lateral confinement pressure, f_L (MPa)**					
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**
N40	0.0105	0.0145	0.0180	0.0212	0.0241	0.0268
N50	0.0097	0.0130	0.0160	0.0187	0.0213	0.0236

Note: these values are determined using Equation 5.

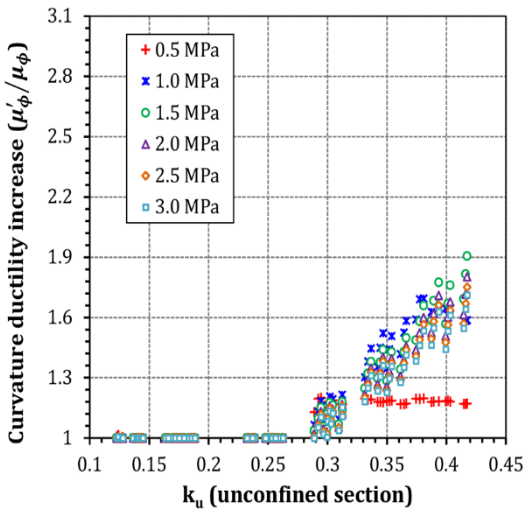
There are essentially two main types of flexural failure modes for an RC element. The first is a compression-controlled mechanism where the ultimate capacity of the section is constrained by the compressive strains in the extreme compressive fibre, and similarly, the second is a tension-controlled mechanism where the ultimate capacity of the section is constrained by the tensile strains in the extreme tensile reinforcement bar. Typically, walls with a tension-controlled mechanism will have a greater curvature ductility than walls governed by a compression-controlled mechanism, given all else is equal. Providing confinement in a compression-controlled wall can increase the curvature ductility, but only up to a value corresponding to the wall switching from a compression to tension-controlled mechanism. Hence continuously increasing the effective lateral confinement pressure by adding additional confinement steel does not continuously increase the curvature ductility indefinitely, and in the case of a tension-controlled wall, can result in no increase at all. This was observed in the results of the parametric study.

The increase in curvature ductility (i.e. μ'_ϕ/μ_ϕ) for the different effective lateral confinement pressures used in the parametric study are presented in Figures 5(a) and 5(b). The values are presented with respect to the k_u ratio for the corresponding 'baseline' cross-section. The k_u ratio is equal to the depth to the neutral axis of the section (d_n) at the ultimate state, divided by the length of the wall (L_w). Figures 5(c) and 5(d) then present the same data, however the data points have been separated based on the axial load ratio (n), as opposed to effective lateral confinement pressure.

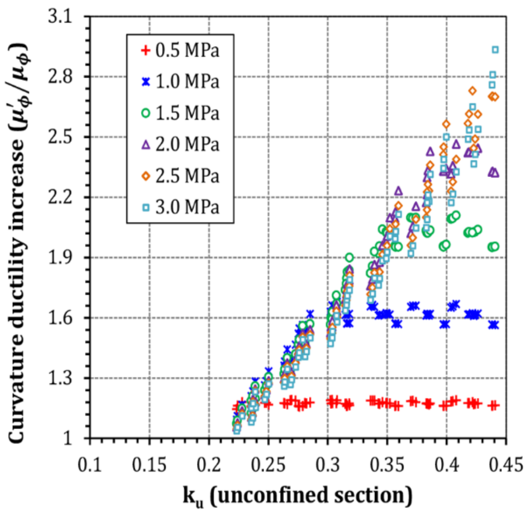
Figures 5(a) and 5(b) suggests that increasing the effective lateral confinement pressure (i.e. providing confinement steel) has no effect on the curvature ductility for walls with a k_u ratio less than about 0.2 and 0.25 for vertical reinforcement ratios of 2.1% and

1.1%, respectively. Further, for the more moderately reinforced sections (i.e. p_v~1.1%), when the k_u ratio was greater than about 0.25, and a compression-controlled mechanism was typically observed in the 'baseline' section, the maximum increase in curvature ductility was observed once an effective lateral confinement pressure of 1.0 MPa was provided. However, for the more heavily reinforced sections (i.e. p_v~2.1%), much higher effective lateral confinement pressures needed to be provided to observe the maximum increase in curvature ductility.

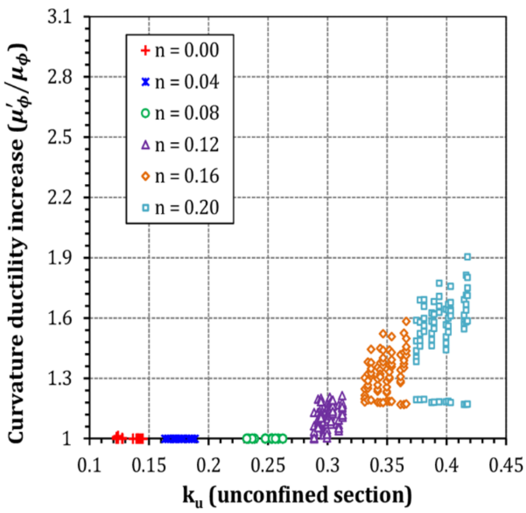
Figures 5(c) and 5(d) clearly show that increasing the axial load ratio increases the k_u ratio of the section, which is to be expected. These figures suggest that for walls with a modest axial load ratio less than around 0.10, which would be the case for a lot of walls in real buildings (Menegon et al. 2017), and moderate to low reinforcement ratios (i.e. $p_v \leq 1.1\%$), providing additional lateral confinement steel results in little or no benefit to the overall curvature ductility of the element.



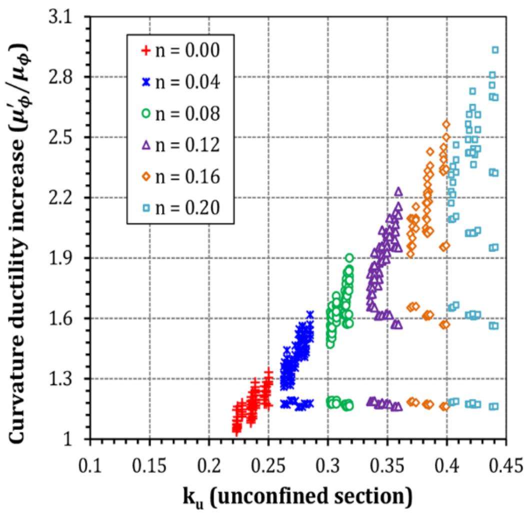
(a) p_v~1.1% (data separated by effective lateral confinement pressure)



(b) p_v~2.1% (data separated by effective lateral confinement pressure)



(c) p_v~1.1% (data separated by axial load ratio)



(d) p_v~2.1% (data separated by axial load ratio)

Note: k_u is the ratio of the neutral axis depth to the wall length at the ultimate performance.

Figure 5: Parametric study results – curvature ductility increases with varying effective lateral confinement pressures.

4 Effective Lateral Confinement Pressure of AS 3600:2018 Boundary Elements

The boundary element rules in AS 3600 are not based on providing a given amount of effective lateral confinement pressure, but rather, are prescriptive requirements, as outlined previously in the paper. A standard detail, which complies with these prescriptive requirements, was developed for two scenarios: **scenario 1**, where the vertical bar spacing is greater than 150 mm; and **scenario 2**, where the vertical bar spacing is less than or equal to 150 mm. The standard detail is shown in Figure 6.

Four reference examples were developed for each scenario with different wall thicknesses and reinforcement configurations, thereby resulting in a total of eight reference examples. These eight examples are summarised in Table 3. The examples were developed such that they complied with the 'minimum requirements' of AS 3600. The effective lateral confinement pressure for each reference example was calculated and summarised in Table 3.

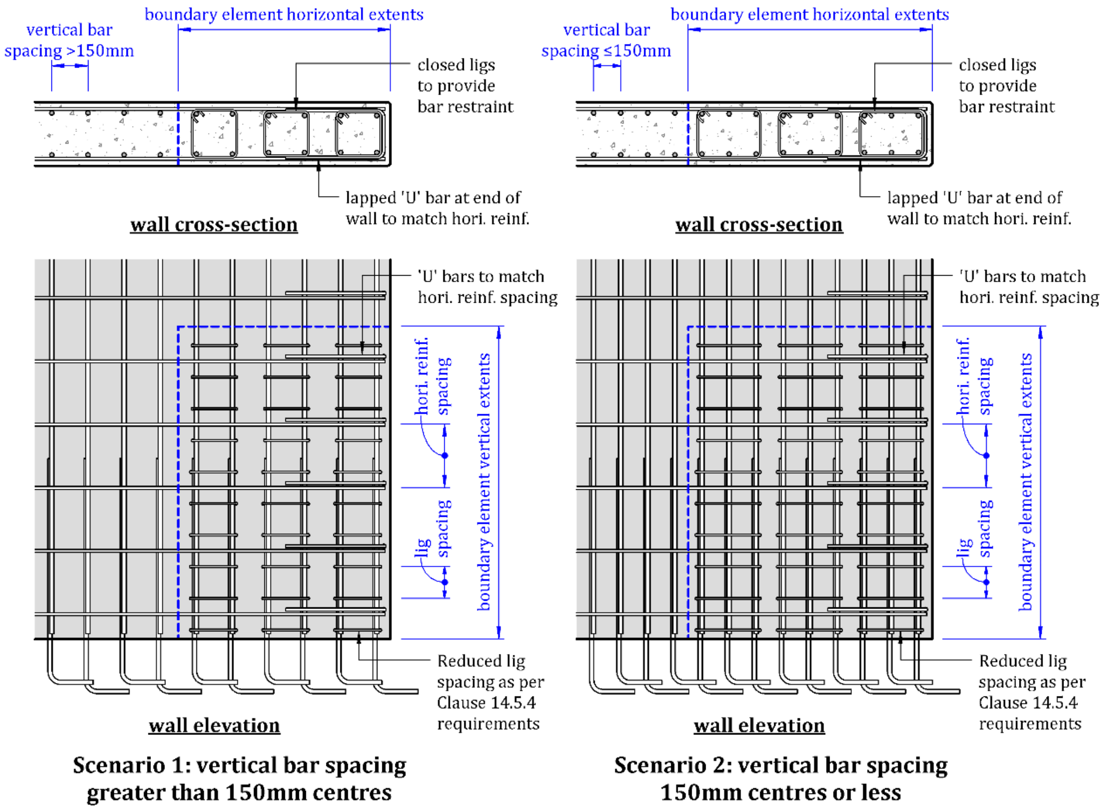


Figure 6: Four-storey limit for simplified limited ductile detailing requirements.

The reference examples were selected to keep the horizontal reinforcement ratio between 0.0025 to 0.0040 and the vertical reinforcement ratio between 0.013 to 0.017 for scenario 1 and 0.010 to 0.013 for scenario 2. The ligature size was selected to meet the minimum requirements, which is dependent on the size of vertical bars.

Table 3 shows that an effective lateral confinement pressure of 0.8 MPa or greater was achieved for each scenario. A confinement pressure of 1.0 MPa or greater was shown in the previous section to be higher enough to ensure a tension-controlled mechanism could develop, which allows for the maximum curvature ductility of the section to be utilised, in walls with a vertical reinforcement ratio of approximately 1.1%. This suggests the AS 3600 boundary element rules may likely be sufficient to ensure tension-controlled mechanisms are developed in low to moderately reinforced walls. However, for higher reinforcement percentages, it seems the AS 3600 boundary element requirements are not sufficient enough to ensure the maximum curvature ductility of a section can be utilised, for moderate to high k_u ratio sections.

If the boundary element requirements were broadly refined such that all ligatures had to be a minimum of an N10 bar size, then the effective lateral confinement pressures for the references examples in Table 3 would increase from 0.80–1.29 MPa to 1.38–3.29 MPa. Considering the results of the previous section, this increase would allow the majority of walls to be able to utilise their maximum curvature ductility available. A requirement of this nature, results in some of the reference examples having very high confinement pressures around 3 MPa, which would likely be unnecessary. Further research is recommended to develop and propose refined boundary element requirements that allow the maximum curvature ductility of a section to be utilised.

Table 3: Ductility classes for RC walls in AS 3600.

Ref.	t_w **mm**	$d_{b,v}$	s_v **mm**	$d_{b,h}$	s_h **mm**	d_f	s_f **mm**	f_L **MPa**
1	200	N16	150	N10	200	R6	100	1.25
2	200	N16	200	N10	200	R6	100	1.29
3	250	N20	150	N12	250	R6	125	0.99
4	250	N20	200	N12	250	R6	125	1.02
5	300	N20	150	N12	300	R8	150	0.80
6	300	N20	200	N12	300	R8	150	0.84
7	350	N24	150	N16	350	R10	175	1.01
8	350	N24	200	N16	350	R10	175	1.07

[1] The rows coloured **blue** denote scenario 1 and **red** denote scenario 2.
[2] N10, N12, N16, N20 and N24 denotes 10, 12, 16, 20 and 24 mm nominal diameter grade D500N deformed bars with a characteristic yield stress of 500 MPa to AS/NZS 4671.
[3] R6, R8 and R10 denotes 6, 8 and 10 mm nominal diameter grade R250N round bars with a characteristic yield stress of 250 MPa to AS/NZS 4671.
[4] $d_{b,v}$, s_v, $d_{b,h}$, s_h, d_f and s_f denotes vertical bar size, vertical bar spacing, horizontal bar size, horizontal bar spacing, ligature bar size and ligature bar spacing, respectively.

5 Discussion and Concluding Remarks

Boundary elements are provided in the compression region of RC walls to increase the ductility of the element. The confinement reinforcement in boundary elements provides two key functions: the first function is to increase the effective lateral confinement pressure of the core region of the wall, which allows for increased ductility and tension-controlled mechanisms to develop; and secondly, it provides restraint against local buckling of the vertical reinforcement under reversed cyclic loading.

Recent experimental work has shown that the boundary elements of limited ductile RC walls without confinement steel can undergo local tension strains of around 4% before local buckling of the vertical reinforcement occurs on the subsequent reversed load cycle (Menegon et al. 2019a). Limited ductile walls would likely need not develop tensile strains greater than this value to ensure the ductility requirements of the building can be generated (i.e. $\mu = 2$). Moderately ductile walls however, may need to develop higher tensile strains than this to ensure the increased ductility requirements of the building can be generated (i.e. $\mu = 3$). As such, it could broadly be argued that confinement steel is required for moderately ductile walls to prevent local bar buckling and then not required for limited ductile walls.

The parametric study presented within suggests that the effectiveness of lateral confinement pressure (i.e. confinement reinforcement in boundary elements) is highly dependent on the k_u ratio for the section (note: k_u is the ratio of the neutral axis depth to wall length for the ultimate performance point, i.e. $k_u = d_n/L_w$). Confinement steel seemed to have no benefit and did not increase the curvature ductility of the walls with low k_u ratios less than around 0.2. Whereas, confinement steel allows walls with higher k_u ratios greater than around 0.25 to 0.3 to generate a significantly higher amount of curvature ductility.

The results of this study suggest limited ductile walls with small k_u ratios and lapped 'U' bars at the ends do not require additional confinement steel to achieve adequate performance. However, this is only a preliminary investigation and additional research is recommended to further develop rational detailing recommendations based on the k_u ratio of the wall.

6 Acknowledgements

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