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Detailing Provisions to Control Bar Buckling in Ductile RC Walls

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ABSTRACT

Bar buckling in ductile reinforced concrete (RC) walls is a commonly observed failure mode which limits their deformation capacity. To delay this undesirable failure mode in RC walls, most design codes emphasize on restricting the spacing of transverse reinforcement in the plastic hinges of RC walls. On the other hand, past research has shown that bar buckling in RC structures could span multiple tie spacings and the efficacy of transverse reinforcement to restrain bars against buckling is a function of the effective axial stiffness of transverse reinforcement in addition to the spacing of transverse reinforcement. To overcome these design limitations, a new mechanics-based design procedure to control bar buckling in ductile RC walls was recently proposed. In this paper, the newly developed guidelines for designing transverse reinforcement to control bar buckling in RC walls are summarized. Restrictions on both the axial stiffness of the tie legs and spacing of transverse reinforcement along the longitudinal reinforcing bars are proposed to confine bar buckling between the consecutive stirrups. Further, the average cyclic stress-strain response of reinforcing bars is utilized to limit compressive stress degradation in reinforcing bars until the design ductility demands are met.

Introduction

Reinforced concrete (RC) walls with a high shear-span ratio are commonly used as a lateral-load resisting system in structures located in seismically active regions and are susceptible to failure due to compression-dominated failure modes such as bar buckling and concrete crushing when subjected to moderate-to-high seismic excitations. The performance of flexural RC walls during the past earthquakes and laboratory tests have shown the proneness of this structural system to such undesirable compression-dominated failure modes which not only restricts their deformation capacity but also exacerbate the uncertainty associated with their performance in future earthquakes and aftershocks [1-6]. Of these failure modes, buckling of longitudinal bars is one of the most commonly observed failure mode that has been of interest to designers for decades.

Bar buckling results in the reduction of the compressive stress capacity of reinforcing bars and is mainly a result of inferior transverse reinforcement detailing. In a reinforcing bar subjected to monotonic compression, compressive stress degradation can be delayed by limiting the unsupported length of reinforcing bars (also called the buckling length) to less than 6 times the diameter of the longitudinal bar. Therefore, most design codes focus only on restricting the spacing of transverse reinforcement to be less than 6 times the diameter of longitudinal bars. However, this assumption has been based on the pretence that current detailing requirements

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would confine buckling to single tie spacing; on the contrary, the performance of RC structures during the past earthquakes and reported experimental observations have clearly confirmed otherwise. The emphasis of design codes around the world on providing closely-spaced transverse reinforcement to restrict bar buckling in ductile RC walls is evident from Table 1 below.

However, analytical research on bare reinforcing bars [7, 8] and experimental tests on RC walls [6, 9, 10] and their boundary elements [11] have clearly shown that these design provisions are unable to confine bar buckling between two consecutive ties. This allows bars to buckle across multiple tie spacings, thereby increasing the bar slenderness (i.e. buckling length to diameter) ratio and subsequently leading to accelerated stress degradation in the reinforcing bars. This is because bar buckling in RC structures is not just a function of the spacing of transverse reinforcement, as is the basis of current design provisions. In reality, bar buckling is governed by the effectiveness of the tie legs in restraining buckling tendency of the bars which is a function of tie spacing, bar diameter and tie-leg stiffness [7].

Table 1. Summary of transverse reinforcement detailing requirements in some design standards [12].

Design code	**Anti-buckling reinforcement**	
	Spacing (s)	**Area (A_{te})**
NZS3101:2006 [13]	$s \leq \begin{cases} 6d_b \text{ (Ductile plastic regions)} \\ 10d_b \text{ (Limited ductile plastic regions)} \end{cases}$	$A_{te} = \frac{\sum A_b f_y}{96 f_{yt}} \frac{s}{d_b}$
ACI-318 [14]	$s \leq \begin{cases} 6d_b \\ 152.4 \text{ mm} \end{cases}$	Assumes that the confinement reinforcement is adequate. However, recommends minimum diameter of the tie bar.
Eurocode-8 [15]	No specific requirement for anti-buckling	No additional requirement for anti-buckling

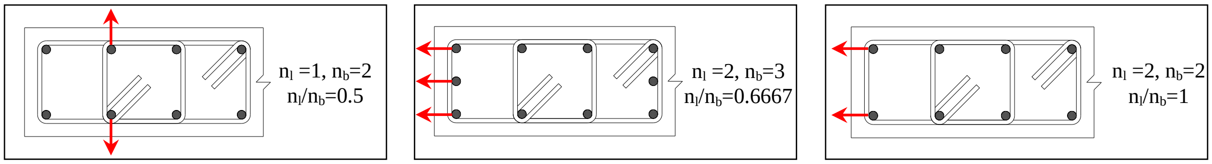
As can be seen in Table-1 above, NZS3101:2006 is the only design code that recommends an expression to estimate the diameter of transverse reinforcement required to restrict bar buckling (i.e. anti-buckling transverse reinforcement). To assess the validity of this provision in NZS3101:2006, it is compared with the results of bar stability model by Dhakal and Maekawa [7] for some typical wall sections. Note that the bar stability model [7] has been verified with a large number of experimental results. It was found that for anti-buckling transverse reinforcement NZS3101:2006 requires the tie diameter to be well below the minimum bar diameter available in the market (i.e. 6 mm), which is well below that required to satisfy the stability criteria [7]. Further, NZS3101:2006 infers that to restrict bar buckling smaller transverse stirrups are required as the spacing is decreased. This holds true for confinement, as with reduced spacing the volumetric transverse reinforcement ratio increases; thereby enhancing both the strength and ductility of the confined concrete and consequently improving the inelastic flexural response of the structure. However, reducing the spacing of transverse reinforcement increases the buckling-induced demands imposed by longitudinal reinforcing bars on the stirrups/ties, therefore requiring larger/stiffer ties to restrain the longitudinal bar buckling within single tie spacing. Therefore, two key objectives of an efficient anti-buckling detailing configuration are; firstly, controlling or restricting the buckling to single tie spacings; and secondly, limiting the compressive stress degradation in reinforcing bars due to buckling until the designed drift demands are met.

This paper presents improved transverse reinforcement detailing requirements to control bar buckling in the plastic hinge regions of ductile RC walls. The key objectives of this study are; (i) scrutinize the current detailing requirements in international design standards; (ii) develop improved detailing requirements to limit bar buckling to single tie spacings; and (iii) avoiding or controlling compressive stress degradation in reinforcing bars until the design drift demands are achieved. This paper provides a summary of the proposed detailing method, and readers are highly recommended to read [12] for detailed background and discussions.

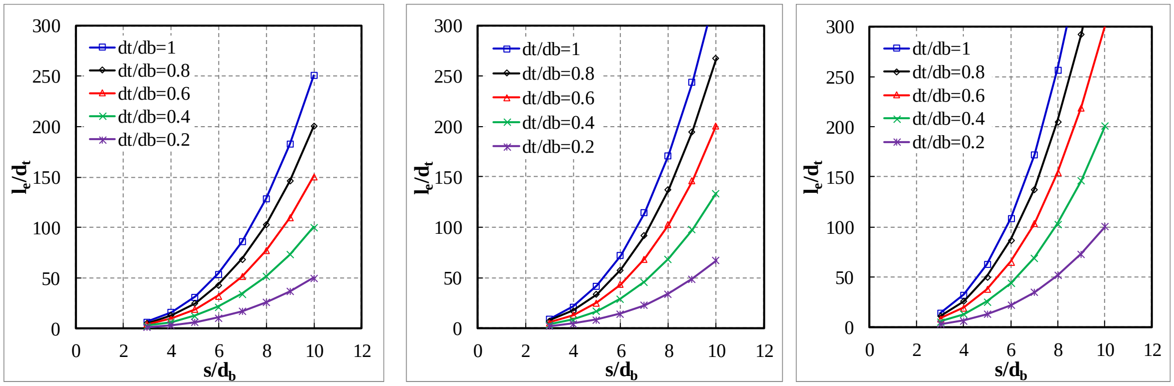
Design of Transverse Reinforcement for Limiting Buckling to Single Tie Spacing

In this study, the bar-stability model proposed by Dhakal and Maekawa [7] was adopted to develop improved guidelines for detailing transverse reinforcement to control bar buckling in RC walls. Dhakal and Maekawa [7] found that the buckling tendency of longitudinal reinforcing bars is not just a function of transverse reinforcing spacing but also a function of the effective lateral stiffness provided by the transverse reinforcement against buckling. Simplifying their analytical formulation, Equation 1 can be derived for the maximum ratio of tie leg length to diameter to ensure that bar buckling is restricted to single tie spacing. The effect of different design parameters in Equation 1 on the tie leg length to diameter ratio is shown in Figure 1. The anti-buckling restraint provided by the transverse reinforcement mainly comes from the axial stiffness of the tie legs. Therefore, to improve the anti-buckling characteristics of the transverse reinforcement, shorter stirrups should be used. Further, increasing the ratio of the number of tie legs (n_l) restraining the buckling prone longitudinal bars to the number of longitudinal bars undergoing simultaneous buckling (n_b) increases the anti-buckling effectiveness of transverse reinforcement. A detailed discussion about the effect of different design parameters on the efficacy of transverse reinforcement to restraint bar buckling is discussed elsewhere in detail [12].

$$\frac{l_e}{d_t} \le \frac{8.7}{\sqrt{f_y}}\left(\frac{s}{d_b}\right)^3\left(\frac{d_t}{d_b}\right)\left(\frac{n_l}{n_b}\right) \tag{1}$$



(a) Case-1, n_l/n_b=0.5 (b) Case-2, n_l/n_b=0.6667 (c) Case-3, n_l/n_b=1.0



(d) n_l/n_b=0.5 (e) n_l/n_b=0.6667 (f) n_l/n_b=1

Figure 1. Variation of the tie leg length as a function of transverse reinforcement spacing to longitudinal bar diameter ratio for Grade 300E reinforcing bars.

Controlling Compressive Stress Degradation in Reinforcing Bars

In the current code-compliant design methodology, it is presumed that compressive stress degradation initiates under the influence of large compressive strains, therefore, in walls, transverse reinforcement is only required in regions subjected to compression yielding. However, previous research on reinforcing bars have shown that bar buckling initiates while unloading from tensile strains and the strain corresponding to the initiation of compressive stress degradation is a function of the bar's slenderness ratio. Hence, it is proposed that the spacing and stiffness of the transverse reinforcement be designed to limit the compressive stress degradation in longitudinal bars at the maximum tensile and compressive strains expected at the limiting curvature. Herein, limiting curvature is defined as the maximum allowable curvature in the plastic hinge regions of the RC structures designed using NZS3101:2006.

To determine the maximum tensile and compressive strains expected at the limiting curvature, a linear strain distribution along the wall length was assumed and the strain range demand (i.e. the difference between the maximum tensile and compressive strains) on reinforcing bars at the limiting curvature was estimated. Further, using the results from bare bar tests, the strain range capacity (i.e. the difference between maximum tensile and compressive strain) that a reinforcing bar can be subjected to without undergoing an unacceptable level of compressive stress reduction was also determined. Thereafter, the strain range demand and capacities were compared and spacing limits for transverse reinforcement for ductile and limited ductile walls were determined. Table 2 below summarizes the strain range demand and capacity for ductile and limited ductile RC walls with Grade 300E and 500E reinforcing bars at the limiting curvature and the recommended maximum allowable spacing of transverse reinforcement. The authors would like to acknowledge that due to space restrictions, only the maximum allowed spacing has been shown in this paper and a detailed comparison of this can be found in Tripathi and Dhakal [12].

Table 2. Strain range demand and capacity at limiting curvature.

300E	**s/d_b**	**$\Delta\varepsilon_d$**	**$\Delta\varepsilon_c$**	**500E**	**s/d_b**	**$\Delta\varepsilon_d$**	**$\Delta\varepsilon_c$**
	Ductile walls				**Ductile walls**		
	6	0.048	0.0501		5.5	0.068	0.0718
	Limited ductile walls				**Limited ductile walls**		
	9	0.027	0.0317		8	0.038	0.0396

Additional Requirements

In the current design methodology, wall web reinforcing bars are often exempt from being restrained against buckling. This is mainly due to the fact that wall web reinforcing bars are never exposed to high compressive strain demands. However, as highlighted before, research on bare reinforcing bars have shown that bars under cyclic loading are subjected to compressive stresses which are in excess of the yield stress while unloading from tensile strains. If these reinforcing bars are not effectively restrained against buckling using anti-buckling transverse reinforcement, they may prematurely buckle resulting in the loss of deformation capacity of the wall. Therefore, it is recommended that all wall web longitudinal reinforcing bars should be restrained using the improved transverse reinforcement detailing proposed herein unless the reinforcing bars are surrounded by thick concrete cover.

Conclusions

Bar buckling in plastic hinge regions of reinforced concrete walls can be controlled by succinctly designing transverse reinforcement that satisfies the following criteria:

1. For a given detailing, the length of the tie legs in the direction of potential buckling shall be less than the critical length evaluated using Equation 1.
2. The spacing of transverse reinforcement along the longitudinal reinforcing bars shall be less than as given by Table 2.
3. All longitudinal reinforcing bars in the potential plastic hinge regions should be effectively restricted against buckling using anti-buckling ties designed using (1) and (2).
4. In the boundary zones, all longitudinal bars (except inner-layer bars located well inside the stirrup perimeter) shall be restrained using anti-buckling stirrup/tie legs.
5. All reinforcing bars in the wall web shall be restrained using anti-buckling ties designed using the proposed detailing requirements unless the bars are well-surrounded by thick concrete cover.

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