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Influence of Structural Parameters on the Buckling of Longitudinal Steel Bar in RC Structural Wall

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Abstract

Reinforced Concrete (RC) structural wall is widely used in multistoried RC frame buildings to enhance lateral stiffness and lateral strength for earthquake resistance. One of the possible failure modes, observed during strong earthquake shaking, is the buckling of longitudinal steel reinforcement in the boundary elements of the wall. This also assumes importance in establishing damage states for seismic fragility analysis of RC wall. Although a few past studies have focussed on longitudinal bar buckling in RC members, detailed parametric study is absent particularly for such instability of bars in the boundary elements of the wall. In the present study, displacement-controlled nonlinear static analysis of several wall specimens is carried out using fibre-discretization of cross-section and distributed plasticity modelling in OpenSEES. Here, 27 different models of the isolated slender wall are created considering variations in six structural parameters, namely (a) length ratio of the boundary element to the wall, (b) axial force ratio, ratios of (c) longitudinal steel in web, and (d) transverse steel and (e) longitudinal steel in the boundary elements. The effect of wall thickness is accounted for through variation in axial force ratio. Using the analytical results from the nonlinear analysis of the wall models, the trends in drift ratio at the onset of longitudinal bar buckling damage states as functions of various key structural wall properties, has been investigated.

Keywords: Cantilever Reinforced Concrete Structural Wall, Boundary Element, Longitudinal Bar buckling, Lateral Drift Ratio

1. Introduction

During the last few decades, earthquake has proved to be one of the most disastrous natural phenomenon which has claimed numerous human lives and valuable properties. Every year around the globe on an average 20 major earthquakes (having magnitude greater than 7) are reported which have had catastrophic effects on the human life. Also the rapid economic growth and the modern urbanisation have led to the concentration of large proportion of the population in relatively smaller urban regions. As a consequence, the construction of the higher and slender reinforced concrete (RC) buildings has significantly increased, in order to meet the demand of accommodating the ever-increasing population. In earthquake-prone areas, the lateral load resisting system of the multistoreyed RC buildings consists of moment resisting frames, supplemented with RC structural wall also known as shear wall, to enhance both the overall lateral strength and stiffness of the building.

Shear wall is a structural element used to resist horizontal forces parallel to the plane of the wall. These walls have high in-plane stiffness and in-plane lateral strength which can be used to simultaneously resist large lateral loads and support vertical loads. These walls are proportioned and designed to resist combinations of shear forces, bending moments and axial forces that are induced in the plane of the wall due to wind, earthquake and other forces. They can also exhibit the desired ductility and energy dissipation capacities, during strong earthquake shaking, with proper detailing of steel reinforcement [1].

In the past, structural walls have been classified based on different criteria. The most common method of classification is based on aspect ratio (ratio of height to length) of the wall. As per IS 13920:2016 [2], the walls with aspect ratio less than 1.0 and more than 2.0 are classified as squat walls and slender walls respectively. And those with aspect ratio in between 1.0 and 2.0 are referred to as intermediate walls. According to the available literature [1, 3], an RC wall may fail in various modes during strong earthquake shaking. Even when designed to meet

codified provisions for tension-controlled response, the most common failure mode for slender flexural structural walls is compression, which includes longitudinal bar buckling (Fig. 1) followed by crushing of core concrete [3]. The predominance of this failure mode is confirmed by post-earthquake reconnaissance.

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Fig. 1. Damage in slender RC walls due to bar buckling [3]

Longitudinal bar buckling in the boundary elements of an RC wall, is also adopted as a key limit state threshold for performing seismic fragility analysis of RC structural walls. For proper establishment of limit state threshold, appropriate interpretation of different damage states in the wall is required. Among the various damage states, buckling of the longitudinal bars in the structural elements demands special attention because this level of damage may result in partial replacement, and a provisional interruption of functionality of the building. In the past, several parametric studies [4–7] have been carried to evaluate seismic response of RC structural walls. But little attention has been paid to investigate the effect of parametric variation of structural wall properties on bar buckling in boundary elements.

The aim of this analysis is to study the effect of changing key structural wall parameters on the initiation of longitudinal bar buckling in the structural walls. The primary wall parameters considered in this study are length ratio of the boundary element to the wall, transverse reinforcement ratio in the boundary element, axial load ratio, the amount of longitudinal web reinforcement, and the amount of longitudinal reinforcement at the confined boundary of structural wall models. A total of 27 number of wall specimens, conforming to IS: 13920-2016, are analysed in this study. The modelling and nonlinear analysis of the RC structural wall specimen are performed in OpenSEES program. The cross-sections of the specimen are discretized into fibres, with the material considered as M25 concrete and Fe500 steel reinforcement. The specimens are subjected to displacement-controlled nonlinear static analysis for evaluation of seismic strength and displacement capacities. Also, for analysis in the current study, all the wall models considered are slender walls, i.e., the aspect ratio is kept constant as 2.

2. Structural Modelling and Material Models

For any detailed structural analysis using finite element method, structural modelling and material models used in the analysis are of utmost importance and require due consideration. This section discusses modelling of the structural component and the material models taken for this study.

2.1 Modelling of Component

In the past, significant research has been carried out on the modelling and design aspect of a structural wall. Analytical and experimental studies have been carried out to simulate the nonlinear behavior of shear wall under static and dynamic loading and different modelling methods have been presented in the literature. Dasgupta [8] categorized the analytical models for the study of RC walls for seismic analysis under two categories namely (a) microscopic models and (b) macroscopic models. In the present study, the Equivalent Frame Model is implemented for modelling of the shear walls, wherein it is modelled as frame elements at the centre line of the wall having the same sectional properties as that of the wall.

2.2 Material Models

In any nonlinear structural analysis, not only the response of the structure at peak loading is important but also the response of the structure over the entire regime of analysis may be important. This is because reinforced concrete structures demonstrate strength degradation during inelastic deformation. Therefore, it is important to select material models that are capable of displaying these properties.

The concrete model selected is Concrete07 which is an implementation of the Chang and Mander's concrete model [9], with the qualitative stress-strain curve shown in Fig. 2. In the figure, E_c is the initial elastic modulus of concrete, f_c and ε_c are the concrete compressive strength and concrete strain at maximum compressive strength, x_n is a non-dimensional term that defines the strain at which the straight line descent begins in compression. f_t, ε_t and x_p are the corresponding values in tension.

As stated earlier, a selected material model should be capable of displaying strength degradation and hysteretic behavior. For reinforcing steel, the strength degradation is due to the buckling of the reinforcement in the region where the concrete has cracked or spalled. The material model for reinforcement is defined by the command SteelMPF. This command is used to construct a uniaxialMaterial SteelMPF (Fig. 3), which represents the well-known uniaxial constitutive nonlinear hysteretic material model for steel proposed by Menegotto and Pinto [10], and extended by Filippou et al. [11] to include isotropic strain hardening effects.

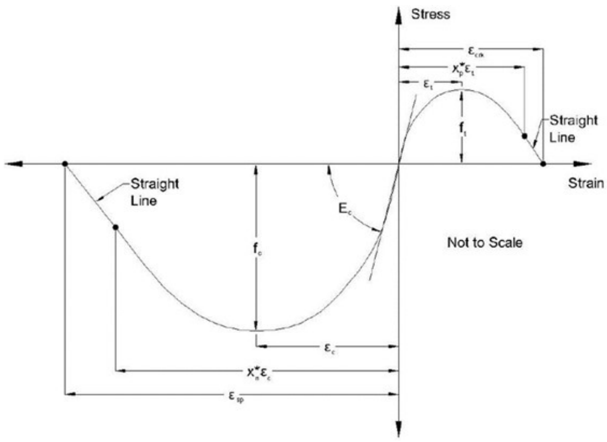

Fig. 2. Concrete07 material model [12]

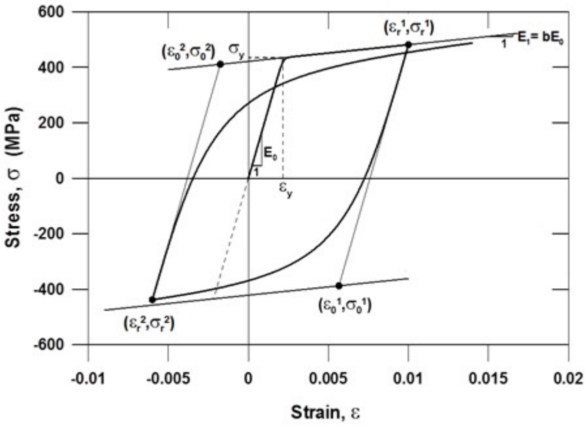

Fig. 3. SteelMPF material model [12]

3. Bar Buckling Strain

In this study, the onset of longitudinal bar buckling in boundary elements is established by observing the attainment of the limiting strain in concrete which is based on past studies on RC elements under compression. The lateral drift ratio at the onset of bar buckling is considered for studying the parametric influence. A comprehensive review of some of the recommendations available in the literature for calculating the critical concrete strain at which the bar buckles, is made. The formulations proposed by Papia and Russo [13], Eberhard and Berry [14], Chai and Elayer [15], Goodnight et al. [16] and Talat and Mosalam [17] are incorporated for identifying the critical bar buckling strain for a particular wall specimen with a given reinforcement ratio. Based on the observation of results obtained, it is concluded that the recommendations proposed by Papia and Russo provide more accurate bar buckling strain as compared to the other alternatives. Thus, in this analysis the bar buckling strain is calculated as per the recommendations of Papia and Russo, whereby the following analytical expression for the calculation of buckling strain of longitudinal reinforcement is suggested. The equations are presented as,

$$\varepsilon_{cr} = \varepsilon_{ho} + \begin{bmatrix} \frac{3}{4}(Logk - 2.5)(\lambda_{\max} - \lambda)^{1.5\lambda^{-\zeta}} \\ + \eta\left(1 - \xi 1.5^{(0.2\lambda - 2)}\right)\left(0.029\lambda^2 - 2.67\lambda + 64\right) \end{bmatrix} 10^{-3} \quad (1)$$

$$\zeta = 0.17\left(\frac{\lambda_{\max}}{54}\right)^{0.75} \quad (2)$$

$$\eta = \left(\frac{345}{f_y}\right)^{0.5} \quad (3)$$

$$\xi = 1 - \left(\frac{f_u}{1.5 f_y}\right)^{0.5} \quad (4)$$

where, ε_{cr} is the strain at buckling stress level in longitudinal bar, ε_{ho} is the strain in longitudinal reinforcement at onset of strain hardening, k is the parameter of transverse stiffness defined as $4\alpha/l$, α is stiffness of hoop, l is moment of inertia, λ is slenderness of the bar hinged between two consecutive supports, and $\lambda_{\max}$ is limiting value of λ under which the strain hardening is achievable.

In this study, the concrete stress-strain results are studied for several locations near the boundary element reinforcement bars. And, it is observed that for all the parametric study the reinforcement bar situated at the extreme location along the length of the boundary wall, reaches the critical buckling strain at an earlier stage as compared to those located at an interior position.

4. Influence of Wall Parameters on Bar Buckling

In the past, several analytical parametric studies were conducted on structural walls to investigate their deformation and strength properties ([6]; [7]). The parameters (variables) of these research studies are evaluated to form the parameter set of this study. A thorough examination of previous studies revealed the following primary parameters, namely (i) ratio of wall cross-sectional area to floor-plan area, (ii) fundamental natural period, (iii) shape of the structural wall cross-section, (iv) axial load ($P/A_g f'_{ck}$), (v) length of the wall, (vi) amount of web reinforcement, (vii) percentage of the transverse reinforcement in the boundary element (ρ_t), (viii) percentage of the longitudinal reinforcement (ρ_b), (ix) confinement of compression zone concrete, (x) aspect ratio (H_w/L) and (xi) configuration in the plan.

In the light of discussion that summarizes the outcomes of the previous parametric research on structural walls, it is decided that the primary variables of the parametric study would be wall length, wall thickness, longitudinal reinforcement ratio at the boundary element, longitudinal web reinforcement ratio and axial load ratio. The influence of the above wall parameters on the longitudinal bar buckling is discussed as follows:

- Ratio of boundary element length to wall length (L_{be}/L): In order to comprehend the effect of changing the wall length to the drift ratio at the onset of longitudinal bar buckling at the boundary element, three different wall models are analysed. All the three wall specimens have a common boundary element transverse reinforcement ratio of 0.32%, longitudinal reinforcement ratio of 1.5% at the boundary element, longitudinal web reinforcement ratio of 1% and axial load ratio of 3%, except the wall lengths which are 2m, 3m and 5m. However, it is observed in the study that the boundary element length has a significant effect upon the buckling strain, so a dimensionless ratio of boundary element length to wall length is assumed as a new parameter. The change in drift ratio at the initiation of longitudinal bar buckling for the different ratios of boundary element length to wall length is shown in Fig. 4.

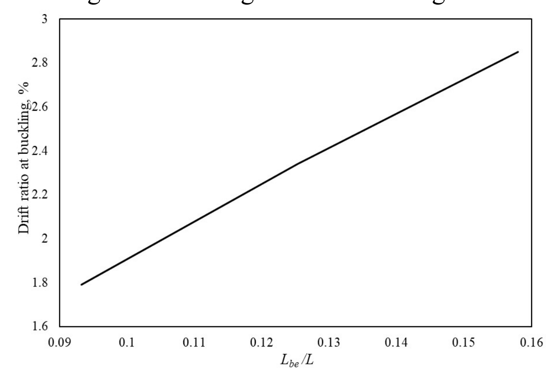

Fig. 4. Comparison of buckling drift ratio for different ratios of boundary element length to wall length

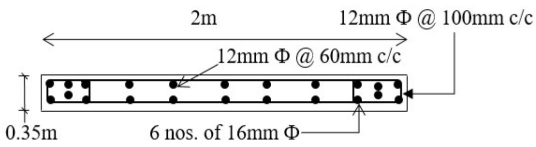

Fig. 5. Reinforcement details of wall specimen analyzed with different axial load ratios

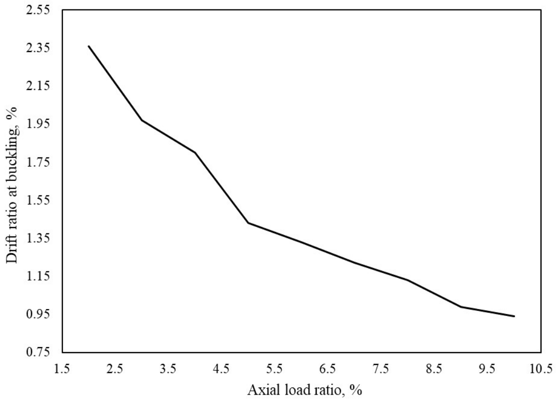

Fig. 6. Comparison of drift ratio at bar buckling initiation for different axial load ratios

Axial load ratio ($P/A_g f'_{ck}$): The common range of axial load ratios in practice with cantilever walls is reported to be in the range $0 \leq P/A_g f'_{ck} \leq 0.15$ for short to medium height buildings [18]. A cantilever shear wall specimen of 2m length, 0.32% boundary element transverse reinforcement ratio, 0.8% longitudinal reinforcement ratio at the boundary element and 1% longitudinal web reinforcement ratio is analysed with different axial load ratios of 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 and 0.1 in order to comprehend the effect of axial load ratio upon the occurrence of bar buckling (Fig. 5). The change in drift ratio at the initiation of longitudinal bar buckling for the different axial load ratios is shown in Fig. 6. It can be inferred from the plot that the occurrence of the longitudinal bar buckling is advanced with the higher axial load ratio, which is the expected tendency because with higher axial load ratio higher is the compressive force on the reinforcement and hence the buckling occurring at an earlier drift ratio.

Longitudinal web reinforcement ratio (ρ_w): Although not considered as an independent parameter in earlier studies, longitudinal web reinforcement ratio appears to be an important parameter affecting response of shear walls. As will be shown in the following discussion, for the walls that have all other variables as common but different longitudinal web reinforcement ratios the deformation characteristics can be quite different. To substantiate the effect of longitudinal web reinforcement ratio upon the occurrence of bar buckling eight different wall specimens having the same wall length of 5m (Fig. 7), boundary element transverse reinforcement ratio of 0.57%, longitudinal reinforcement ratio of 0.8% at the boundary element and axial load ratio of 0.03, but with eight different longitudinal web reinforcement ratio ($0.25\% < \rho_w < 5\%$) are analysed. The change in drift ratio at the initiation of longitudinal bar buckling for the different axial web reinforcement ratios is plotted in Fig. 8.

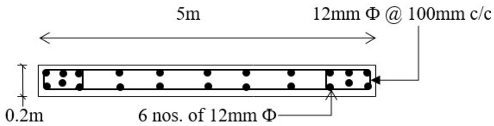

Fig. 7. Reinforcement details of wall specimen analysed with different web reinforcement ratios

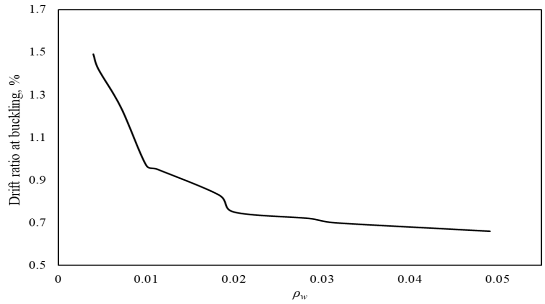

Fig. 8. Comparison of drift ratio at initiation of bar buckling for different web reinforcement ratios

It can be inferred from the plot that the occurrence of the longitudinal bar buckling is advanced as the longitudinal web reinforcement ratio is increased. This essence of bar buckling occurring at an earlier drift ratio with the higher longitudinal web reinforcement ratio can be attributed to the fact that as the web reinforcement ratio is increased, the entire wall section tends to exhibit over-reinforced behaviour. In an over-reinforced section, the concrete segment is subjected to more stress and the cover concrete spalls off at an earlier drift ratio leaving the boundary element bars exposed and thus the boundary element bars buckle at an earlier drift ratio for the section with higher web reinforcement ratio as compared to the lower ones.

Transverse reinforcement ratio in the boundary element (ρ_t): Transverse reinforcement plays an important role in the occurrence of the significant damage states in RC structures, as a result of effective confinement it provides to the core concrete. In order to apprehend the effect of changing the transverse reinforcement ratio in the boundary element to the drift ratio at the onset of longitudinal bar buckling at the boundary element, three different wall models were analyzed. All the three wall specimens had a common wall length of 3m (Fig. 9), longitudinal reinforcement ratio of 0.8% at the boundary element, longitudinal web reinforcement ratio of 1% and axial load ratio of 3%, except the boundary element transverse reinforcement ratio which were 0.28%, 0.44% and 0.64%. The boundary element ties have a same spacing of 100mm c/c for all the three models, but the diameter of the ties used were 8mm, 10mm and 12mm for the three models respectively. The ratio of the ties area to the area of concrete between two consecutive ties is defined as the transverse reinforcement ratio. The change in drift ratio at the initiation of longitudinal bar buckling for the different transverse reinforcement ratio is plotted in Fig. 10. It can be inferred from the plot that the occurrence of the longitudinal bar buckling is delayed with the higher transverse reinforcement ratio, which is expected due to increased confinement of the longitudinal bars. With a higher percentage of the transverse reinforcement provided to the boundary element, the effective confinement of the core concrete achieved is more and thus buckling of longitudinal bars and bulging of core concrete get delayed.

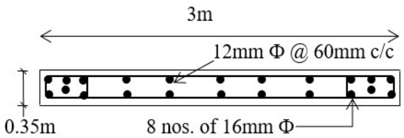

Fig. 9. Reinforcement details of wall specimen analysed with different boundary element transverse reinforcement ratios

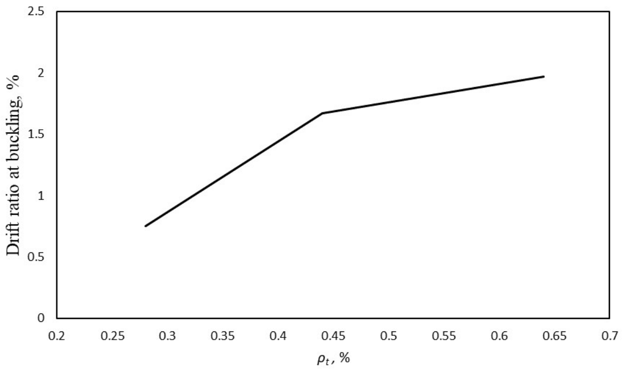

Fig. 10. Comparison of drift ratio at initiation of bar buckling for different boundary element transverse reinforcement ratios

Longitudinal reinforcement ratio at the boundary element (ρ_b): The flexural wall reinforcement ratio, defined as the ratio of total longitudinal steel area (A_{st}) in the boundary element to the area of boundary region, in typical rectangular shear wall sections is in the range of $0.005 \leq \rho_b \leq 0.04$. Three different values of boundary element reinforcement ratios used in this study, namely 0.008, 0.015 and 0.04. A cantilever shear wall specimen of 3m length, 0.32% boundary element transverse reinforcement ratio, 2% longitudinal web reinforcement ratio and 0.03 axial load ratio is analyzed with three different boundary element reinforcement ratio in order to comprehend the effect of boundary element reinforcement ratio upon the occurrence of bar buckling. The change in drift ratio at the initiation of longitudinal bar buckling for the different boundary element reinforcement ratios is plotted in Fig. 11. However, it is observed that the change in boundary element reinforcement ratio does not result in significant variation of drift ratio at which bar buckling occurs. With increase in ρ_b the reinforcement diameter and the number of bars get increased, so the bar buckling is delayed but with the increase in ρ_b. Also, the length of the boundary element is increased leading to poor confinement action and the bar buckling occurs earlier. Thus, the aforesaid nullify each other's influence and ultimately, the variation in drift ratio at bar buckling with change in ρ_b is insignificant.

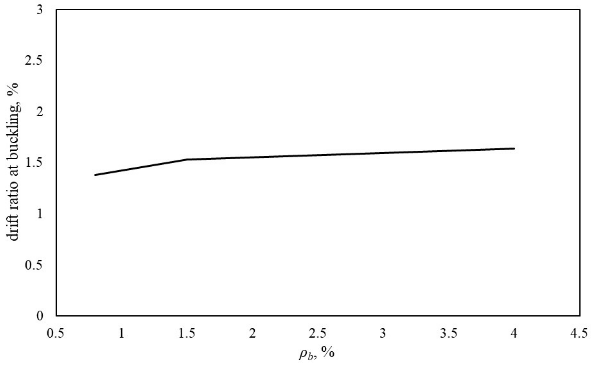

Fig. 11. Comparison of drift ratio at initiation of bar buckling for different boundary element reinforcement ratios

Table 1. Influence of key wall properties considered on drift ratio at bar buckling

	L_{be}/L	$P/A_g f'_{ck}$	ρ_w	ρ_t	ρ_b
Expected	---	Decrease	Decrease	Increase	Increase
Observed	Increase	Decrease	Decrease	Increase	---

5. Conclusions

This study provided insight into the seismic behaviour of isolated cantilever rectangular structural walls and into key components in these walls that could influence their longitudinal bar buckling. While generating seismic fragility functions of these structural walls to assess their vulnerability, the discussed wall parameters should be considered for efficient fragility functions. It is observed that bar buckling gets initiated at an earlier lateral drift ratio with increase in axial load ratio and the vertical steel in the web. With increasing web reinforcement, the effective strain in those bars tends to reduce, thus making the boundary element bars prone to early buckling. However, with increase in the length ratio and transverse reinforcement ratio in the boundary element, the bar buckling tends to get delayed. The present study gives insight in providing parametric limits to prevent longitudinal bar buckling in the boundary elements of the wall. Table 1 summarizes the influence of key wall properties considered on drift ratio at the onset of bar buckling.

Disclosures

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