Effect of Reinforcement Compression Capacity on In-Plane Flexural Behaviour of Slender RC Walls

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ABSTRACT: In a well detailed reinforced concrete (RC) wall subjected to lateral loading, bar buckling is one of the critical and common modes of failure, contributing to premature concrete crushing and failure of the wall. In the current study, the results of a numerical investigation carried out on slender RC walls are summarised and the effect of reduction in compression stress capacity of reinforcement on the overall in-plane behaviour of flexurally dominated shear walls is scrutinized. Nonlinear fibre based analyses of walls are carried out using OpenSees software, with path-dependent cyclic uniaxial constitutive models of concrete and reinforcement fibres. Numerical models are validated by comparing the predicted load-displacement hysteresis with the experimental results available in the published literature. Furthermore, parametric studies are carried out on the validated models to evaluate the effect of compressive capacity of reinforcement and the axial load level on the behaviour of walls. Based on the numerical investigation, the effect of reduction in compressive stress capacity of reinforcement on deformation and energy dissipation capacity of walls is reported. Furthermore, results of numerical investigation on slender shear walls with varying axial load are also reported.

1 INTRODUCTION

Reinforced concrete (RC) shear walls are the prevalent lateral load resisting systems in medium to high rise buildings around the world. The recent earthquakes in Chile and New Zealand (Canterbury) have demonstrated the criticality of RC walls and have highlighted the shortcomings of existing design guidelines. The critical failure modes of RC walls witnessed in these earthquakes include global buckling of walls, buckling of reinforcing bars, crushing of toes of walls, shear failure, etc. Out of these observed failure modes, in RC slender walls failure associated with reinforcement buckling was one of the most widely observed mechanism, which triggered the overall failure of RC walls (Wallace et al. 2012, Sritharan et al. 2014). Buckling of reinforcing bars results in reduction of the compression capacity of reinforcing bars (Dhakal and Maekawa 2002) and is mainly caused due to inferior detailing of transverse reinforcement in RC structures. In a typical RC member, buckling of longitudinal reinforcing bars can span multiple tie spacing's depending on the effective lateral restraint (governed by the spacing and stiffness) of the transverse reinforcement (Dhakal and Maekawa 2002). Contrary to this, currently most design codes emphasise only on the spacing of transverse reinforcement as the major criterion for providing lateral resistance against buckling. The compressive stress degradation due to buckling is generally ignored in the design process by assuming buckling occurring at high compressive strains only, whereas it is evident from the literature that the reinforcing bars, when subjected to cyclic loading, buckle in the tensile strain region while the stresses are compressive in nature (Kashani 2014). This leads to overprediction of the inelastic lateral response of the RC structures in the design phase; thereby potentially leading to weaker and unsafe structures in reality.

RC structures when subjected to lateral loading exhibit cracking, resulting in the net tensile forces to be resisted solemnly by the reinforcing bars with small fraction of tensile forces being resisted by uncracked concrete. When the lateral load is reversed, due to the presence of residual cracks in concrete along with reinforcement elongation, the entire compressive forces need to be resisted by reinforcing bars alone until the cracks close. If these reinforcing bars are not effectively restrained in lateral direction, they will be bound to fail by buckling, followed by the abrupt closure of cracks in the compression region thereby transferring the huge compressive stresses to the concrete; thereby subsequently leading to the crushing of concrete.

In the past decade, numerous experimental and numerical investigations have been carried out to evaluate the performance of RC structural walls under lateral loading, but little information is available about the influence of reinforcement buckling on hysteresis behaviour of RC structural walls. The compressive stress degradation due to buckling results in reduction of compressive resistance of reinforcing bars, thereby leading to increased compressive demand on the concrete to balance the net tensile forces carried by the bars in tension. Furthermore, premature buckling of reinforcing bars in tensile strain domain results in the reduction of energy dissipation capacity of the reinforcing bars. Energy dissipated by a structure under lateral loading is identified as an important parameter in defining the overall performance of the structure under cyclic loading. Due to inherent complexity in RC structures due to the presence of reinforcement and concrete, the energy dissipation capacity of any RC structure can be simplified as the summation of energy dissipated by concrete and reinforcement cyclic responses. Therefore, the premature buckling of reinforcing bars may result in reduction of the overall energy dissipation capacity of the structural walls and hence, influence the lateral performance of the structure.

In this paper, a numerical model capable of predicting the hysteresis behaviour of flexurally dominated slender RC walls is developed and validated against the experimental results from the published literature. The main aim of the present paper is to conceptually demonstrate the effects of compression buckling of reinforcing bars on global behaviour of slender RC walls. Furthermore, the effect of axial load ratio on triggering the early strength degradation in RC walls is also evaluated.

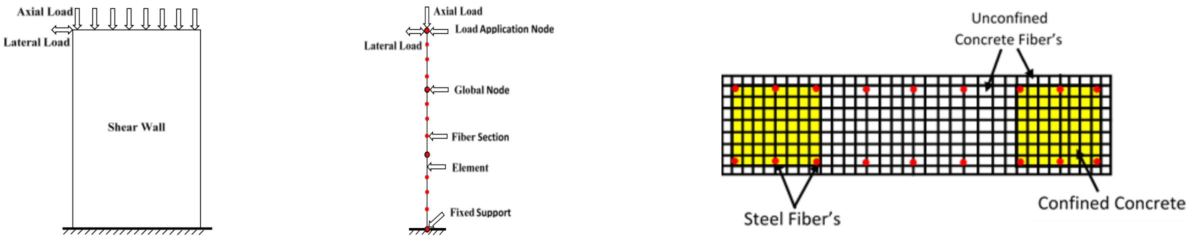
2 NUMERICAL MODELLING AND VALIDATION STUDIES

In the present study, to numerically evaluate the effect of compression capacity of reinforcing bars on the in-plane flexural behaviour of RC slender walls, nonlinear fibre element analysis has been carried out using OpenSees (Mazzoni et al. 2006). In the fibre based analysis, the behaviour of a structural wall is simulated by integrating the local behaviour, i.e. the behaviour of uniaxial fibres (concrete and steel), into the global level. Nonlinear behaviour of uniaxial fibres is simulated using uniaxial path-dependent cyclic constitutive material models. The wall is modelled using series of force based beam-column elements connected at the nodes and fixed at the base, with the axial load and the lateral loads being applied at the top node. Force based beam-column elements are based on flexibility formulations with assumed internal force distribution of constant axial load (Pugh 2012). The entire wall is further discretized into sections containing uniaxial concrete and steel fibres depending upon the geometrical aspect and reinforcement detailing of the RC wall. Figure 1 shows the schematic representation of the numerical modelling strategy used in the present study.

Concrete material model proposed by Chang and Mander (1994) and implemented into OpenSees as ConcreteCM is used for modelling the uniaxial cyclic behaviour of concrete. The compression and tensile behaviour of concrete has a parabolic ascending and descending branch followed by a linear strength degradation (Figure 2a). Confined concrete is simulated through modification of material parameters for ConcreteCM material model using recommendations proposed by Saatcioglu and Razvi (1992), to take into account strength and ductility increment due to lateral confinement. Reinforcement material model proposed by Menegotto-Pinto (Menegotto and Pinto 1973) and modified by Filippou (Filippou et al. 1983), which is available in OpenSees as SteelMPF, is used for modelling uniaxial cyclic behaviour of reinforcing bars. The compressive stress degradation due to buckling is not taken into account in this model. Figure 2 depicts the schematic representation of the uniaxial cyclic behaviour of concrete and reinforcing bars used in the present study. Material regularisation has been carried out to avoid localisation of material response at critical sections and to obtain objective global response Coleman and Spacone (2001).

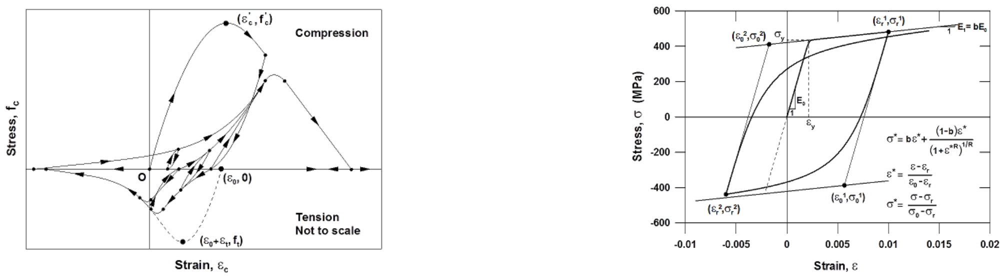
2.1 Validation studies

In order to validate the efficacy of the numerical model, three slender shear walls from the published literature are adopted and nonlinear fibre analyses are carried out for these three walls. The selection of walls is carried out to only include walls with in-plane flexural modes of failure. The material properties for concrete and steel are adopted from the experimental test results, or are calculated based on simplified assumptions from the literature. The wall is modelled using two nonlinear/force based beam column elements connected at the nodes and fixed at the base. The section is discretized into uniaxial concrete and steel fibres with cell dimensions of 6.5x6.5 mm. The analysis of walls is carried out in series of steps starting with uniform steady application of the axial load, followed by the displacement controlled loading history as applied in the tests. The numerical model is validated by comparing the base shear versus lateral drift response of shear walls obtained from the test results with the numerical predictions.



(a) Schematic representation (b) Fibre element modelling (c) Typical fibre section

Figure 1. Schematic representation of non-linear fibre element modelling in OpenSees

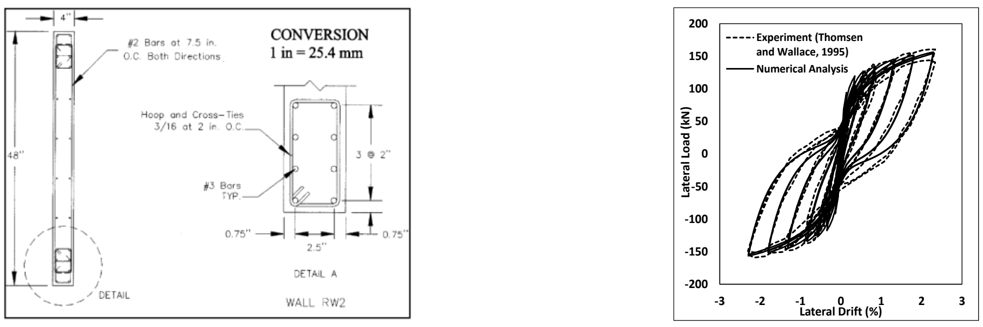


(a) Concrete material model (b) Reinforcement material model

Figure 2. Uniaxial constitutive material models used in numerical analysis (Mazzoni et al. 2006)
Shear wall specimen- RW2

2.1.1 *Shear wall specimen- RW2*

Specimen RW2 was tested by Thomsen and Wallace (1995) to evaluate the effect of boundary zone transverse reinforcement detailing on performance of RC shear walls. A constant axial load of $0.07A_gf_c$ was initially applied to the wall before the application of lateral loading. The wall was flexurally dominated with a high shear span ratio of 3. The ultimate failure of the wall was observed due to buckling of boundary zone reinforcing bars at 2.5% drift. Figure 3 shows the geometrical aspects and reinforcement detailing, along with the comparison of hysteresis behaviour of specimen RW2 obtained from the experiment and numerical analysis. From the comparison of load versus drift plot it's clear that the numerical model is capable of predicting the overall hysteretic behaviour of RC wall with reasonable accuracy until the bar buckling induced failure occurred at 2.5% drift.

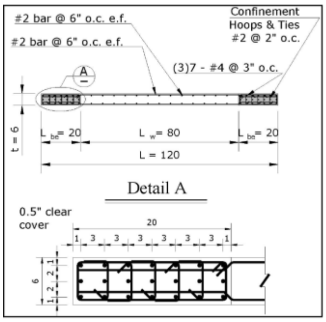


(a) Shear wall layout (Thomsen and Wallace 1995) (b) Comparison of hysteresis response

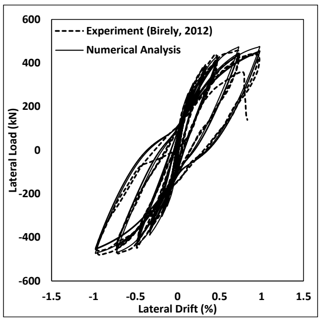
Figure 3. Shear wall layout and comparison of hysteresis behaviour of shear wall

2.1.1 *Shear wall specimen- PW4*

Specimen PW4 was tested by Birely (2012) to evaluate the seismic behaviour of RC walls with varying longitudinal reinforcement detailing and lateral loading. A constant axial load of $0.12A_gf_c$ was applied to the wall before the application of lateral loading. The reversed cyclic loading was applied in a way to keep the ratio of lateral load to the overturning moment constant and thereby generating base shear equivalent to a 10 storey RC shear wall. This effect is undertaken in the numerical analysis by providing an additional elastic element over the height of the tested specimen with displacement history being applied at the top of the elastic element, thereby keeping the ratio of base shear to overturning moment as constant throughout the analysis. In other words, the overturning moment and the base shear applied in the tests was applied in the analysis by increasing the height of the model. The ultimate failure of the specimen was observed due to buckling of reinforcing bars followed by crushing of concrete during the third cycle of 1.0% drift, thereby leading to sudden drop in the overall capacity of the RC wall. Figure 4(a) shows the geometry and reinforcement detailing of specimen PW4. Figure 4(b) shows the comparison of hysteresis behaviour of shear wall specimen PW4. From Figure 4(b) it is evident that the numerical model is capable of simulating the overall hysteretic behaviour of this specimen with reasonable accuracy. However, the loss in lateral load carrying capacity due to premature buckling of reinforcing bars is not captured by the model.



(a) Shear wall layout (Birely 2012)

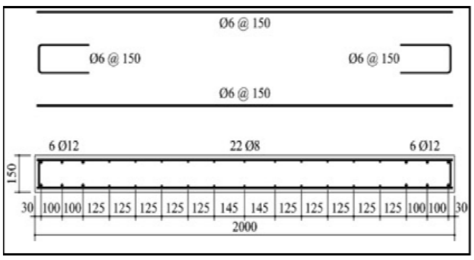


(b) Comparison of hysteresis behaviour

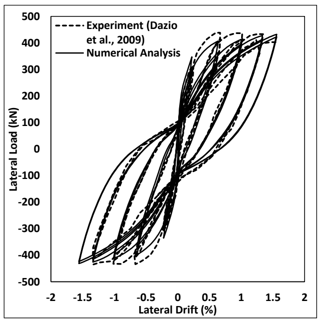
Figure 4. Shear wall layout and comparison of hysteresis behaviour of shear wall PW4

2.1.2 *Shear wall specimen WSH4*

Specimen WSH4 was tested by Dazio et al. (2009) to experimentally evaluate the effect of reinforcement detailing and its ductility on the behaviour of RC shear walls. A constant axial of $0.057A_gf_c$ was applied to the wall before the application of lateral loading. The wall WSH4 differs from the other two walls (RW2 and PW4) in terms of the boundary zone confinement reinforcement. The ultimate failure of specimen WSH4 was due to buckling of reinforcing bars followed by crushing of unconfined concrete in the compression zone. Figure 5(a) shows the geometry and reinforcement detailing of specimen WSH4. Figure 5(b) shows the comparison of hysteresis behaviour of shear wall specimen WSH4. From Figure 5(b) it is evident that the numerical model is capable of simulating the overall hysteresis behaviour of this specimen with reasonable accuracy but, lacks in predicting the loss in lateral load carrying capacity due to rebar buckling that was observed in the test.



(a) Shear wall layout (Dazio et al. 2009)



(b) Comparison of hysteresis behaviour

Figure 5. Shear wall layout and comparison of hysteresis behaviour of shear wall WSH4

The results presented and discussed in the above section clearly demonstrate the efficacy of the numerical model in predicting the lateral response of flexurally dominated RC walls, with the limitation of capturing the failure associated with bar buckling.

3 PARAMETRIC STUDY OF SLENDER SHEAR WALL

Repeated experimental tests to investigate the effect of all the parameters influencing the behaviour of a typical RC wall are overly demanding (both in terms of time and resources). Hence, numerical investigations are carried out in this study to conduct parametric studies on the validated numerical models to evaluate the effect of reinforcement axial compression capacity and axial load on the behaviour of slender RC walls.

3.1 Effect of axial compressive capacity of reinforcement on hysteresis behaviour of slender walls

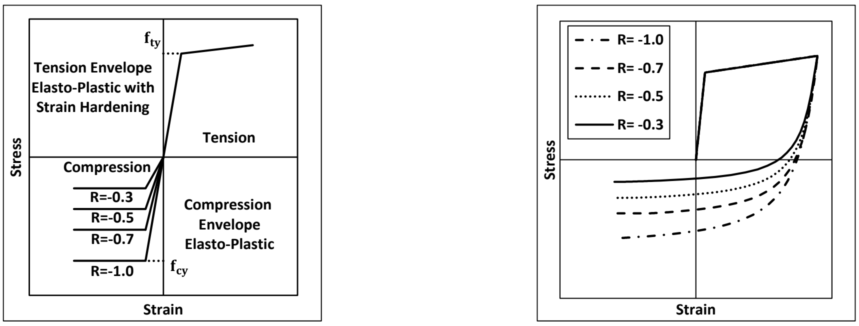
The buckling of reinforcing bars in RC structures has been long recognised as one of the limit states resulting in reduction of axial compression capacity of the reinforcing bars. The major issues related to buckling of reinforcing bars in RC walls lie around the premature buckling of reinforcing bars within the tensile strain region. Reinforcement buckling under cyclic loading results in reduction of compressive yield strength of the rebar, which can reduce to as low as 20% of yield strength of the unbuckled rebar (Dhakal and Maekawa 2002). The amount of reduction in the compression capacity and the strain corresponding to it depends upon the slenderness ratio (L/D) (i.e. ratio of the buckling length to the diameter of reinforcing bar) and the yield strength. Due to the limitation of the current model in capturing the buckling of reinforcing bars, the reduction in compression capacity was implicitly accounted for in the numerical model by modifying the compression behaviour of reinforcing bars. The compression behaviour was defined using an elasto-plastic envelope curve in compression, with cyclic rules being defined using asymptotic curves proposed by Menegotto-Pinto. A total of four different cases are considered for each wall with R=-1.0, -0.7, -0.5, & -0.3. Where, R is the ratio of compression capacity/compressive yield strength of reinforcement to the tensile yield strength. Figure 6 shows the schematic representation of the monotonic envelope function and cyclic material model used for reinforcing bars in the present study.

$$R = \frac{f_{cy}}{f_{ty}} \qquad (1)$$

Where,

f_{cy} = Compression capacity/compressive yield strength of reinforcing bars

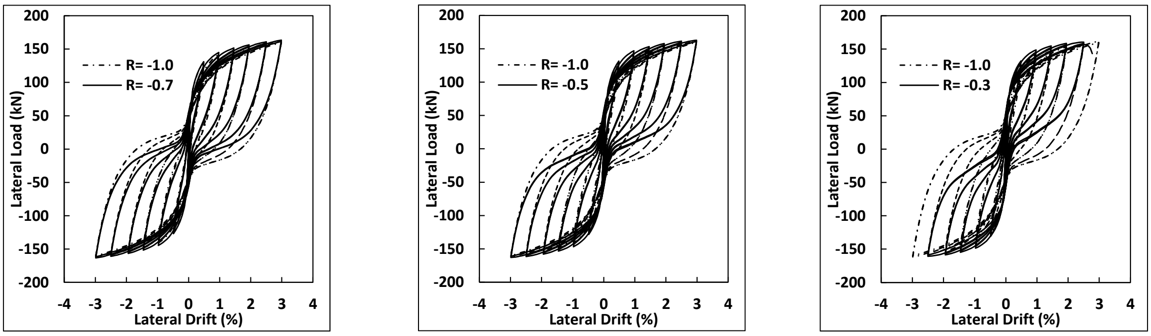
f_{ty} = Tensile yield strength of reinforcing bars



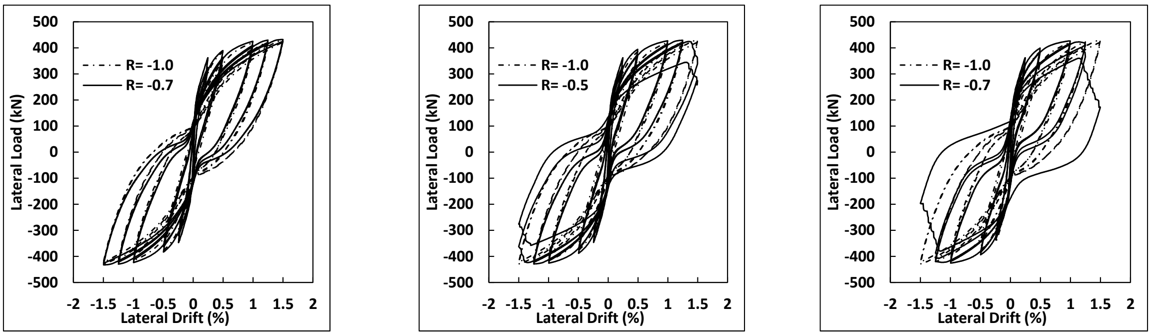
(a) Envelope Curve (b) Cyclic material model

Figure 6. Schematic representation of reinforcement material model used in the present study for conducting parametric studies

The selection of R values is carried out to accommodate the range of cases considering, no buckling with R=-1.0, to a case of significant buckling with R= -0.3. The validated numerical models of the RC walls are adopted and nonlinear analysis has been carried out under the application of constant axial load. The walls are subjected to lateral displacement loading history until the degradation in the lateral strength is observed. The results of only Specimen RW2 and Specimen WSH4 have been reported and discussed in the present paper. Figure 7a and Figure 7b show the comparison of hysteresis response of shear wall RW2 and WSH4 with different levels of axial compression capacity of reinforcing bars, respectively. It is evident from the comparison of the load versus drift plots that with the reduction in axial compression capacity of reinforcing bars (i.e. f_{cy}), the hysteresis behaviour exhibits more pinching compared to the benchmark specimen with R= -1.0. This pinching behaviour is associated with the reduction in energy dissipation contribution of reinforcement due to premature buckling as compared to an unbuckled reinforcement. This change in the behaviour is due to the reduction in energy dissipation of reinforcing bars in the transitional phase when the stresses being resisted are compressive within the tensile strain region. Moreover, the reduction in compression capacity also leads to reduction in the deformation capacity of the wall due to earlier crushing of the concrete as observed in wall WSH4. Further, reduction in axial compression capacity of reinforcing bar in wall RW2 and WSH4 resulted in reduction of equivalent viscous damping mainly associated with the reduced energy dissipation capacity of reinforcing bars due to buckling as shown in Figure 8.

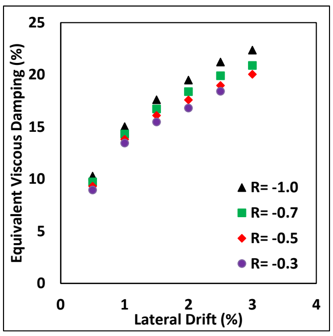


(a) Comparison of hysteresis response of shear wall RW2

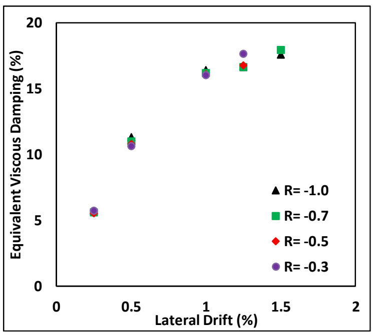


(b) Comparison of hysteresis response of shear wall WSH4

Figure 7. Hysteresis response of RC wall with different level of compression capacity of reinforcing bar



(a) Wall RW2

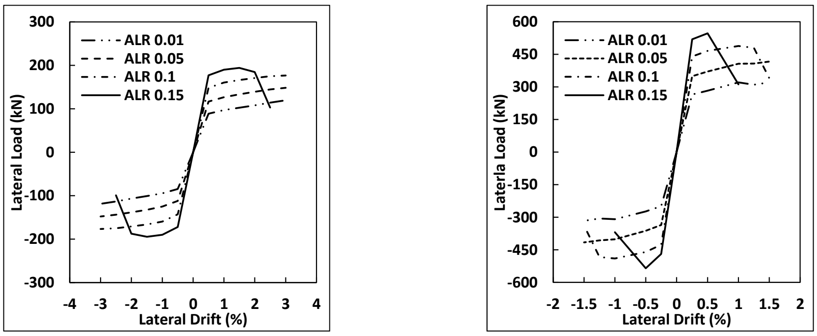


(b) Wall WSH4

Figure 8. Comparison of equivalent viscous damping for shear wall with different level of axial compression capacity of reinforcing bars

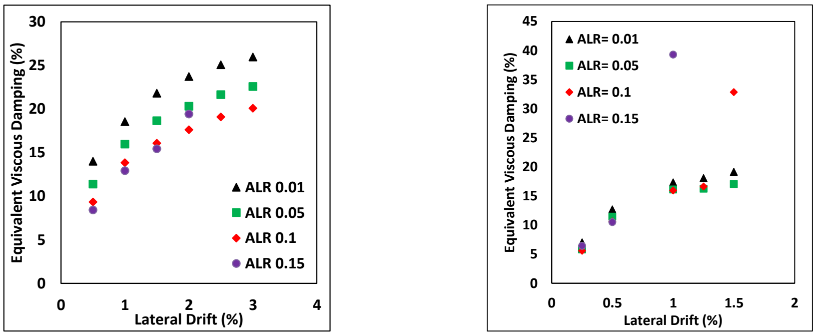
3.2 Effect of axial load on hysteresis behaviour of slender walls

The axial load acting on a structure is one of the major governing parameters that significantly influences the hysteresis behaviour (post peak cyclic response, pinching and energy dissipation) of RC structures (Dhakal and Maekawa 2002). Axial load plays a vital role in defining the deformation capacity and the mode of failure. Therefore, in the present paper a numerical investigation has been carried out to understand the effect of axial load on the in-plane flexural behaviour of RC walls. Four different levels of axial loads (with axial load ratio (ALR) of 0.01, 0.05, 0.1 and 0.15) are applied to walls RW2 and WSH4. Cyclic analysis has been carried out and cyclic response curves are used to evaluate the load-drift envelope and equivalent viscous damping for wall RW2 and WSH4. Figure 9 and Figure 10 show the comparison of load-drift envelope and the equivalent viscous damping with different level of ALR for wall RW2 and WSH4 respectively. It is evident from the comparison that the lateral load carrying capacity of the wall RW2 increased by 89.5% and equivalent viscous damping decreased by 29.2% at 1.5% drift for an increase in ALR from 0.01 to 0.15. Further, the lateral load carrying capacity of the wall WSH4 increased by 93.3% and equivalent viscous damping decreased by 17.2% at 0.5% drift for an increase in ALR from 0.01 to 0.15. Increase in ALR also reduces the deformation capacity of wall due to increased compressive strain demands leading to premature reinforcement buckling followed by crushing of the concrete.



(a) Wall RW2 (b) Wall WSH4

Figure 9. Comparison of lateral load versus lateral drift envelope for shear wall RW2 and WSH4 with varying ALR



(c) Wall RW2 (d) Wall WSH4

Figure 10. Comparison of equivalent viscous damping for shear wall RW2 and WSH4

4 CONCLUSIONS

This paper presents the results of the numerical investigations carried out on flexurally dominated RC shear walls subjected to in-plane cyclic loading. For walls tested and reported in the published literature, numerical models were developed and validated against the experimental results. The efficacy of the numerical model was evaluated through the comparison of load-drift plots for the benchmark specimens. Further, parametric studies were carried out on the validated numerical models to scrutinize the effect of the axial compression capacity of reinforcing bars (implicitly representing the effect of bar buckling) and the axial load ratio on hysteretic behaviour of RC walls. Through the numerical investigations, it is concluded that reduction in compression capacity of reinforcing bars due to buckling results in reduction of deformation capacity and hence the ductility of RC walls. Moreover, it also results in reduction of the energy dissipation capacity of wall due to the reduced energy dissipation by the buckled reinforcing bars. Furthermore, through the numerical investigation on walls with varying level of axial loads, it can be concluded that an increase in axial load ratio leads to significant increase in the lateral load capacity of the wall, but also a substantial reduction in the deformation capacity thereby making walls comparatively brittle compared to walls with no or nominal axial load.

The nonlinear fibre model adopted in the study is capable to simulate the overall behaviour of flexurally dominated RC walls with reasonable accuracy and can be used to scrutinize the parameters governing buckling of reinforcing bars in RC wall structures. The investigations presented in the present paper are a part of a multi-objective project that are being carried out to investigate the causes and remedial measures for buckling of reinforcing bars in RC shear walls. Further experimental and numerical studies are currently undergoing and results will be presented in future publications.

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