AXIAL COMPRESSION EFFECT ON DUCTILITY DESIGN OF REINFORCED CONCRETE STRUCTURAL WALLS

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ABSTRACT

Reinforced concrete walls can render medium- to high-rise buildings excellent lateral stability and ductility. However, modern building design often lead to the vertical structural members subjected to very high axial compression ratio (ACR), which can deprive the inherent ductility. To evaluate and quantify the effect of ACR on the structural performance of RC walls, a comprehensive statistical analysis with 474 sets of experimental data has been conducted. Stipulated limits on ACR and their evaluation methods in various design codes are then compared. Based on the analysis results, it is found that EC8 provisions on ACR limits can generally satisfy the target ductility level of ductility. Nevertheless, more experimental studies on the squat walls behaviour under high ACR are needed to draw a confirmative conclusion.

INTRODUCTION

Catastrophic collapse of reinforced concrete (RC) buildings clearly necessitates dragging down of vertical structural members, for instance, failure of structural walls can lead to potential overall structural instability. In view of this, capacity protection of walls and primary columns with the use of special design and detailing approaches is one of the most critical issues in seismic design paradigms. It has been demonstrated in many disastrous earthquakes (Fintel, 1992) that well designed structural walls can render excellent lateral stability and drift ductility to medium- to high-rise RC buildings under seismic actions. To achieve the goal of capacity design, enhancing and preserving sufficient ductility of RC structural walls are done with confinement details, of which requirements are significantly influenced by the level of axial force induced on the walls. The 2010 Chile earthquake is a good example on the effect of high axial forces on seismic performance of RC walls. Post-earthquake field investigations observed that thin walls, with thickness range from 150 to 200mm, in the newly built high-rise buildings were subjected to higher axial compression and surprisingly suffered more severe damage than the thicker walls in the old buildings during the earthquake (EERI, 2010). Not only in Chile, modern complex structures and super high-rise skyscrapers in other parts of the civilised world are also often characterised by high compression forces in the members with high slenderness, as a consequence of architectural designs maximising clear floor heights and usable floor areas. Recent studies (Wallace et al., 2012; Su and Wong, 2006) have indicated that structural wall elements in modern high-rise buildings would sustain axial compression ratios, as high as 0.4 or above, which is already outside the typical range between 0 and 0.2 investigated in experiment.

The effect of axial force on the seismic behaviour of RC walls is known as a posteriori but they are correlated in multiple aspects. Although the curvature ductility of RC sections can be readily

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evaluated at different axial force levels, the relationships of axial force with buckling tendency of longitudinal reinforcing bars and cyclic fatigue of the members are quite complicated in particular under seismic loading. Meanwhile, the axial force can also bring in some positive effect on the structural behaviour such as suppressing shear sliding and premature anchorage failure (Kappos, 1996). Hence, the actual seismic responses of the RC walls under significant influence of axial force can be complicated, given that interactions amongst different axial force effects and failure mechanisms further perplex the situation. Nonetheless, both research studies and disastrous earthquakes (Wallace et al., 2012) have repeatedly revealed that adverse effect brought by axial compression on RC walls generally overwhelms the benefits introduced.

To avert undesirable brittle failures of RC members, on the basis of the work by Chronopoulos and Vinzileou (1995), Eurocode 8 (EC8) stipulates the limits for normalised axial force or also known as axial force ratio for RC members at various ductility classes, despite the largely scattered results (Tassios, 1996). Chinese and Hong Kong design codes also impose similar requirements as by EC8. Yet, not every modern design code, for instance, New Zealand and ACI codes, takes on the same measure to limit the axial compression ratio in the design of RC structures. There is apparently no consensus amongst different engineering and research communities on whether limiting the axial compression ratio is crucial to the ductile or capacity design of RC walls withstanding seismic loading. In view of this issue, this paper presents a revisit and statistical analysis for the effect of axial compression ratio on seismic performance of RC structural walls, followed by a comparison and discussion on the rationale of relevant provisions found in various design codes. The work presented in this paper would shed light on the justification of the use of axial compression ratio in design of RC walls and determination of a suitable limit for controlling seismic performance of RC structures.

DEFINITIONS AND EFFECTS OF AXIAL COMPRESSION RATIOS

To parametricise the axial compression effect on the structural performances of RC walls, in the literature, the axial compression is generally normalised by the concrete uniaxial compressive strength times the sectional area of the concrete member i.e. the axial compression ratio (ACR) is defined as

$$\eta = \frac{N}{f_c A}$$  \hspace{1cm} (1)

Besides the confinement detailing, aspect ratios, lap and splices, etc., axial compression ratio is a very important indicator in evaluating the expected ductility and fragility of the RC walls during earthquakes. However, it should not be confused with the limit state design concepts, since the axial compression ratio alone cannot represent or be used to assess the actual seismic performances of the RC walls.

Axial force has a crucial role in governing the drift ductility of RC walls. An apparent and instant effect with higher axial compression is reducing the curvature ductility of the walls (Paulay and Priestley, 1992). The relationship between curvature ductility $\mu_\alpha$ and axial compression is illustrated in Figure 1. If the strain penetration effect is deemed to be negligible and assuming the plastic hinge length $l_p = 0.5l_w$, the normalised drift capacity and ductility of flexural-controlled wall segments can then be estimated by the following equation,

$$\mu_\Delta = \frac{\Delta_w}{\Delta_y} = 1 + \frac{1}{\alpha_y} \left[ 0.75 \left( \frac{l_p}{c} \right) \left( \frac{\varepsilon_{cu}}{\varepsilon_y} \right) - 1.5 \right]$$  \hspace{1cm} (2)

where $\alpha_y = \text{vertical aspect ratio} \ (H/l_w)$.
Figure 1. Relationship between curvature ductility and internal forces of walls

By assuming the walls fail in flexural mode, the influence of axial compression ratio on the displacement ductility can be evaluated as shown in Figure 4.

Figure 2. Influence of ACR on the displacement ductility of RC walls

Figure 2 shown above has clearly demonstrated the indispensable need of an ACR limit, in view of the diminishing effectiveness of confinement on enhancing the displacement capacity at high level of ACR. It is shown that a quite drastic drop in the displacement capacities following the increase of ACR from 10% to 30%, after where the relationship curves become stagnating and tend to converge to the same value of ductility or ultimate displacement, thus the confinement details become irrelevant thereafter. Meanwhile, it is interestingly observed that high aspect ratios inflict negative effect on the ductility but is beneficial to the ultimate displacement, though it is less sensitive to aspect ratios in comparison with the ductility. The realistic relation between ACR and displacement capacity is far more complicated, what will be seen later, owing to the fact that each influential factor can interact with other ones resulting in complex overall structural behaviour, for instance, various factors including axial force, aspect ratio, stiffness, cracks, etc. can come into play of the elasto-plastic buckling of walls.
STATISTICAL ANALYSIS ON THE EFFECT OF ACR

Besides the confinement detailing, aspect ratios, lap and splices, etc., axial compression ratio is a very important indicator in evaluating the expected ductility and fragility of the RC walls during earthquakes. However, it should not be confused with the limit state design concepts, since the axial compression ratio alone cannot represent or be used to assess the actual seismic performances of the RC walls. Besides the confinement detailing, aspect ratio and axial compression, the ductility and general seismic performances of RC columns can be influenced by other various factors, for instance the anchorage, loading pattern, etc., of which effect in turn interact with confinement and axial load effect. In view of this complicated behaviour, the quantification of the effect of axial compression on RC walls’ seismic performance has been very much relying on experimental data.

Evaluation and quantification for the effect of axial force ratio on RC walls’ seismic performance were carried out with a comprehensive statistical study. Total 474 sets of data, composed of experimental results of small to full-scale RC walls of various shapes and detailing methods, were collected from literatures. The gathered load-displacement data are then analysed, where the definitions of yield displacement, ultimate displacement and displacement ductility of the loading curves are based on Park (1989). In the collected database, more than 60% of the tests are conducted under relatively low axial force ratio below 0.05; in contrast, there are only about 15% and 7% were tested with axial force ratio above 0.15 and 0.30 respectively. Nonetheless, these high axial force tests demonstrated that the RC walls would fail in a very different manner such as out-of-plane buckling, resembling to the observed damage modes of the walls in the 2010 Chile earthquake. RC walls failed in out-of-buckling generally are very brittle exhibiting low ductility, and the classical ductility evaluation methods assuming in-plane flexural failure are no longer applicable to these walls.

The relationship between ultimate displacement capacity and axial compression ratio of various types of RC shear walls is also plotted in Figure 3. Similar to the analytical study (Figure 2) presented before, there is a trend of diminishing ultimate displacement capacity of slender walls with increasing axial compress ratio, as shown in Figure 3(b), owing to the reduction in neutral axial depth, low cycle fatigue effect as well as potential out-of-plane buckling. Nevertheless, the ultimate displacement capacity of squat walls tends to increase with axial compression ratio (Figure 3(c)). This reversed trend is actually due to the fact that the shear strength and sliding resistance of cracks in the squat walls are enhanced by axial compression.

On the other hand, Figure 4a shows the relationship between drift ductility and axial force ratio of RC walls of various kinds. It can be seen that RC walls can easily achieve high ductility ($\mu_\Delta \geq 6$) at low axial force ratio ($\eta \leq 10\%$) as long as the boundary elements are well detailed and designed. However, when the axial compression ratio increases to above 20%, the RC walls can only barely maintain moderate ductility ($4 < \mu_\Delta \leq 6$) and special detailing methods like composite-reinforced boundary elements are necessary in order to acquire high ductility. Above 35% axial compression ratio pre-emptive out-of-plane buckling can be the dominating failure mode as reported in the literatures (Zhang and Wang, 2000), resulting in RC walls not being suitable to provide lateral and vertical resistances in seismic design. It is recognised that squat RC walls with aspect ratios ($H / L$) lower than 1.5 would be prone to shear failure in particularly sliding shear failure rather than flexural failure and the displacement ductility is not necessarily reduced by increase of axial compression. In contrast to slender RC walls (Fig. 4b), the ductility of squat RC walls (Fig. 4c) is less influenced by axial compression ratio that the ductility generally maintains in the range $2 < \mu_\Delta \leq 4$.

Another important structural property of RC walls related to the axial compression is the shear strength. For comparison purpose, the peak base shears reported by the tests in the database are further normalised by the following equation:

$$v_n = \frac{V_p}{\sqrt{A_w}}$$

where $A_w = $ web area of the wall.
Figure 3. Relationship between ultimate displacement ratio and ACR: (a) all types; (b) slender walls (H/L > 1.5); and (c) squat walls (H/L < 1.5)
Figure 4. Relationship between displacement ductility and ACR: (a) all types; (b) slender walls (H/L > 1.5); and (c) squat walls (H/L < 1.5)

Figure 5 shows the relationship between normalised shear strength and axial compression ratio. Higher axial compression tends to increase the shear strength of all types of RC walls, in particular squat RC walls (Figure 5c). This is because axial compression not only can enhance the shear strength of walls, but also the moment resistance in some cases (Wallace et al., 2012). Nevertheless, the enhanced shear strength attributed to axial compression generally cannot compensate for the adverse effect of reduced drift capacity, as after all, the system ductility is far more important than the strength in seismic design.

CODES PROVISIONS ON AXIAL COMPRESSION RATIOS

In view of the adverse effect of axial compression on the seismic performance of RC structural walls as illustrated in the last section, most of the modern design codes of practice for RC structures stipulate upper limits of the axial compression ratio. RC walls with an axial compression ratio beyond the limits are generally deemed to be ineffective in resisting seismic action even with confinement detailing in the critical regions (expected plastic hinges) of the members. These provisions, in addition to confinement detailing, intend to ensure that sufficient drift ductility and axial force carrying capacity can be retained in RC structures during earthquakes or other exceptional load cases.

Eurocode 8 (EN 1998-1:2004)

EC8 stipulates upper limits of axial compression ratios (normalised axial force) for ductile walls and columns designed for ductility classes moderate and high (DCM and DCH), but no restrictions for ductility class low (DCL) as follows

\[
\frac{N_{ED,EC}}{f_{cd} A_e} \begin{cases} 
0.35 & \text{DCH} \\
0.4 & \text{DCM} \
\end{cases} \quad (\text{BS EN 1998-1:2004})
\]  

where \( N_{ED,EC} \) = design axial force from the analysis for the seismic design situation and \( f_{cd} = \) the design (factored with safety factor 1.5) cylinder strength of concrete under uniaxial compression at 28 days. The design axial force in Eq. 4 consists of two major components- (i) axial force induced by representative gravity action and (ii) axial force induced by seismic action. Although axial forces incurred in cantilever walls by seismic loads are relatively minor compared with permanent gravity action in general, coupled shear walls would have to bear significantly extra axial forces incurred by seismic actions due to the coupling action aggregated from the shear forces of the coupling beams.
Therefore, the definition of the axial compression ratio (ACR) used by EC8 can be considered the most appropriate description of realistic stress states experienced by the RC structures during earthquakes. Actually, the limits of ACR stipulated in EC8 can be readily compared with experimental studies to see whether the provisions can assure sufficient ductility of the RC members.

**Chinese seismic design code 2010 (GB50011-2010)**

In the Chinese seismic design code, the upper limits of axial compression ratios for RC shear walls (sectional aspect ratio L/t>8) take different values under different design fortification earthquake intensities and structure grades (4 classes from I to IV: grade I structures have high drift ductility, grade II and III structures have moderate to high drift ductility, and grade IV structures have relatively low drift ductility) as follows
where \( N_{w,c} \) = the factored axial force for the wall and \( f'_c \) = the design axial compressive strength of concrete under uniaxial compression at 28 days, which is equal to the characteristic axial strength of concrete \( f'_{ck} \) divided by the safety factor 1.4. The characteristic axial strength \( f'_{ck} \) is determined by 150 × 150 × 300 mm prism compression test. In the GB code, it can be conservatively taken as 0.67 of the characteristic cube strength \( f_{cu,k} \). The average value of the ratio \( f'_{ck} / f_{cu,k} \) or so-called effectiveness factor is around 0.76 based on experimental studies (Zhang, 1993).

More stringent provisions are set for short pier RC shear walls \((4 < L/t \leq 8)\) such that the axial compression ratios for the grades I, II and III short pier walls should not exceed 0.45, 0.50 and 0.55 respectively in the critical regions (JGJ3-2010). The axial force in Eq. 5 is calculated from the representative gravity action, instead of ultimate gravity action, expected to be taken by the structure during earthquakes and the multiplying factor 1.2 is used to account additional axial force incurred by unforeseen and excluded actions on the walls. In the calculation of the representative gravity action, the combination coefficient \( r_{d,t} \) is used to consider the reduced likelihood that full variable actions are present during earthquakes and for instance, the combination coefficient for residential floor live load is 0.5.

**Hong Kong concrete code 2013 (HKConcrete 2013)**

In the Hong Kong concrete code, the upper limit of axial compression ratios for RC walls is specified as follows

\[
\frac{N_{w,HK}}{0.45 f'_{cu} A_c} \leq 0.75
\]

where \( N_{w,HK} \) = the design axial force for the wall due to ultimate gravity load; \( f'_{cu} \) = the characteristic cube strength of concrete under uniaxial compression at 28 days; and \( A_c \) = the gross area of concrete section. It is noted that the safety factor for the concrete compressive strength used in the HK code is 1.5, by which dividing the characteristic concrete strength gives the design strength. The constant 0.45 = 0.67/1.5 in the denominator converts the characteristic concrete strength into equivalent design compressive strength for the sections subjected to dominate flexural bending action, wherefore another multiplying factor 0.67 is used. Meanwhile, the axial force in the numerator takes the ultimate load value due to sole gravity action, without considerations of possible non-permanent live load reduction or representative gravity action during rare events with exceptional loading actions like earthquakes.

**New Zealand concrete code (NZS 3101:Part1:2006-A1&A2) and other design codes**

The NZ code does not have similar provisions on the axial force ratios as in the EC, GB and HK codes but limiting sectional curvatures or strains in potential plastic hinge regions are specified for different RC members. Limiting material strains is apparently the most direct method to control curvature dualities of RC members; however, whether it is sufficient to prevent the low cyclic fatigue phenomenon or rapid strength and stiffness degradation of RC members under cyclic loading is uncertain.

It is also worthy to mention here that United States’ concrete design code ACI 318-11 also does not introduce similar limits on the axial compression ratios for RC columns and walls. Nevertheless, a standard for seismic rehabilitation of buildings ASCE/SEI 41-06 has stated that RC walls with axial...
loads greater than 35% of nominal axial load strength $P_o$ shall not be considered effective in resisting seismic forces. The Canadian concrete code CSA A23.3-04 (R2010) also stated that for flexural members with factored axial loads in excess of 0.35 $P_o$ shall have a nominal resistance greater than the induced member force, i.e. not to be designed to form potential plastic hinges and dissipate energy in any circumstances under seismic effects.

**Comparisons of the Code Provisions**

Although the definitions of the axial force ratios in the EC, GB and HK codes are somehow not alike particularly the axial forces in the numerators, the compressive strength terms in the denominators can be readily transformed to characteristic cylindrical strength $f_c = 0.8 f_{cu} = f_{cd} / 1.5$ for comparisons. Table 1 summarises the key comparisons of the provisions on the axial compression ratios defined in the three codes.

**Table 1. Comparisons of codes provisions on ACRs for RC walls**

<table>
<thead>
<tr>
<th>CoP-SUC 2013</th>
<th>GB50011-2010</th>
<th>EN 1998-1:2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original definition of ACRs</td>
<td>$\frac{N_{W,HK}}{0.45 f_{cu} A_c}$</td>
<td>$\frac{N_{W,C}}{f_c A_c}$</td>
</tr>
<tr>
<td>Limit(s)</td>
<td>$\leq 0.75$</td>
<td>$\leq 0.4$ Grade I, Intensity 9 $\leq 0.5$ Grade I, Intensity 7 or 8 $\leq 0.6$ Grade II or III Grade IV</td>
</tr>
<tr>
<td>Seismic/lateral forces effects</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>Variable load reduction</td>
<td>$\times$</td>
<td>✓</td>
</tr>
<tr>
<td>Renormalised ACRs limits wrt $f_c$</td>
<td>$\frac{N_{W,HK}}{f_c A_c} \leq 0.42$</td>
<td>$\frac{N_{W,C}}{f_c A_c} \leq 0.22$ Grade I, Intensity 9 $\leq 0.28$ Grade I, Intensity 7 or 8 $\leq 0.34$ Grade II or III Grade IV</td>
</tr>
</tbody>
</table>

* Limits for grades I, II and III short pier RC shear walls ($4 < H / B \leq 8$) are 0.45, 0.50 and 0.55 respectively.

The ACR limits stipulated in the GB code are resemble to those in the EC8, but again the combinations of actions for calculating the axial forces are different in the two codes as mentioned before. For cantilever walls, the GB code is virtually more stringent because of the safety factor 1.2 is used to amplify the action. But for coupled shear walls, it is not conclusive that which one of the two codes is more conservative, since the 1.2 factor may not be sufficient to cover the exceeding axial forces induced by the coupling action. Nevertheless, the EC8 provide a more realistic assessment for these cases by taking in considerations of seismic or generally lateral forces effects. At the first sight looking at the last row in Table 1, the HK code has the least stringent limit on the ACR for RC walls compared with the other two codes. But it should be noticed that the axial force in the numerator is generally much larger, given that full ultimate gravity action is considered instead of representative gravity action.

If the figure of relationship between displacement ductility and ACR (Figure 4) is introduced again and plotted together with the code specified limits on ACRS, the expected achievable ductility of RC walls can be closely evaluated as shown in Figure 5. In EC8, for multi-storey uncoupled RC walls building with fundamental period $T_1$ larger than the period $T_c$ at the upper limit of the constant acceleration region of the responses spectrum, displacement ductility factor $\mu_\delta$ is equal to the behaviour factor $q$ (EC8), of which basic values take on 3.0 and 4.8 for DCM and DCH respectively. EC8 provisions undoubtedly satisfy this target level of ductility, provided that boundary elements are properly detailed. The grade I structures designed to GB code can also satisfy this target but the grade II or III structures may only have restricted inherent ductility and are susceptible to out-of-plane buckling. However, the HK code limit is somehow unjustifiable in a sense of targeting to control the ductility and is way beyond the other limits stipulated in the GB and EC8 codes.
Figure 5. Codes specified ACR limits and expected achievable ductility: (a) all types; (b) slender walls (H/L > 1.5); and (c) squat walls (H/L < 1.5)

Figure 5a can be deaggregated into two cases of slender walls (H/L > 1.5) and squat walls (H/L < 1.5) as what has been done before, and the resulted plots are shown in Figs. 8b and c. For the slender walls, it can be seen that there is still room for the ACR limits stipulated in EC8 to be relaxed, for instance, to 0.25 and 0.3 for DCH and DCM; whereas for the squat wall, the ACR limits are seemingly needed to be tightened up. However, Figure 3c indicates that axial force, meanwhile, tends to increase the ultimate displacement of squat RC walls, which is clearly beneficial in the state-of-the-art displacement based design methods. One may conclude that the squat walls are not suitable to be designed to allow inelastic deformation and as an energy dissipating element. Obviously, in view of the scarce data, more experimental studies on the squat walls behaviour under high ACR are necessary before confirmative conclusions can be drawn.

Closing remarks

Excellent lateral stability and drift ductility of reinforced concrete walls are of important buildings in design of medium- to high-rises building against seismic effects and other exceptional loading cases. However, walls in modern buildings are often subjected to very high axial compression, which has been pushing the limits of the conventional design and analysis theories.
A comprehensive statistical analysis with 474 sets of experimental data has been conducted to investigate the effect of axial compression ratio (ACR) on the structural performance of various types of RC walls. It is shown that the ductility of the walls is generally diminishing with increasing of ACR and this trend is particularly noticeable for slender walls with aspect ratio greater 1.5. Provisions on the limits of ACR stipulated in various codes are then compared and the expected attainable ductility of RC walls designed to different codes are evaluated against the statistical analysis results.

Based on the analysis results, it is found that EC8 provisions on ACR limits can generally satisfy the target ductility level of ductility. Nevertheless, ACR limits may take on different values for the slender and squat walls, in view of their distinct structural behaviour. The ACR limits for slender walls may be relaxed, whereas the ACR limits for squat walls are seemingly needed to be tightened up. Obviously, there is a need of more experimental studies on the squat walls behaviour under high ACR before confirmative conclusions can be drawn.

**Acknowledgement**

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