STABILITY OF REINFORCED CONCRETE WALLS UNDER SEISMIC LOAD

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Abstract: The damage to reinforced concrete walls, observed after the earthquakes in Chile (2010) and New Zealand (2011), shows that the walls did not achieve the expected ductile behavior and could fail due to local and global instability. Therefore, extensive experimental and numerical research is presently conducted in this direction in order to define the failure mechanism of reinforced concrete walls, especially in relation to their possible buckling. This paper describes one existing mechanism of lateral buckling of walls. Since lateral buckling of reinforced concrete walls is affected by a large number of parameters, it is necessary to continue with the research of this complex phenomenon.

Key words: reinforced concrete walls, ductility, lateral buckling.

STABILNOST ARMIRANO BETONSKIH ZIDOVA PRI SEIZMIČKOM OPTEREĆENJU

Sažetak: Oštećenja armirano betonskih zidova, uočena nakon potresa u Chileu (2010) i Novom Zelandu (2011), pokazuju da zidovi nisu postigli očekivano duktilno ponašanje, te mogu otkazati zbog lokalne i globalne nestabilnosti. Stoga se danas, u tom pravcu, vrše opsežna eksperimentalna i numerička istraživanja kako bi se definirao mehanizam otkazivanja armirano betonskih zidova, posebice u odnosu na njihovo moguće izvijanje. U ovom radu je opisan jedan postojeći mehanizam bočnog izvijanja zidova. Kako na bočno izvijanje armirano betonskih zidova utječe veliki broj parametara, nužno je nastaviti s istraživanjima ovog složenog fenomena.

Ključne riječi:armirano betonski zidovi, duktilnost, bočno izvijanje.

1. Introduction

The use of reinforced concrete walls in building construction is virtually unavoidable due to their efficiency and cost-effectiveness. As a load-bearing element, they are often used in combination with reinforced-concrete frames and masonry walls, as well as prestressed concrete elements. Approximate response of such mixed bearing systems to seismic activity can be obtained by applying modern numerical structural analysis methods. Reinforced concrete walls are used to take gravity loads, but their role is more important in taking lateral loads such as seismic or wind loads. Due to high stiffness of such walls in their plane, they have become practically irreplaceable in building construction structures. They also have an indispensable role in repair and reinforcement of existing facilities that do not meet modern seismic regulations.

Due to their stiffness, reinforced concrete walls take far greater shear forces than frame structure columns. Their ductility is therefore lower than the ductility of frame structures, primarily because of the possibility of shear fracture, which is considered brittle. Despite the frequent use of these walls in the design of buildings, they are insufficiently discussed in our professional literature. Analysis of walls is usually reduced to their in-plane behavior, while their out-of-plane behavior is ignored because of the small stiffness of the wall in the lateral direction. However, in many cases it has been observed that deformations occur out of wall plane, which can lead to a loss of their stability.

Reinforced concrete walls are mainly divided into squat and slender walls, and connected and unconnected walls. Squat walls usually mean the walls whose total height h_w to length l_w ratio is less than two. They are usually lightly reinforced and subjected to shear deformation. Slender walls are the walls for which the ratio is greater than two. The minimum thickness of walls $d_{\min} = 15cm$ is defined in most national regulations. Similarly, the minimum wall clear height to thickness ratio is defined in certain national regulations for slenderness limitation. Slender walls are characterized by hysteretic behavior and failure due to bending.

In high seismicity areas, it is not common to dimension walls to remain in the elastic domain during an expected earthquake. Seismic forces that the wall must take are reduced by allowing the occurrence of nonelastic strains. In order to ensure stable nonelastic behavior, it is necessary to provide sufficient ductility of the wall in the critical area. Experiments have shown that in case of proper reinforcement of the critical zone, slender walls achieve stable hysteretic behavior and significant ductility. Walls of a rectangular cross-section or connected walls of such a cross-section without reinforcement of boundary sections are used in many countries. For example, walls with 15-20cm thickness, without boundary reinforcements, are used in Chile and other countries. Such walls are susceptible to buckling. An example of this behavior is evident in Chile after the M=8.8 magnitude earthquake in 2010 (Figure 1), and in New Zealand after the 6.3 magnitude earthquake in 2011 (Figure 2). The damage to L and T shaped walls is particularly noticeable here because the compressive strain of concrete reaches the limit value before tensile yielding of reinforcement.

The tendency of wall buckling is believed to considerably depend on the ratio of floor clear height h_e of the wall to its thickness b_w, loading history and the magnitude of compressive force. There are two hypotheses on the modes of failure or stability loss. One hypothesis is that tensile yielding, for loading in one direction, softensthe boundary zone in the subsequent change of loading direction, leading to lateral instability of the wall boundary section. The second hypothesis is that concrete crushes first in the wall boundary section, leading to reduction in its cross section. In this case the wall becomes immediately unstable, or subsequent compressive and tensile stress cycles will lead to instability of the reduced cross section of the wall boundary section according to the first hypothesis. Still, the most likely seems to be the situation when lateral buckling of the wall occurs after crushing of the wall boundary section. Although lateral buckling occurs when boundary wall section is in compression, buckling can be significantly influenced by the magnitude of tensile strain in the previous loading cycle [2]. This is because residual tensile strains in boundary reinforcement, which has previously yielded, create cracks in the boundary section concrete, leading to reduced lateral stiffness of the wall. The residual strength of the wall must ensure that the deformed wall plane withstands the gravity load.

Figure 1. Wall damage - earthquake in Chile

Figure 2. Wall damage - earthquake in New Zealand

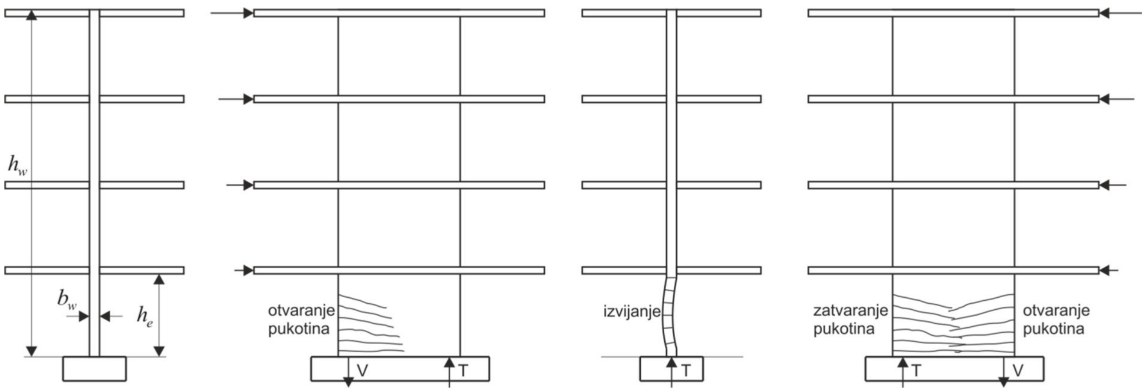

Figure 3. Lateral instability of the wall [1]

2. Wall lateral buckling mechanism

Paulay and Goodsir [7, 8] first described the development of a mechanism of lateral buckling of slender reinforced concrete walls. This mechanism is described in the following text. During extensive wall in-plane rotations, the boundary zone is subjected to high tensile strains that cause approximately horizontal cracks. This leads to tensile yielding of longitudinal boundary reinforcement. The subsequent change of loading direction results in recovery of the elastic part of the total reinforcement strain, and therefore cracks remain partly open because residual plastic deformations remain in reinforcement. During this compressive part of the wall boundary loading cycle, compressive stresses are taken only by reinforcement. At this point, lateral wall displacements occur since a very small misalignment in reinforcement placement results in eccentricity. As long as reinforcement has sufficient longitudinal stiffness, lateral displacements remain small. When increasing the compressive stress, reinforcement of one side of the wall begins to yield due to eccentricity, which results in nonuniform distribution of stresses on the two layers of vertical wall reinforcement. Reinforcement on the other side of the wall has not yielded and it is the only source of current lateral stiffness. Depending on the magnitude of the previously achieved reinforcement tensile strain (before the change of loading direction), different possibilities may result from increasing compressive stresses. The cracks may completely close, establishing compressive stress transfer through concrete and reinforcement, or they may remain open, leading to compressive yielding of reinforcement along one face of the wall. In the latter case, lateral displacements rapidly increase, leading to buckling failure. Independently of the scenario that will occur, lateral displacements and second-order moments will affect the in-plane wall behavior, which should be taken into account [2].

3. Buckling of prismatic elements under cyclic loading

A wall configuration with hinges at inflection points of the wall strain plane is adopted as a realistic assumption based on experiments with reinforced concrete columns. So far, there are several indications how to evaluate or define the wall area where lateral buckling occurs (the area $l_b \times h_b$ shown in Figure 4). This also concerns the relation of this consideration with existence of a confined boundary section of the wall. The influence of boundary conditions and strain gradient along the cross section of the wall is also insufficiently studied, and so is the verification of the expression for determining buckling length l_0.

The effective wall height h_{eff} can be defined in terms of wall fixity degree at different floors (Figure 4). In case of slender walls, the wall can be assumed to be completely fixed to the lower and upper floors, and therefore the effective wall height $h_{eff} = 0.5h_e$. As a calculation approximation, it can be assumed that the critical slenderness, defined as the wall effective height to thickness ratio

$$\lambda_{cr} = \frac{h_{eff}}{b_w}, \tag{1}$$

is related to tensile strain.

Theoretical assumptions from paper [2] are used here. The maximum lateral displacement can be expresses as a function of wall thickness ($\delta = \xi b_w$). The relationship between the maximum lateral displacement and curvature $\theta_{\max}$ can be expresses in the form:

$$\delta = \xi b_w = \theta_{\max} \left(\frac{kh_e}{\pi} \right)^2. \tag{2}$$

On the other hand, as an approximation, the maximum curvature can be defined as the ratio of the difference between the reinforcement maximum tensile strain ε_{sm} and reinforcement residual strain ε_{res} to static cross-sectional height d:

$$\theta_{\max} = \frac{\varepsilon_{sm} - 0.005}{d}. \tag{3}$$

The residual tensile strain of reinforcement is the strain in reinforcement after the tensile zone has changed into a compression zone by the change of loading direction. So, it is the strain of reinforcement immediately before it is compressively loaded, and equals:

$$\varepsilon_{res} = \frac{\varepsilon_{sm} - f_{sm}}{E_s - \varepsilon_y}, \tag{4}$$

where ε_y is reinforcement yield strain, and f_{sm} is maximum tensile stress in reinforcement. For simplicity, the reinforcement residual strain in Expression (3) is assumed to be $\varepsilon_{res} = 0.005$.

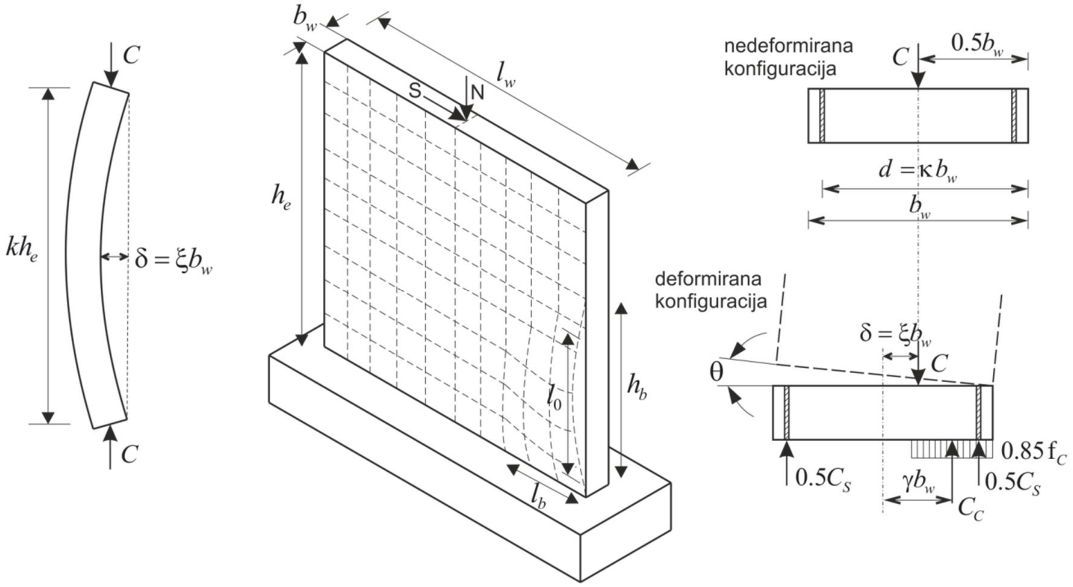

Figure 4. Wall geometry and equilibrium of forces in the middle of the buckling area [1]

Equilibrium of forces and moments in cross section with maximum lateral displacement gives:

$$\sum F = 0 \quad \Rightarrow \quad C = C_S + C_C, \tag{5}$$

$$\sum M = 0 \quad \Rightarrow \quad C\xi b_w = C_C \gamma b_w. \tag{6}$$

Equilibrium of moments is observed in relation to the center of cross section.
Assuming f_y is the stress in longitudinal reinforcement, and compressive force in concrete C_C represented by uniform stress $0.85 f_c^{'}$, the following can be written:

$$C_S = \rho b_w f_y, \tag{7}$$

$$C_C = 0.85 f_c^{'} (1 - 2\gamma) b_w. \tag{8}$$

Substituting Equations (5) and (7) in (8) yields after processing:

$$(1 - 2\gamma)\left(\frac{\gamma}{\xi} - 1\right) = \frac{\rho f_y}{0.85 f_c^{'}} = \frac{m}{0.85}, \tag{9}$$

where $m = \rho f_y / f_c^{'}$ is mechanical reinforcement ratio. The previous equation has a real solution only if the following condition is satisfied:

$$\xi \le 0.5\left(1+\frac{2m}{0.85}-\sqrt{\left(\frac{2m}{0.85}\right)^2+\frac{4m}{0.85}}\right). \tag{10}$$

Substituting this value in Equation (2) and solving it for b_w / h_e, while marking wall thickness as the critical thickness $b_{w,cr}$, results in:

$$\frac{b_{w,cr}}{kh_e}=\frac{1}{\pi}\sqrt{\frac{\varepsilon_{sm}-0.005}{\kappa\xi}}. \tag{11}$$

The main variables in the previous equation are: wall slenderness ratio kh_e / b_w, maximum tensile strain ε_{sm} in longitudinal reinforcement, static height parameter κ for longitudinal reinforcement, and ξ. Parameter κ can be defined from the relationship $d=\kappa b_w$, but it can be assumed that $\kappa \approx 0.8$. Parameter ξ relates to the mechanical reinforcement ratio. For practical problems the value of this parameter can be assumed to be $0.4 \le \sqrt{\xi} \le 0.6$. Adopting the values $\kappa = 0.8$ and $\sqrt{\xi}=0.5$, Equation (11) becomes:

$$\frac{b_{w,cr}}{kh_e}=0.7\sqrt{\varepsilon_{sm}-0.005}. \tag{12}$$

In case the protective concrete layer has separated before loss of stability (this usually occurs at compressive strains 0.003-0.005), than it is more logical to assume $\kappa = 1$, and for critical wall thickness $b_{w,cr}$ to use the thickness of wall core (confined concrete part). Typical slender wall geometries can be assumed to be fixed at floor levels, therefore $k=0.5$. In that case Equation (12) becomes:

$$\frac{b_{w,cr}}{h_e}=0.35\sqrt{\varepsilon_{sm}-0.005}. \tag{13}$$

In case of fatigue at a lower number of loading cycles, the maximum tensile strain of longitudinal reinforcement is approximately $\varepsilon_{sm}=0.05$. In this case, Equation (13) results in $h_e / b_{w,cr}=13$. This analysis is based on an idealization of the wall boundary zone, which means that a uniform distribution of compressive strain over the boundary zone is adopted. The actual distribution of compressive strain over the wall length is different, which makes the above result a conservative estimate.

4. Observations and conclusions

Buckling of slender reinforced concrete walls primarily depends on the clear floor height to wall thickness ratio (h_e / b_w). The lateral instability seems to result from concrete crushing in the wall critical zone. Regulations should limit wall slenderness, using the confined part of cross section as the wall thickness. Tensile strain of boundary reinforcement can be singled out as the main cause of wall lateral instability. This parameter is important as it controls the formation of cracks in the wall tensile boundary zone. Similarly, wall length is the key parameter controlling the development of lateral instability mechanism. The parameter of compressive stress, or normalized compressive force, is also very important as it can control the profile of strains along the wall. The effect of this parameter is different in the elastic and inelastic domains. It can cause an increase or decrease of lateral displacements, depending on the interaction with other parameters. The character of cyclic loading is yet another parameter that has a significant effect on wall lateral stability. The behavior can be significantly influenced by the wall horizontal reinforcement and its anchoring in boundary zones. Besides, ductility of wall boundary zones is considerably influenced by confining reinforcement, both by its spacing and cross section. It is evident that a large number of parameters affect the lateral stability of reinforced-concrete walls, which makes analysis more difficult and suggests that they all need to be taken into account.

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