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ANALYTICAL LIMIT STATE PREDICTION OF LIGHTLY REINFORCED CONCRETE WALLS

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ABSTRACT: Lightly reinforced concrete (LRC) walls are commonly used as infill in moment-resisting framed buildings in Japan. Damage to such walls can hinder building functionality. This issue can be tackled by appropriately selecting the infill walls for required performance. A two-dimensional macroscopic model was validated against experimental results of LRC walls subjected to in-plane cyclic loading. Two limit states were characterized based on damage evolution in the experiment, and they were quantified by strain-based criterion for damage evaluation. Analytical damage evaluation is intended to provide predictions of damage scenarios, which can facilitate the development of appropriate designs for LRC walls.

Keywords: *Lightly reinforced concrete walls, SFI-MVLEM, Numerical analysis, Damage states, Damage evaluation*

1. INTRODUCTION

In Japan, lightly reinforced concrete (LRC) walls are the popular choice of infill in RC buildings. The LRC walls are not designed to resist lateral load, and the common practice is to cast these walls monolithically with the surrounding frame elements. The rigidly connected LRC walls, characterized by a low shear span to wall length ratio, are susceptible to brittle shear failure[1)] and have been observed to incur premature damage in past earthquakes[2)]. The aftermath of 2011 Tohoku earthquake and 2016

Kumamoto earthquake have shown that even if the structural components have not suffered much damage, damage to non-structural walls can cause severe building deterioration[3)]. It has been observed that while design efforts have successfully achieved life safety, less emphasis has been placed on addressing the resilience and potential damage states that might develop before the collapse.

In the past two decades, seismic design provisions in several design codes have been incorporating performance-based design (PBD), where the structures are designed to achieve multiple performance levels when subjected to different levels of seismic hazards[4)]. Each performance level needs to be explicitly described and associated with a damage state. Resilience and functionality can be targeted using PBD by enabling designers to control damages developed under earthquakes. Since the current design practice of the LRC walls is not backed by seismic analysis, a practical strategy could involve designing them to withstand controlled damage during earthquakes. Previous research mainly focused on damage analyses for conventional structural systems. The damage evaluation and quantification specific to LRC walls are still limited. Yuniarsyah et al.[5)] assessed the damage level of LRC walls using the 2004 Architectural Institute of Japan (AIJ) Guidelines[6)], which takes into account the level of damage, such as residual crack width or stress level of concrete and reinforcement. However, the damage analysis was carried out based on the experimental observations, and the damage levels in the 2004 AIJ Guidelines are primarily defined for the structural flexural components. In this regard, this paper intends to evaluate the response of LRC walls under in-plane cyclic lateral loading and perform analytical damage evaluation. A simple numerical model capable of simulating the response of LRC walls was chosen and validated using the previous experimental results. Two limit states were defined based on the severity and progression of damage. The limit states were linked to material strain using experimentally validated numerical models. Two strain values were assigned for each damage state: one representing concrete compressive strain and the other representing reinforcement tensile strain. The limit state was assumed to be governed by the strain limit that is reached first. The combination of numerical analysis and damage evaluation in this framework is expected to serve as a tool for predicting the damage condition of a given LRC wall under a specific demand parameter.

2. NUMERICAL ANALYSIS

Since LRC walls are typically characterized by a low shear span-to-wall length ratio and low reinforcement ratio, an interaction exists between the shear and flexural response[7)]. One method for analyzing such walls involves using the cyclic shear-flexure interaction model for RC walls, referred to as Shear-Flexure Interaction-Multiple Vertical Line Element Model (SFI MVLEM)[8)]. It uses the two-dimensional fiber-based macroscopic representation of RC panel to couple the axial and shear responses and has been widely used and validated through numerous experimental results[7),9)]. This paper adopts SFI MVLEM for analysis.

2.1 Description of numerical model

The non-linear SFI MVLEM consists of RC panels subjected to in-plane actions integrated into a two-dimensional macroscopic fiber model formulated by Orakcal et al.[10)] as shown in Figure 1. The behavior of the RC panel is described by the modified formulation of the Fixed-Strut-Angle-Model (FSAM)[11)], which includes dowel action of reinforcement and shear aggregate interlock. The concrete behavior under biaxial loading is modeled with a concrete model (ConcreteCM) that modifies the Chang and Mander formulation[12)] to include compression softening, hysteretic biaxial damage, and tension stiffening effects. The uniaxial stress-strain relationship for the reinforcing steel is represented by the non-linear hysteretic model of Menegotto and Pinto[13)] extended by Filippou et al.[14)] (SteelMPF) to include strain hardening.

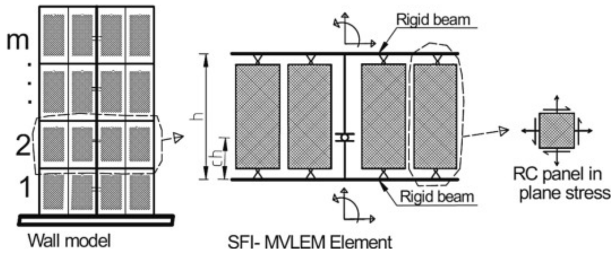


Fig. 1 Representation of SFI MVLEM model[9)]

2.2 Analytical results and comparison with test results

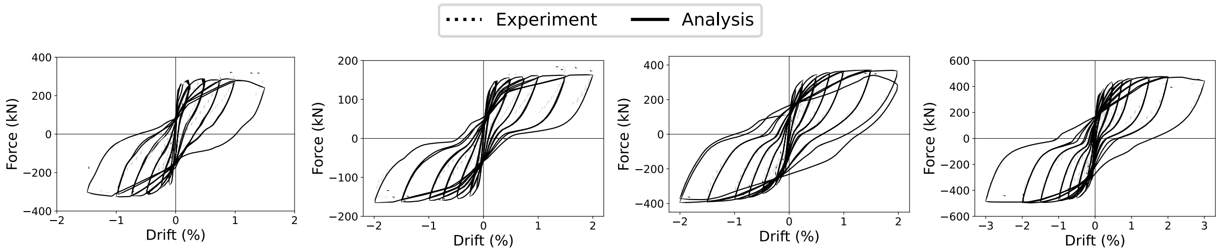
Four full-scale RC wall specimens, tested by Yuniarsyah et al.[5),15)], were selected as LRC walls for the numerical model validation. All the specimens were tested under constant axial load and reversed cyclic lateral load conditions. The details on geometry and loading conditions are shown in Table 1.

Table 1 Specimen details[5)]

Specimen name	NSW3	NSW4	NSW5	NSW6
Thickness (mm)	120			200
Length (mm)	1050			900
Height (mm)	2100			1800
Vertical rebar	D10@250			D10@200 double
Vertical rebar at end region	2-D13		4-D13	
Horizontal rebar	D10@125 single		D10@60 single	D10@100 double
Concrete strength (MPa)	24.2		22.2	
Shear span ratio	1.0	2.0	1.0	1.0
Axial load ratio	0.15			

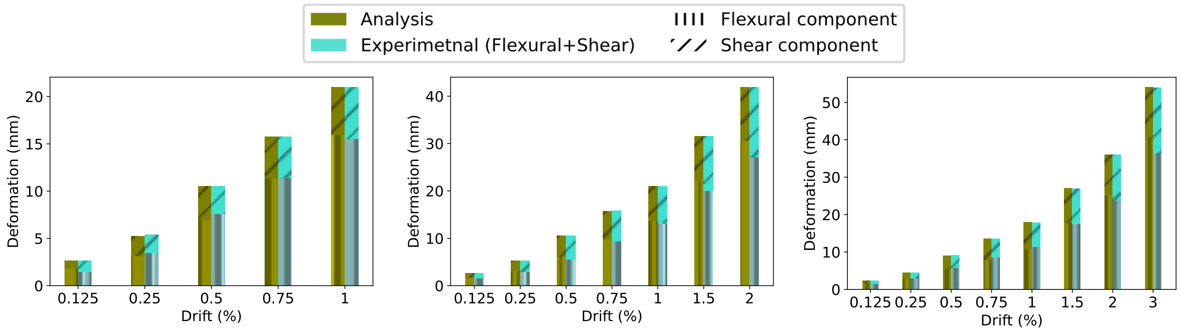
All the specimens were modeled with a vertical stack of eight SFI MVLEM elements, with seven RC panels along the wall length. It should be noted that the analysis parameters are not finely calibrated to fit the experimental response. The numerical predictions are compared to the test results in terms of lateral load versus drift ratio, and shear and flexural displacements at the top. The lateral load capacity and the lateral stiffness of the specimens are captured reasonably well for most of the lateral drift levels, as shown in Figure 2. In terms of global cyclic behavior, the numerical model established wall strength within a ±10% range of experimentally measured values. The degradation in lateral stiffness of specimens NSW4, NSW5, and NSW6 during the negative drift of 2%, 2%, and 3%, respectively, is due to buckling of the longitudinal reinforcement. The numerical response does not reflect this behavior because the model does not consider reinforcement bar buckling.

Figure 3 compares numerical and experimental displacement components. The numerical model provides a good prediction of the lateral displacement components, specifically for lower drift ratios. The experimental shear displacement increased with increasing drift demand for higher drift ratios of 1.5% and beyond, whereas the numerical prediction remained roughly constant. This observation is consistent with the findings of Faraone et al.[9)]. It can be attributed to the severe shear damage disrupting the shear strain distribution in the wall section, and ultimately the shear displacement during the experiment.



(a) NSW3 (b) NSW4 (c) NSW5 (d) NSW6

Fig. 2 Numerical and experimental Lateral load vs. Drift ratio



(a) NSW3 (b) NSW5 (c) NSW6

Fig. 3 Numerical and experimental Shear and Flexural deformation

3. ANALYTICAL DAMAGE STATES

To establish meaningful damage levels, it is reasonable to categorize damage according to the visual observation, such as crack width, compressive damage, etc. The progression of damage observed in the experiment in the four specimens was categorized into two distinct limit states (LS): the serviceability limit state (SLS) and the damage limit state (DLS). These limit states were systematically classified based on the required repair effort for each state. Specifically, no repair is needed before reaching the SLS, followed by minor repair after the SLS and prior to reaching the DLS, and finally, major repair after reaching the DLS. Table 2 shows the damage description of two LS.

Table 2 Description of damage states

Limit state	Damage description
Serviceability limit state	Initiation of cracking No compressive damage
Damage limit state	Maximum residual crack width < 1mm Initiation of compressive damage

Since the objective of this study is to enable the damage evaluation of LRC walls using a simple analysis method, it is necessary to associate LS with the engineering limit state that can be recorded in the analysis. Each LS was linked to both the concrete and reinforcement strains because material strains are intrinsically related to the damage. The LS was assumed to have initiated at the lower value of the drift ratios corresponding to two strain values, as shown in Equation 1.

$$R(\%) \text{ at the onset of } LSi = \text{minimum} \begin{cases} R(\%) at\ \epsilon_s = \epsilon_s(LSi) \\ R(\%) at\ \epsilon_c = \epsilon_c(LSi) \end{cases} \quad (1)$$

where, $R(\%)$ is the drift ratio, LSi represents one of the four damage states, ϵ_s and ϵ_c are the reinforcement tensile and concrete compressive strain recorded in the analysis, and $\epsilon_s(LSi)$ and $\epsilon_c(LSi)$ are the value of predefined reinforcement and concrete strains corresponding to LSi.

To associate the strain to the LS, material strain values were obtained from each LRC wall analysis at the drift ratio corresponding to when the damage state was observed in the experiment. The two LS, were correlated with both concrete compressive and reinforcement tensile strains. Table 3 lists the strain values defined for each LS.

Table 2 Damage state definitions

Limit state	Reinforcement tensile strain	Concrete compressive strain
Serviceability limit state	ϵ_y	ϵ at $2/3\ f_c'$
Damage limit state	0.015	0.004
ϵ_y : yield strain of longitudinal rebar f_c' : concrete compressive strength		

Damage evaluation based on the numerical simulation was done for the four specimens. Figure 4 shows the comparison of the experimental and the analytical drift ratio triggering the LS. The experimental drift ratios were determined based on the reported visual observations, while the analytical drift ratios were derived from the material strains in the numerical simulation. The comparison indicates a reasonable prediction of the limit states. The condition of each specimen at the analytical drift ratio is shown in Appendix.

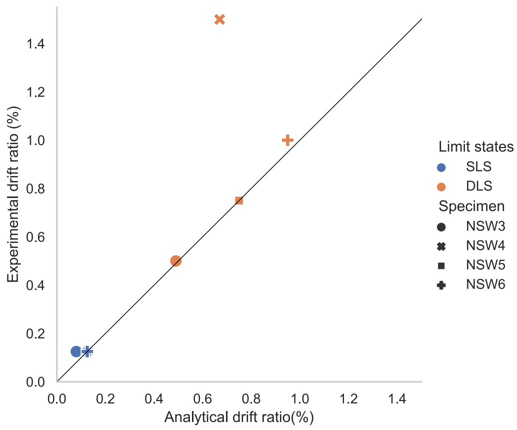


Fig. 4 Comparison of experimental and analytical drift ratio at each limit state

4. CONCLUSIONS

The non-linear SFI MVLEM model is used to simulate the global lateral load drift ratio and local deformation components of four previously tested LRC wall specimens. The results indicate an agreement between the numerical model's simulation and the observed experimental response. However, it lacks the ability to replicate strength and stiffness degradation due to the buckling of reinforcement and displacement components at severe damage.

Two limit states are defined for the LRC walls used in Japan based on the damage evolution and repair method needed to reinstate the component. Each limit state is quantified in terms of tensile and compressive strains, such that it can be used with the numerical model to anticipate the damage condition of LRC walls. The developed analytical damage evaluation facilitates the prediction of damage scenarios at different drift ratios, enabling the design of LRC walls for predefined damage levels in line with the principle of performance-based design.

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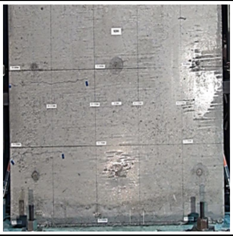
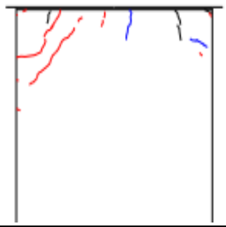
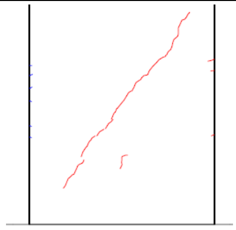
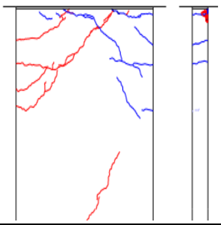
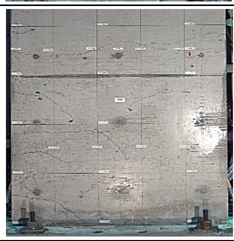
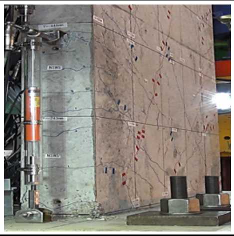
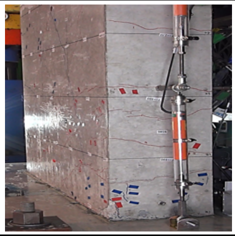
APPENDIX: EXPERIMENTAL OBSERVATION AT THE ANALYTICAL DRIFT RATIOS

	NSW3	NSW4	NSW5	NSW6
SLS				
DLS				

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