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Seismic behavior and cross-scale refinement model of damage evolution for RC shear walls

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ABSTRACT

The influence on the seismic behavior of RC shear walls by axial loads is evaluated and the observed damage in the earthquake damage investigation of RC shear walls is reproduced in this paper. Six RC shear walls with aspect ratio of 2 were analyzed by the method of nonlinear finite element under different axial load ratios, and the suggested modeling techniques and the accuracy of the numerical method were verified. The seismic performance of shear walls including load–displacement responses, ductility performance, stiffness degradation and energy dissipation capacity were discussed. The analysis results indicate that axial load has a significant effect on the seismic performance of RC shear walls. On the basis of this, the qualitative and quantitative relationships between the development of material damage and the deterioration of component performance were analyzed. It realizes the cross-scale conversion of damage information about structural components of RC shear wall from the local material scale to the component scale. Then the cross-scale refinement model of damage evolution of RC shear walls in the whole process was established, simplified and verified. The results show that, the refinement model can explain the development and distribution of damage evolution of RC shear walls in the whole process quickly and easily. The research results can provide a reference for the refinement of seismic design, damage assessment and reinforcement of RC shear walls.

1. Introduction

Lateral force resisting systems consisting of reinforced concrete (RC) shear walls have been widely used for high-rise buildings located in seismic regions to ensure the safety because of their high lateral strength and stiffness [1]. However, RC shear walls are always damaged and destroyed severely under earthquake. The damage was likely attributed to poor concrete confinement, inadequate horizontal reinforcement detailing, high axial loads, and thin wall thickness [2–6]. They concluded that the axial load affects the cracking pattern, failure mode and ductility of the walls. In many cases, buildings with 20 stories were built with 150–200 mm wall thicknesses and axial load ratio which is ALR = $N/f_c' A_g$, where N is the axial load, f_c' is the concrete compressive strength, and A_g is the gross cross section of the wall – that could range from 0.20 to 0.50 [6]. The M/Vl_w ratio (where M is the bending moment at the base of the walls, V is the shear force and l_w is the length of the walls) is an important property for the walls behavior, and if this ratio is small, the wall is considered as squat and it probably would exhibit a shear mode of failure [7]. It is generally believed that shear wall limbs ($M/Vl_w \le 1.0$) are considered as squat shear walls, shear wall limbs ($1.0 < M/Vl_w < 2.0$) are considered as intermediate shear walls and shear wall limbs ($M/Vl_w \ge 2.0$) are considered as slender shear walls. A survey of critical walls of damaged RC buildings was conducted in this study to obtain representative characteristics of damaged shear walls. Five damaged high-rise apartments buildings were considered in this survey. The average of M/Vl_w ratios of critical walls about damaged buildings is 2.02, which means that these walls cannot be considered as squat, and hence flexural behavior is relevant. Rectangular walls represent 32% of total shear walls of the selected buildings, the other 68% of the total shear walls are “T” type, “L” type and so on [2]. The effect of high axial loads on the flexural behavior of RC walls was studied experimentally by Zhang and Wang [8] and Su and Wong [9], axial-load ratio is found to have a significant effect on the cracking pattern, flexural strength, failure mode, and ductility of reinforced concrete shear walls.

Performance-based design on structures becomes the preferred seismic design method, and it has been applied in the design of new buildings and rehabilitation of existing structures. At the same time, the damage degree on structures needs to be quantified [10]. So far, significant efforts had been made to develop efficient damage functions to express quantitatively the state of damage of structures under

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Nomenclature

N	the axial load
f_c'	the concrete compressive strength
A_g	the gross cross section of the shear wall
M	the bending moment at the base of the shear wall
V	the shear load
l_w	length of shear wall
E_0	the initial elastic stiffness of the material
ε_c^{pl}	plastic strains for compression
ε_t^{pl}	plastic strains for tension
d_c	uniaxial compressive damage variables
d_t	uniaxial tensile damage variables
E_c	the elastic modulus of concrete
ε_t	the strain at which the maximum tensile strength is reached
ε_c	the strain at which the maximum compressive strength is reached
f_c	design value of concrete axial compressive strength
μ	the displacement ductility coefficient
D_y	the lateral displacement at yielding
D_u	the horizontal displacement corresponding to failure of the specimen
D_{th}	the degree of tension damage of the component material in vertical directions
D_{tl}	the degree of tension damage of the component material in vertical directions
D_{ch}	the degree of compression damage of the component material in vertical directions
D_{cl}	the degree of compression damage of the component material horizontal directions
D	the component damage index
D_i	the component damage index at the beginning of the i-th stage
ΔD_t	the total increment of tension damage index
ΔD_c	the total increment of compression damage index
α_{ti}	the relative coefficient of total increment of tension and compression damage index
α_{di}	the total damage adjustment factor

earthquake excitations. Benavent-Climent et al. [11], Guptaet et al. [12], Khashaee [13], and Williams et al. [14] developed many damage indices correlate with the maximum deformation as well as the ductility of structures, while Khashaee et al. [15], Kraetzig et al. [16], and Park et al. [17] developed others damage indices which are related to the energy dissipation. In general, these damage indices can be broadly classified into two groups according to what the index accounts for: (a) non-cumulative damage and (b) cumulative damage. The widely used parameters are story drift [14] and ductility ratio [13,14], which relate the damage only to the maximum deformation and are still regarded as key design parameters in seismic codes. However, these two damage parameters are not considered to be reliable, unless they take into account the influences of cumulative inelastic deformation and strong earthquake duration [18,19]. Several cumulative damage indexes accounting for the effects of cyclic loading has been proposed. Kraetzig et al. [16] developed the damage index from the aspect of hysteretic energy in two consecutive half-cycles. Two cumulative damage indexes from the aspect of a different set of 20 accelerograms were proposed: (a) the maximum ratio of hysteretic to input energy; and (b) the ratio of maximum hysteretic energy to maximum input energy [15]. Park and Ang [17] suggested a combined damage index from the aspect of the combined effect about deformation and energy dissipation. Ghobarah et al. [20] suggested a damage index from the aspect of initial stiffness change before and after the structure was hit by an earthquake, and the comparison between proposed damage index and common damage index indicated a good correlation between the examined damage indexes by designing a three-story moment-resisting frame. Elenas et al. [21] examined the correlation among the story-drift, floor-acceleration and Park-Ang damage index when an 8-storey building structure was subjected to 20 earthquake records by the method of numerical simulation. The strong correlation between the peak displacement ductility demand and cumulative plastic displacement ductility demand, residual displacement ductility demand, number of yield events was found by investigating the relationship of four seismic demand indexes for SDOF systems [22].

Traditional damage models for evaluating components performance are usually based on some macroscopic parameters such as displacement, which not only make it difficult to collect data on site, but also have strong dependence on experiments, and the evaluation results on component damage is not stable enough. It should be noted that the damage of structures and components is essentially a macroscopic representation of material damage evolution, so material damage reflects the nature of structural seismic damage material-related damage measures tend to be better indicators of the seismic damage to structures, and it has a high degree of refinement, the information collection of material damage on site is relatively easy. So cross-scale refinement model of damage evolution for RC shear walls is established very necessarily.

Six RC shear walls identified were designed with representative characteristics obtained from the survey. The seismic performance of shear walls, including load-displacement responses, ductility performance, stiffness degradation and energy dissipation capacity were discussed. On the basis of this, the qualitative and quantitative relationships between the development of material damage and the deterioration of component performance were analyzed. It realizes the cross-scale conversion of damage information about structural components of RC shear walls from the local material scale to the component scale. Then the cross-scale refinement model of damage evolution of RC shear walls in the whole process was established and simplified. The research results can provide a reference for the refinement seismic design, damage assessment and reinforcement of RC shear walls.

2. Finite element models

2.1. Design of shear walls

Six identical RC shear walls identified as SW1, SW2, SW3, SW4, SW5 and SW6 were designed with representative characteristics obtained from the survey described in Section 1. The other parameters are determined according to the Chinese Code for design of concrete structures (GB 50010-2010) [23]. The cross section of wall is 1000 mm wide, 125 mm thick, and the height of wall is 2000 mm. The upper beam (1400 mm long × 300 mm deep × 300 mm thick) provides anchorage for vertical reinforcement, and the lower beam (2000 mm long × 500 mm deep × 500 mm thick) provides a rigid base. The detailed dimensions and reinforcement configuration of the wall is shown in Fig. 1. The strength grade of concrete is C30.

2.2. Numerical models and relevant material properties

In the study, numerical simulation is performed by using the FE-code ABAQUS/Standard [24], which is general-purpose analysis software that can solve a wide range of linear and nonlinear problems involving the static and dynamic response of components [25]. The concrete damaged plasticity (CDP) model available can effectively simulate the nonlinear response of concrete structures under cyclic