SEISMIC PERFORMANCE OF CORRODED REINFORCED COMCRETE MOMENT-RESISTING FRAMES

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Abstract

Corrosion of steel reinforcement reduces the seismic capacity of reinforced concrete (RC) structures and makes them more vulnerable to earthquake hazards. It is necessary to evaluate the time-dependent seismic performance of RC structures considering the material property degradation of concrete and steel reinforcement due to corrosion of steel reinforcement. In this study, numerical study with the aid of the software ABAQUS was conducted to investigate the seismic performance of corroded RC moment-resisting frames. In order to improve the computation efficiency and guarantee the calculation accuracy, multi-scale modelling technique was adopted for corroded RC moment-resisting frame structures. The multi-scale modelling technique was validated based on the test data from both component level and structural level. The carbonation depth and corrosion ratio of RC frame structures with different service time were evaluated. Then, the seismic performance of corroded RC frame structures was further studied based on time-history analytical results of a four-story RC frames with different service time. The results indicate that with the increase of corrosion ratio, the displacement responses and damage of RC frames under seismic excitation increase gradually.

Keywords: RC moment-resisting frame, steel reinforcement corrosion, seismic performance

1. Introduction

Corrosion of steel reinforcement in reinforced concrete (RC) structures is a common and natural phenomenon that causes structural capacity degradation over time. For RC structures located in earthquake prone regions, the adverse effects of reinforcement corrosion, i.e, loss of steel area, cracking and spalling of concrete cover, and deterioration of bond performance between steel bar and the surrounding concrete, may gradually make the structure more vulnerable under seismic excitation. A structure that is originally designed to meet code specifications may not have the same margin of safety once the structure has undergone significant corrosion [1]. It is necessary to evaluate the seismic performance of RC structures considering the degradation of concrete and steel reinforcement over time.

In recent decades, significant research efforts have been devoted to the effect of reinforcement corrosion on the mechanical behavior of both steel material and RC components [2, 3]. A number of studies on the seismic performance of corroded RC components have been conducted. Ou et al. investigated the seismic performance of RC beams with corroded transverse steel reinforcement [4], and RC beams with corroded longitudinal reinforcement in different location [5]. Experimental studies on seismic performance of corroded RC columns were conducted by some researchers [6, 7]. Based on the previous studies, it is found that with the increase of corrosion ratio, the loading resistance, the deformation capacity and energy dissipation capacity of RC members decrease, the ductile failure mode may switch to brittle failure mode, and the hysteretic behavior may become less stable. Thus, the seismic performance of RC members is significant affected by the corrosion ratio of steel reinforcement.

Due to significant effect of reinforcement corrosion on the seismic performance of RC components, the seismic behavior of RC structure may degrade with the increase of service time. With the aid of the software ABAQUS, this paper aims to evaluate the time-dependent seismic performance of RC frame structures exposed to general atmosphere environment, considering the corrosion effect of RC structures due to concrete carbonation.

2. Numerical modeling technique

2.1 Corrosion damage model

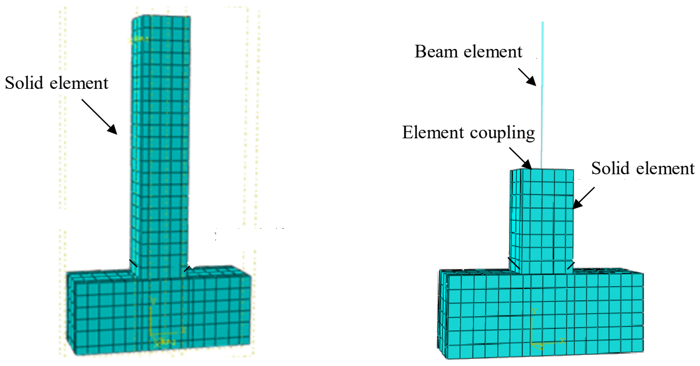
In order to investigate the corrosion effect of steel reinforcement on the structural performance of RC frame structures, the effects of corrosion damage should be carefully assessed in the numerical model. The following aspects are considered in this study, i.e., the steel area reduction in the steel bars, changes in the material properties of steel reinforcement and concrete cover, and the deterioration of bond strength between the corroded bars and the surrounding concrete. The corresponding corrosion damage model adopted can refer to the work of Liu et al. [8].

2.2 Multi-scale modelling technique

According to the previous study, the seismic damage of flexure-controlled corroded RC components concentrates in plastic hinge regions [6, 7], and the behavior of bonding between the corroded reinforcement and the surrounding concrete in the anchorage zone is important for the global performance of RC components [9], which should be carefully considered in the numerical model. In finite element technique, the micro model can predict the mechanical behavior and damage distribution of the structure with high computation cost, while macro model can predict the global behavior of the structure with low computation cost [10]. The multi-scale model which combines the micro model in critical region and the macro model in the part maintaining elastic is a useful modelling strategy to predict both the global behavior and local damage with the modest computation cost [11].

Adopting the software ABAQUS, an element coupling model (ECM) combining with beam element and solid element by the kinematic coupling is used in this study to predict the nonlinear behavior of corroded RC frame structures. The ECM is divided into two parts, linear region and nonlinear region. The linear region is modelled by the beam element (B31). Assuming that the damage concentrates in the nonlinear region, micro modelling technique should be used in the nonlinear region. In the nonlinear region, the reinforcement is modelled by beam element (B31) and the concrete is modelled by 8-node 3-D solid element (C3D8R). All the steel bars are assumed to exhibit elasto-plastic behaviour. The concrete damage plasticity model with the constitutive relationship recommended by Chinese Code for Design of Concrete Structures [12] is adopted. In the anchorage region, the bond-slip relationship between the longitudinal reinforcement and the surrounding concrete is modelled by connector element. Kinematic coupling is used in the interface between linear region and nonlinear region.

Under horizontal seismic excitation, the damage of RC components normally occurs in the local region such as plastic hinge region, and the rest regions with no obvious damage almost remain elastic. For ECM, the range of potential damage region considered in the numerical model is important for both the computation accuracy and efficiency. A cyclic test on the corroded column [13] is simulated to determine proper nonlinear region. Both global fine model (GFM) and ECM of the column are established, as shown in Fig.1. The modeling technique of GFM model can refer to the work of Liu et al. [8]. According to previous study, the plastic hinge length of RC components ranges from 0.4h to 1.4h [14], where h is the sectional depth of RC component. In the ECM of RC column, four nonlinear region lengths, i.e., l_{d1}=0.5h, l_{d2}=1.0h, l_{d3}=1.5h, l_{d4}=2.0h, corresponding to ECM-1, ECM-2, ECM-3 and ECM-4, are considered and compared. The numerical results of ECM with different ranges of potential damage region are compared with both test results and numerical results of GFM.



(a) GFM (b) ECM

Fig. 1 – GFM and ECM of corroded RC column

The lateral load-displacement curves of test and numerical results, which reflect the global behavior of RC column, are shown in Fig. 2. It is found that the simulation results of GFM are in good agreement with test results. For the ECM, with the increase of the damage region length, the simulation results are closer to the GFM and test results. When l_d is taken as 1.5h, the numerical results are in good agreement with both the GFM and test results.

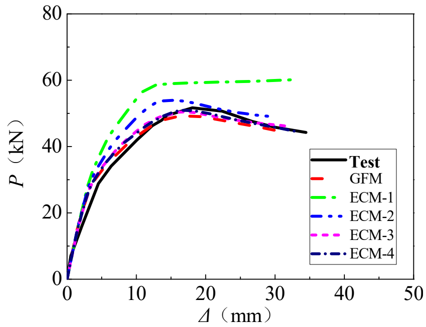
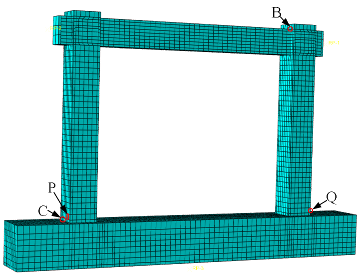


Fig. 2 – Comparison of numerical and test results of corroded RC columns

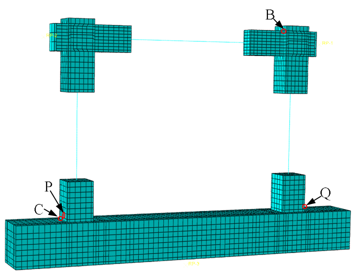
2.3 Model validation

Quasi-static loading tests on six single-bay and single-story RC frames, including five corroded frames and one frame without corrosion, were conducted by the authors [15], which can be used for model validation in this study. Detailed information of the specimen can refer to the work of Liu et al. [15]. Based on the above simulation results of corroded RC column, the length of potential damage region is taken as 1.5*h* in the ECM of RC frames. Both ECM and GFM are established for RC frames, as shown in Fig. 3. Comparison of load-displacement curves between numerical results and test results is shown in Fig. 4. It is found that the load-displacement curves of ECM are in good agreement with GFM and test results. Taking specimen F10-1 as example, the comparison of concrete damage distribution of the frame at failure state is illustrated in Fig. 5. It is found that the concrete damage in both ECM and GFM concentrates in the plastic hinge regions of the RC beam and column, which is in consistent with that of the test results. Both the ECM and GFM can reasonably predict the global behavior and local damage of corroded RC frames.

According to the above comparative analysis, it is indicated that both the GFM and ECM can reasonably predict the global behavior and capture the main damage characteristics of the RC frames. Meanwhile, when the length of damage region l_d is selected to be 1.5h, the computation time of ECM can be significantly reduced in comparison with that of GFM.

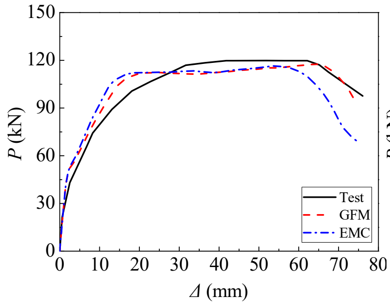


(a) GFM

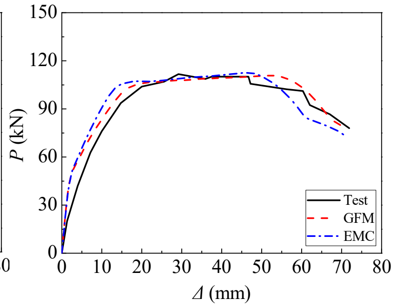


(b) ECM

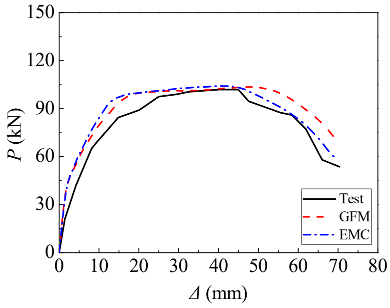
Fig. 3 – GFM and ECM of RC frames



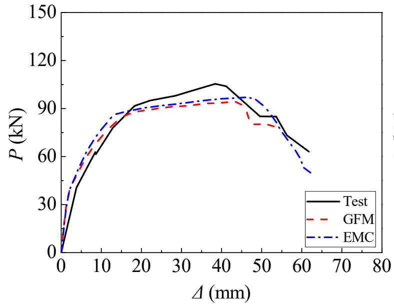
(a) F0-1



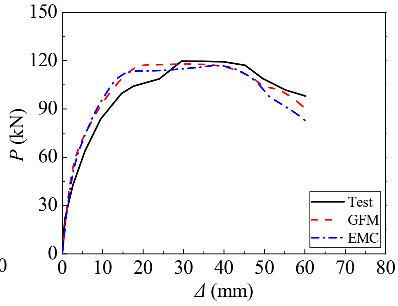
(b) F5-1



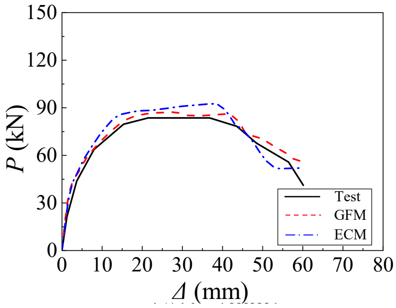
(c) F7.5-1



(d) F10-1

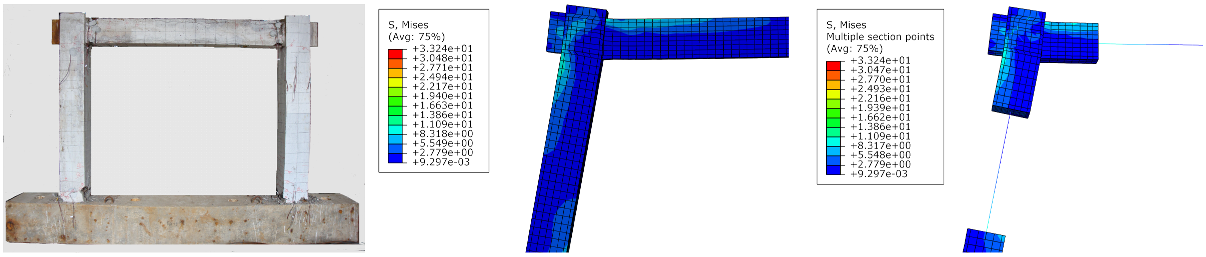


(e) F10-2



(f) F15-1

Fig. 4 – Comparison of load-displacement curves of RC frames



(a) Test (b) GFM model (c) ECM model

Fig. 5 –Comparison of concrete damage distribution of corroded RC frames

3. Analytical model

A typical 4-story RC frame office building located in urban area was chosen as the sample structure. The seismic protection intensity of the structure was 7, and the peak ground acceleration (PGA) values corresponding to frequent earthquake, basic earthquake and rare earthquake, were 35, 100 and 220 gal, respectively. The site soil type considered was Class IV, and the design group was taken as 1. The RC frame structure was designed according to the current Chinese seismic design code. The structural plan layout with cross-sectional dimensions of the components is shown in Fig. 6. The story height of the ground floor was 4 m, while that of the other stories was 3.6 m. The dead load and live load applied on the floor slab were taken as 5 kN/m^2 and 2 kN/m^2, respectively. Considering the gravity of the infill walls, the distributed load applied on the peripheral beams and the interior beams were 12 kN/m and 10 kN/m, respectively. The yielding strengths of longitudinal and stirrup reinforcement were 400 MPa and 335 MPa, respectively, and the cubic compressive strength of concrete was 30 MPa. The software PKPM was used for the structural design. The steel reinforcement area of RC beams and columns was determined adopting the strength-based seismic design principles according to the current Chinese design code. In order to reduce the calculation cost, a typical plane frame from the frame structure was selected as the analytical model. ECM with the potential hinge length of 1.5h was adopted for analytical model, as shown in Fig. 7. General atmospheric environment was considered. According to the environmental condition, the time-based variation of carbonation depth and steel reinforcement corrosion ratio of the structure were calculated and shown in Table 1.

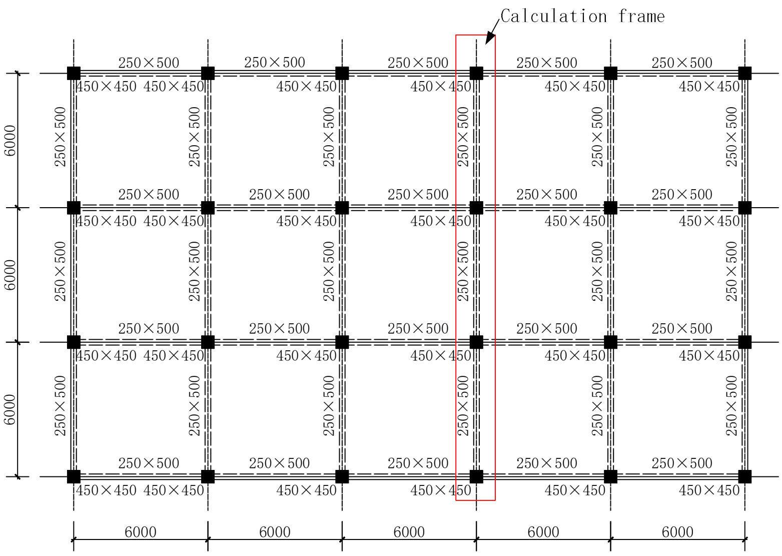


Fig. 6 –Structural plan layout of typical floor

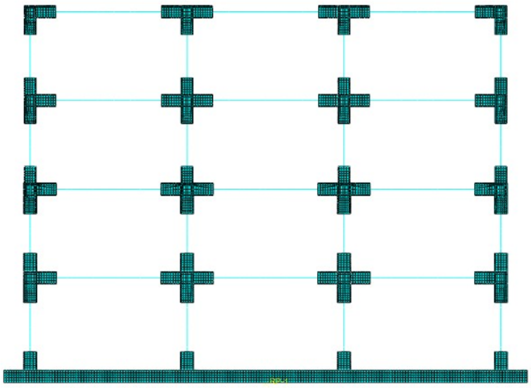


Fig. 7 –ECM of frame structure

3. Analytical results

3.1 Model analysis

The dynamic characteristics of RC frame structures with service time of 0 year, 25 years, 50 years, 75 years and 100 years were evaluated by modal analysis. The natural frequency of the structures is shown in Table 1. For the structure with service time of 25 years, due to the concrete carbonation and little corrosion of steel reinforcement, the stiffness of the structure is a little higher than that of the new structure, which leads to a little larger natural frequency than that of the new structure. For the structures with service time lager than 50 years, the corrosion damage of the structures becomes severe, which results in gradual degradation of structural stiffness and decrease of natural frequency with the increase of service time.

3.2 Time history analysis

According to the site soil condition of Shanghai (sit soil type of IV), a total of 14 earthquake ground motions, including 4 artificially generated motions and 10 natural earthquake motions are recommended in the Shanghai code for seismic design of buildings [16]. In this study, 7 sets of earthquake ground motions, including 2 artificial motions and 5 natural motions are selected from the Shanghai seismic design code [16]. The comparison between response spectrum and design spectra is shown in Fig. 8. It is found that the response spectrum of selected ground motions agrees well with the design spectrum specified in Chinese seismic design code. Meanwhile, the base shear force of the new structures under frequent earthquake ranges from 0.97~1.31 times that obtained from mode-superposition response spectrum method, with an average ratio of 1.12, which indicates that the earthquake motions selected meet the requirement of Chinese seismic design code, and can be used in the time-history analysis.

Table 1 – Natural vibration frequency

Service time (yr)	Carbonation depth (mm)	Corrosion ratio (%)	Natural vibration frequency		
			First mode	Second mode	Third mode
0	0	0	1.036	3.283	5.950
25	20	0.23	1.049	3.327	6.032
50	29	5.97	1.029	3.261	5.910
75	35	13.06	0.992	3.145	5.696
100	41	19.82	0.958	3.043	5.522

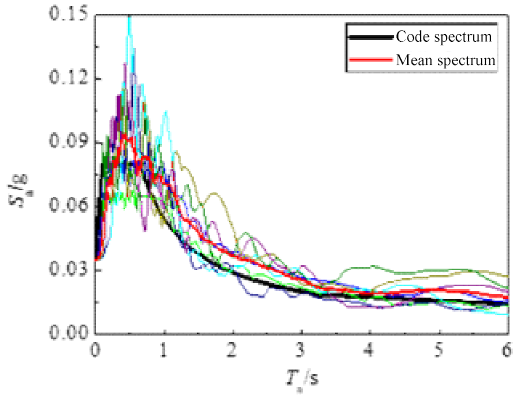
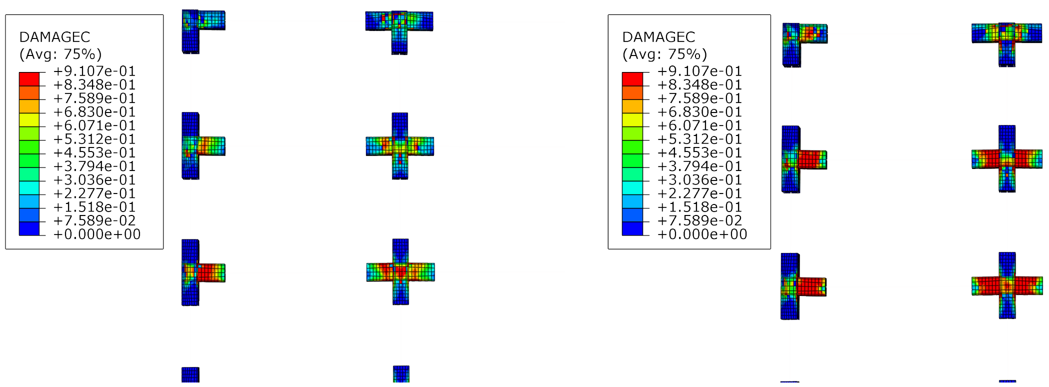


Fig. 8 –Comparison of response spectra

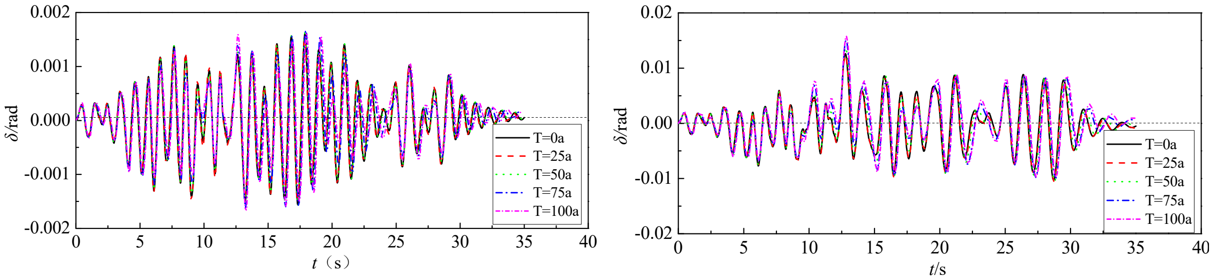
Fig. 9 shows the comparison of concrete damage distribution between new structure and the structure with service time of 100 years under rare earthquakes. It if found that under rare earthquakes, local damage occurs at the end of RC beams and columns. For the structure with service of 100 years, the concrete damage is more severe and distributes in a larger range, in comparison with that of the new structure.

The comparison of inter-story drift ratio history curves of the structures with different service time is shown in Fig. 10. The average envelope of inter-story drift ratio is shown in Fig. 11. As shown in Figs. 10 and 11, it is found that for the structure with service time of 25 years, due to the concrete carbonation and little corrosion of steel reinforcement, the inter-story drift ratio under frequent earthquakes is a little smaller than that of the new structure, while under rare earthquakes the inter-story drift is close to that of the new structure. For structures with service time larger than 50 years, the carbonation depth is larger, and the corrosion damage becomes more severe with the increase of service time, which causes a gradual increase of displacement response with the increase of service time. Under frequent earthquakes, the maximum inter-story drift ratio of structures with service time of 50 years, 75 years, and 100 years increases by 2.0%、4.6% and 4.9 %, respectively, in comparison with that of new structure. While Under rare earthquakes, the maximum inter-story drift ratio of structures with service time of 50 years, 75 years, and 100 years increases by 9.2%、19.8% and 25.1%, respectively. Thus, compared with the displacement response under frequent earthquakes, the service time has more significant effect on the displacement response under rare earthquakes.



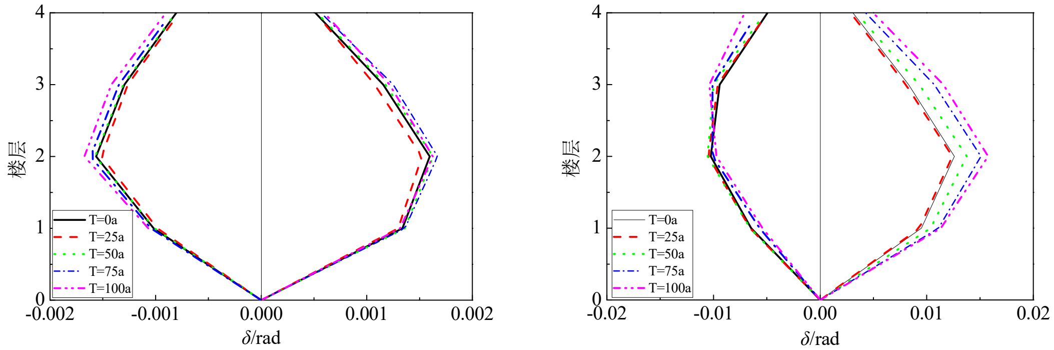
(a) 0 year (b) 100 years

Fig. 9 –Concrete damage distribution of RC frame structures



(a) PGA=35 gal (b) PGA=220 gal

Fig. 10 –Displacement response



(a) PGA=35 gal (b) PGA=220 gal

Fig. 11 –Comparison of the maximum inter-story drift ratio

4. Conclusions

The seismic performance of RC frame structures with different service time was evaluated based on the time-history analysis results. It is found that:

(1) With a superior computation efficiency, the multi-scale modelling technique can be adopted to simulate the global behavior of RC components and frame structures, and capture the main local damage characteristics.

(2) For RC frame structures in normal environmental condition and with service time smaller than 25 years, the performance is similar to that of new structure.

(3) In comparison with the new structure, for RC frame structures with service time of 50 years, 75 years and 100 years, the maximum inter-story under rare earthquakes increases by 9.2%、19.8% and 25.1%, respectively.

4. Acknowledgements

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