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# Nonlinear seismic response analysis on reinforced concrete frame–wall structure with strain rate effect

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## ABSTRACT

The dynamic response on a reinforced concrete (RC) frame-shear wall structure model under seismic excitation is studied in this paper. Based on the model in a shaking table test, a three-dimensional finite element model of RC frame-shear wall structure subjected to both horizontal and vertical component earthquake inputs is established. The structural model is a three-story RC frame-shear wall linked by RC slab and transverse spandrel beams. The side frame is infilled by a reinforced wall. Considering the effects of strain rate, top displacement and acceleration of the model are studied using nonlinear time history analytical method. These results may provide a reference for seismic design of RC structure.

Key words: strain rate; reinforced concrete; frame-shear wall; seismic; nonlinear

## 1. INTRODUCTION

The reinforced concrete (RC) structures are required to resist dynamic loads when subjected to seismic loading. The mechanical and deformation properties of reinforcing steel and concrete are rate dependent under dynamic loads. The strain rate effect of concrete was firstly reported by Abrams (Abrams 1917), and analytical and experimental results presented by numerous investigators over the past few decades. The mechanical properties of concrete and reinforcing steel are studied (Fu *et al.* 1991), (Wakabayashi *et al.* 1980). Strain rates of concrete and reinforcing steel subjected to earthquake loading, which are ranging from $10^{-4}$/s to $10^{-1}$/s. The strain rate of the concrete under a severe earthquake is about $10^{-2}$/s. At this rate, the strength of

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concrete will be increased 1.2 times on the basis of the previous investigations (Shimazaki *et al.* 1998). The strain rate of reinforcing steel is about $10^{-1}$/s under a severe earthquake (Li *et al.* 2010), and the yield strength will be increased more. Hence, the strength, stiffness and ductility of reinforced concrete structures will be affected by strain rate. Since the mechanical properties of concrete and reinforcing steel are strain rate sensitivity, nonlinear seismic response analysis that considering strain rate effect is more accurate. However, investigations on nonlinear seismic response analysis that consider strain rate effect have seldom been reported, due to the lack of dynamic constitutive models of structural materials.

In this paper, a finite element model of a RC frame-wall scale model in a practical shaking table test is established. Using the nonlinear time history analytical method, the dynamic response and damage features under earthquake excitations are studied with strain rate. Finally, some significant conclusions are drawn based on the analytical results.

## 2. DESCRIPTION OF THE ANALYTICAL MODEL

The case study model that is a 3D reinforced frame-wall scale model, composed by three floors and two spans, illustrated in Fig. 1. The finite element model is shown in Fig. 2. The plat form selected for the seismic response is ABAQUS, a commercial software with an extensive library of elements for the engineering analysis of structural system. The proposed fiber beam element is used to simulate the beams and columns, and the beams and columns are modeled by three-dimension one-node linear rectangular beam. The four-node quadrilateral stress/displacement shell elements with rebar layers are used for slabs and shear walls. The nodes of the columns in first floor are fixed on the ground and the rigid connections are used for the beam-column joints.

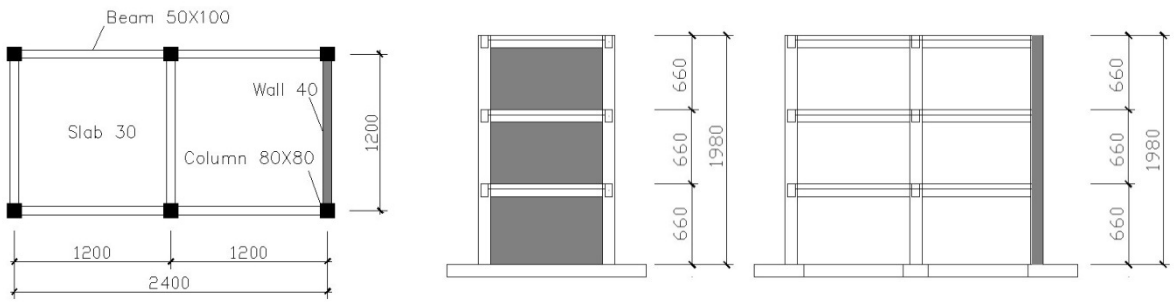



Fig. 1 3D case study model: plan and elevation of the model

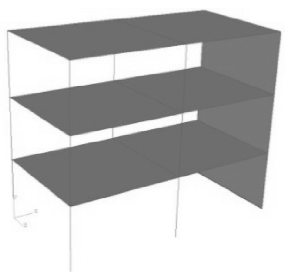


Fig. 2 Finite element model

## 3. MATERIAL MODELS WITH STAIN RATE EFFECT

The scale models in shaking table test are often casted by microconcrete and iron wire instead of concrete and reinforcing steel. Hence, the dynamic constitutive relationships of microconcrete and iron wire are used to calculate nonlinear seismic response of the model.

### *3.1 iron wire*

The Young's modulus of iron wire is about 70000MPa, the yield strength of iron wire in beams and columns is 269MPa, and the yield strength of iron wire in walls and slabs is about 355MPa. The plastic model of metal is used in the analytical model. Based on the dynamic tensile test at earthquake strain rate, the DIF which is the function of strain rate and quasi-static yield strength of iron wire is given as follow:

$$DIF_{fy} = \frac{f_{yd}}{f_{ys}} = 1.0 + 0.0456 \lg\left(\frac{\dot{\varepsilon}_w}{\dot{\varepsilon}_{w0}}\right) \tag{1}$$

Where $\dot{\varepsilon}_w$ is the strain rate, $\dot{\varepsilon}_{w0}$=2.5×10$^{-4}$/s is the quasi-static stain rate, $f_{ys}$ and $f_{yd}$ are the quasi-static and dynamic yield strength, $f_{us}$ and $f_{ud}$ are the quasi-static and dynamic tensile strength.

### *3.2 microconcrete*

The properties of microconcrete (diameter of coarse aggregate less than 5mm) are similar to structural concrete. The compressive strength of microconcrete is 7.5MPa. The uniaxial compressive and tensile constitutive models in code for design of concrete structures (GB50010 2010) in China are used.

For compressive failure stress increase, relationship obtained from dynamic compressive test of microconcrete at earthquake strain rate providing the DIF value is the following:

$$DIF_{fc} = f_{cd}/f_{cs} = 0.9892 + 0.08607 \lg(\dot{\varepsilon} / \dot{\varepsilon}_0) \tag{2}$$

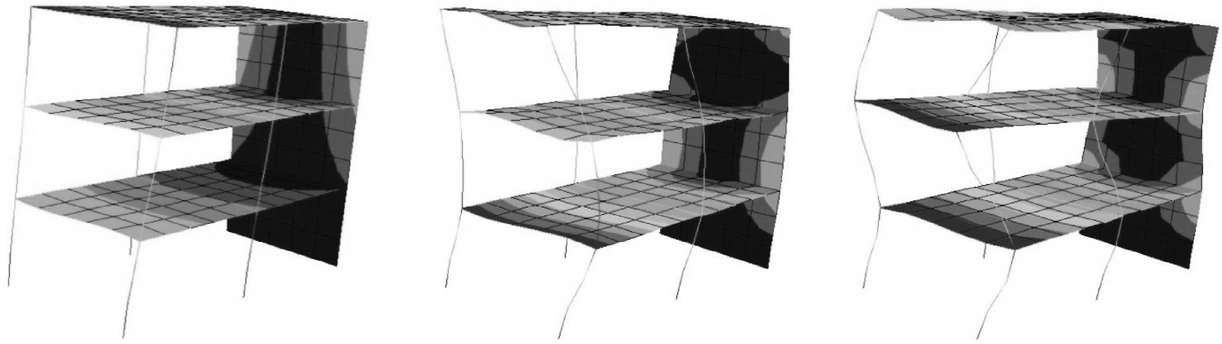
For tensile failure stress increase, relationship obtained from dynamic tensile test of concrete (C10) at earthquake strain rate providing the DIF value is the following (Yan 2006):

$$DIF_{ft} = f_{td} / f_{ts} = 1.0 + 0.135 \lg(\dot{\varepsilon} / \dot{\varepsilon}_0) \tag{3}$$

where $f_{cd}$ and $f_{td}$ are the dynamic compressive and tensile strength, respectively, $f_{cs}$ and $f_{ts}$ are the compressive and tensile strength under quasi-static stain rate, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ =10$^{-5}$/s is the quasi-static stain rate.

## 4. MODAL ANALYSIS

The first three vibration mode shapes of model were shown in Fig. 3. The model results in a first natural frequency of 4.407Hz, as compared with the value of 4.425Hz that was obtained from acceleration measurements under ambient vibration.

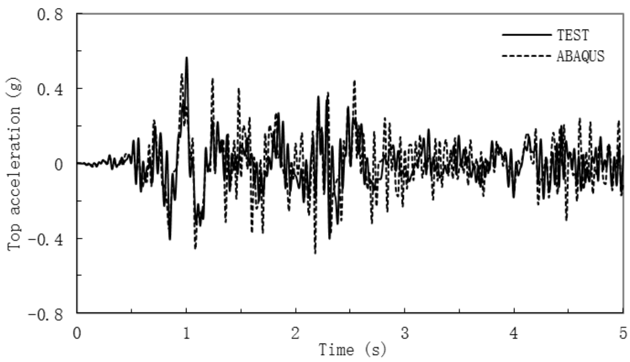


(a) $f_1$=4.407Hz (b) $f_2$=14.132Hz (c) $f_3$=24.414Hz

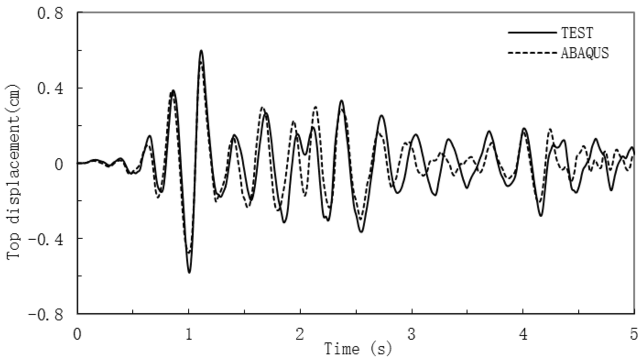
Fig. 3 The first three vibration mode shapes

## 5. NONLINEAR DYNAMIC RESPONSE ANALYSIS

Based on the loading scheme of shaking table test, the El Centro wave is chosen for the seismic excitation. The nonlinear dynamic response of the model subjected to horizontal and vertical seismic excitations are analyzed using the explicit integration method. Considering the effects of strain rate, the responses of top acceleration and displacement obtained from the numerical results are shown in Fig. 4, as compared with the test results in the shaking table test.




(a) Top acceleration




(b) Top displacement

Fig. 4 Responses of model at 0.4g El Centro wave

## 6. CONCLUSIONS

Taking into account the effects of strain rate, the nonlinear dynamic responses of a scale model in shaking table test are studied. The numerical results are match well with the results obtained from the shaking table test. The conclusions can provide a reference for seismic design of RC structures.

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