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Experimental and numerical investigations on seismic responses of reinforced concrete structures considering strain rate effect

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HIGHLIGHTS

- DIFs for the key material parameters of micro-concrete and iron wire are suggested.
- Shaking table test of a 1/5 scaled RC structural model is conducted.
- A three-dimensional rate-dependent fiber beam-column element model is proposed.
- Effectiveness of the proposed model is validated by the shaking table test data.

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ABSTRACT

The strain rate effect can inevitably impact the seismic responses of reinforced concrete (RC) structures because the dynamic properties of RC materials under earthquakes change significantly with the time-varying loading rates. This paper carries out systematic experimental tests and numerical simulations to investigate the effects of strain rates on the seismic responses of RC structures. The dynamic properties of micro-concrete and iron wire used in the shaking table specimen are firstly tested under seismic loading rates and the corresponding dynamic increase factors (DIFs) are estimated based on the test data. The shaking table test of a 1/5 scaled RC structure is performed to realistically reproduce the dynamic responses of RC structures with strain rate effect. Moreover, a three-dimensional rate-dependent fiber beam-column element is developed in the ABAQUS platform to establish the finite element (FE) model of the shaking table specimen, in which the estimated DIFs for the key parameters of micro-concrete and iron wire are employed to consider the strain rate effect. Besides, the rate-independent structural FE model is also developed using the traditional beam-column element with the static RC material constitutive models. The numerical results demonstrate that the seismic responses of RC structures are overestimated when the strain rate effect is neglected. As validated by the experimental data of the shaking table test, the FE model developed using the proposed rate-dependent fiber beam-column element can yield better structural seismic response predictions in comparison with the rate-independent model.

1. Introduction

Reinforced concrete (RC) structures have been extensively used in multistory and high-rise buildings due to their advantages of excellent structural integrity, durability and high economic efficiency. During their service periods, RC structures may be subjected to strong earthquake ground motions. The strain rates of reinforcing steel and concrete materials at critical sections of RC structural members may reach as high as 1 s^{-1}. Fu et al. [1] and Bischoff and Perry [2] systematically reviewed the compressive behavior of concrete at high strain rates, while the strain rate effect on the tensile strength of concrete was reviewed by Malvar and Rose [3] and Thomas and Sorensen [4]. It was reported that the compressive and tensile strength of concrete can be obviously increased at the strain rates induced by seismic loading. Moreover, the tensile strength of concrete is more susceptible to increase than the compressive strength. In addition, the mechanical properties of reinforcing steels under seismic strain rates were also examined by many researchers through dynamic loading tests [5–12]. The experimental findings indicated that the yield strength and ultimate tensile strength of reinforcing steels increase linearly with the logarithmical increase of strain rate, and the effect of strain rate

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on the lower strength reinforcing steels is more significant as compared with that on the higher strength reinforcing steels.

In current literature, many investigations are focused on the effects of loading rates on the seismic behavior of RC members. The dynamic tests of simply supported and doubly reinforced beams were performed by Bertero et al. [13] to assess the influence of loading rate on the behavior of RC beams. It was found that the stiffness before the first yielding of reinforcing steel for the beams under the higher loading rate increases about 10% as compared with that for the beams under the lower loading rate. Significantly increases in the initial yield strength were also observed, but the effect of loading rate on the ultimate strength, flexural failure mode, measured strain, curvature and deflection ductility factors of the beams is not evident. The similar conclusions were obtained by Kulkarni and Shah [14], who carried out the experimental tests of seven pairs of RC beams subjected to static and high loading rates. It was also reported in the aforementioned studies that the failure mode of the RC beams may shift from brittle shear failure at the lower strain rate to the ductile flexural failure at higher strain rates. Otani et al. [15] performed a series of tests on four pairs of cantilever RC beams under static and dynamic loads to study the potential effects of strain rate. The specimens were tested in the vertical position and loaded horizontally using a dynamic actuator. The results showed that the seismic strain rate increased the flexural resistance of RC beams by 7%–20%. Li and Li [16] studied the dynamic behavior of simply supported RC beams with different shear spans through dynamic tests, in which the influence of loading rate on the bearing capacity, ductility, stiffness, failure mode and energy absorbing of beam specimens were systematically analyzed.

Ghannoum et al. [17] investigated the dynamic behaviors of RC columns subjected to the cyclic loadings at different strain rates. The test results showed that the lateral bearing capacity of RC columns can increase up to 33% when the loading rates are taken into account. The mechanical properties of RC columns under multi-dimensional dynamic loadings were investigated by Wang et al. [18]. Comparisons of test results indicated that the strength, stiffness, ductility, damage, energy absorption and failure mode were all influenced by the loading rate. Carrillo and Alcocer [19] studied the seismic performance of 12 RC walls using the quasi-static cyclic loading and shaking table tests. It was observed that stiffness and strength degradation properties of RC walls were dependent on the loading rate.

It should be noted that most of the previous studies are focused on the mechanical properties of RC materials or members under quasi-static and dynamic loadings through the laboratory tests. However, the experimental studies on the influence of strain rate on the seismic responses of RC structures are very rare. Numerical simulation method can provide an alternative way to effectively and practically predict the seismic responses of RC structures with inclusion of strain rate effect. Pandey et al. [20] analyzed the transient dynamic responses of three-dimensional RC structures based on a strain rate dependent concrete model. Guner and Vecchio [21] conducted the global seismic response analyses of RC frame structures, in which the strain rate effects are considered using the dynamic increase factors (DIFs) of concrete and reinforcing steel materials. Wang et al. [22] numerically studied the effect of strain rate on the seismic behaviors of recycled aggregate concrete frame structures. Moreover, the influence of strain rate on the seismic responses and fragilities of RC structures was examined by Asprone et al. [23]. The above-mentioned numerical investigations demonstrated that the rate-dependent properties of RC materials should be reasonably taken into consideration to precisely predict the seismic responses of RC frame structures.

Up to date, shaking table test is universally acknowledged to be the most appropriate and accurate method for reproducing the seismic dynamic responses of RC structures since the actual strain rate effects of RC materials under earthquake excitations can be experienced. In this paper, the shaking table test of a 1/5 scaled RC structure is performed to investigate the effects of strain rates on the dynamic responses of RC structures under earthquake excitations. The dynamic properties of micro-concrete and iron wire used in the test specimen are experimentally investigated under seismic loading rates and the corresponding DIFs are estimated based on the regression analyses of the test results. Moreover, a three-dimensional rate-dependent beam-column element model with fiber sections is developed for the numerical simulation of seismic responses of RC structures with inclusion of strain rate effect. The ABAQUS analysis platform is employed to develop the three-dimensional finite element (FE) model of the shaking table specimen, in which the estimated DIFs are used to simulate the rate-dependent properties of the micro-concrete and iron wire. The numerically calculated structural seismic responses are validated by the experimental data obtained from the shaking table test. The effects of strain rates on the seismic performance of the RC structure are analyzed and discussed in detail.

2. Dynamic loading tests of the materials in shaking table specimen

To fabricate scaled RC structural models for shaking table tests, the micro-concrete and iron wire are commonly used to replace the ordinary concrete and reinforcing steels in the prototype structure. In this section, the dynamic loading tests are conducted to investigate the rate-dependent properties of micro-concrete and iron wire used in the shaking table specimen. The DIFs for the key parameters of these two materials are estimated based on the regression analyses of the test results.

2.1. Micro-concrete

Micro-concrete is composed by a certain proportion of cement, silver sand, gravel (Diameter < 5 mm) and water, and its maximum compressive strength is generally less than 15 MPa. The quasi-static mechanical properties of micro-concrete were experimentally studied by Yang et al. [24]. It was revealed that stress-strain curves of micro-concrete are very similar to those of the ordinary concrete. Shen et al. [25] experimentally investigated the dynamic properties of micro-concrete under compression at different loading rates. The results illustrated that the dynamic compressive strength and elastic modulus of micro-concrete increase with strain rate, and the constitutive relation and failure mode are quite similar to those of ordinary concrete at different strain rates.

In this study, the uniaxial compressive tests of micro-concrete are conducted using the electro-hydraulic servo-controlled system under the loading rates of 10^{-5}–10^{-2} s^{-1}, which corresponds to the range of strain rates induced by seismic loading [2]. The dynamic test equipment and installation of micro-concrete specimen are shown in Fig. 1. The dimension of the micro-concrete cubic specimen is 100 mm × 100 mm × 100 mm, and the test specimens are cured simultaneously with the RC shaking table specimen in the natural environment. Table 1 presents the mixed proportions of the micro-concrete. The displacement control method was adopted in the test and the loading rate remains constant during each loading process. Moreover, the test data is recorded by a high speed data acquisition system. For each loading rate case, at least three specimens are tested and the number of specimens is increased if the dispersion of the test results is relatively large.

Based on the test results, the averaged stress-strain curves for the micro-concrete specimens at different strain rates are calculated, as plotted in Fig. 2. It can be observed that with the increase