Engineering Structures 49 (2013) 248–263

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental studies on nonlinear seismic control of a steel–concrete hybrid structure using MR dampers

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ARTICLE INFO

Article history:
Received 26 April 2012
Revised 9 October 2012
Accepted 16 October 2012
Available online 25 December 2012

Keywords:
Steel–concrete hybrid structure
Magnetorheological (MR) damper
Semi-active control
Shaking table test
Seismic damage
Simple on–off control
Nonlinear seismic control

ABSTRACT

This article presents experimental studies on the feasibility of nonlinear seismic control of a 3-story steel–concrete hybrid structure using magnetorheological (MR) dampers. The control strategies included passive-on control, passive-off control and semi-active control, and strains gathered at the bottom of the steel columns were used as feedbacks to build the semi-active controller. For each control type, the control efficacy on structural response and damage was verified for the El Centro, Taft and Tianjin earthquake with specified peak ground acceleration (PGA) of 0.2*g*, 0.4*g*, 0.9*g* and 1.2*g* respectively. The test results show that (1) it is feasible to control the seismic response of the steel–concrete hybrid structure using MR dampers; (2) structure with semi-active control and passive-on control perform better in the shaking table test considering the maximum inter-story drift, displacement time history and energy dissipation capacity, compared to uncontrolled structure and structure with passive-off control; (3) there is also more structural damage in the passive-off and uncontrolled cases, proving the effectiveness of MR dampers in damage control. In addition, an inverse calculation method for strain is proposed to effectively utilize the strains measured during the shaking table test to obtain the stress and material damage process at measured positions, using damage model of the steel and concrete material.

1. Introduction

Steel–concrete hybrid structures have many advantages, such as the light weight, small cross-section, high stiffness and speedy construction compared to reinforced concrete structures, and good fire resistance, reduction in steel consumption and higher resident comfort level under wind loading compared to steel structures. However, due to their poor performance in the 1964 Great Alaskan Earthquake and the 1995 Kobe Earthquake, no more buildings using steel–concrete hybrid structural system were built afterwards. In recent years, a large number of super high-rise buildings using steel–concrete hybrid structural system were constructed in China, and extensive experimental studies have been conducted in order to explore the seismic performance of this type of structure, with some positive results.

New approaches are needed to enhance the seismic and collapse resistance of steel–concrete hybrid structures, while structural control techniques [1–3] have been proven effective, especially the semi-active control method [4] using MR dampers. For example, Dyke et al. [5] proposed a new clipped-optimal control strategy based on acceleration feedbacks and the control efficacy was verified by the shaking table test of a three-story model building. Ni et al. [6] proposed a neuro-control method for semi-active vibration control of stay cables using MR dampers. Lim et al. [7] conducted a shaking table test of a full-scale one-story building structure equipped with MR dampers, and found that MR dampers could mitigate the structural response under strong earthquake excitations effectively.

In addition, this type of dampers was also proven to have low power consumption, direct feedback, high reliability and fail-safe mechanism. The manufacturing issues, powering, range of variability of the mechanical parameters, dependence on the feed current and overall response time were studied by Occhiuzzi et al. [8], who found that MR dampers are quite versatile for the control of structural dynamic responses, and can be driven to operate in a rather broad range of physical behaviors. Sun et al. [9] conducted a shaking table test of a scaled three-story steel frame structure and the results showed that MR dampers slightly increased the structural stiffness and damping ratio. Yoshida et al. [10,11] conducted theoretical and experimental studies to examine the coupled lateral and torsional motions of building structures with asymmetric stiffness distribution. Shook et al. [12] optimized the fuzzy logic controllers by a genetic algorithm, and the controllers were designed to manage two 20 kN MR dampers for mitigation of seismic loads on a three-story steel frame benchmark building. The results

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http://dx.doi.org/10.1016/j.engstruct.2012.10.031

showed that the controllers were robust and effective in reducing both the displacement and the acceleration, and they further used the controllers to mitigate the torsional response in structures [13].

Most of the studies stated above were within the field of linear system. To consider the characteristics of real structures during a strong earthquake, Ohtori et al. [14] presented the third generation benchmark problem for structural control of three typical steel frame structures considering nonlinear material properties, which has been studied by Yoshida and Dyke [15] and Wongprasert and Symans [16] respectively, and obtained similar conclusions to the linear control systems.

2. Aims and scope

The aim of this study is to verify the feasibility of using MR dampers to reduce the seismic response of steel–concrete structures under small to strong earthquakes. The experiment was conducted on a scaled 3-story steel–concrete hybrid structure model, and three earthquake records, the El Centro, Taft and Tianjin earthquake, were applied to excite the shaking table. The intensities of the earthquake records are 0.2*g*, 0.4*g*, 0.9*g* and 1.2*g*, which are associated with the small, medium and strong earthquake in China, and the 1.2*g* level was chosen for the destructive test. With the increase of PGA, the structure enters the plastic state, so the seismic control using MR dampers should consider the nonlinear property. Furthermore, the present research was focused on the reduction of structural seismic responses instead of control algorithm. The hysteretic behavior of MR dampers were tested and semi-active control algorithm was developed using feedbacks from strains and embedded into the MATLAB/Simulink program. The control efficacy is validated through story drifts, displacement time history responses, energy dissipation capacity and damage analysis.

3. Control algorithm implementation

3.1. Semi-active control strategy

The semi-active control system comprised of sensors, actuators and controller. As the main objective of this study was to investigate the nonlinear control efficacy of steel–concrete hybrid structures during a strong earthquake, the simple on–off control strategy was employed with drift and velocity as feedback, and the semi-active control law was expressed in Eq. (1) as,

$$F(t) = \begin{cases} F_{I,\max} & x\dot{x} > 0 \\ F_{I,\min} & x\dot{x} \leqslant 0 \end{cases} \tag{1}$$

where $F(t)$ is the control force at time t, $F_{I,\max}$ and $F_{I,\min}$ are the maximum and minimum control force, and x and $\dot{x}$ are the inter-story drift and velocity of the piston, respectively. The major components of the control procedure embedded in the MATLAB/Simulink program are shown in Fig. 1.

As the semi-active control law is activated by the sign of the product of displacement and velocity, the strains measured at the bottom of the columns were used as the feedback. It should be noted that the whole Wheatstone bridge with shielded wires must be used to mitigate the AC noise.

3.2. MR dampers

Two self-developed MR-J type dampers were tested on a servo hydraulic dynamic testing machine at Tianjin University of China, as shown in Fig. 2. 30 loading cases were carried out with amplitudes of 5, 10 and 15 mm, frequencies of 0.5 and 1.0 Hz, and current levels of 0, 0.5, 1.0, 2.0, 3.0 A. The performance of MR-J1 damper and MR-J2 damper are shown in Fig. 3, which were subjected to harmonic excitations with an amplitude of 10 mm, a frequency of 0.5 Hz, and varying current levels. It is clear that the maximum output force of MR-J type dampers increased with the applied current, and increased from 0.5 kN to 4 kN as the current varied from 0 A to 3 A.

4. Experimental setup

4.1. Experimental model

Experimental investigations were performed on a 3 × 3 m shaking table, which is capable of carrying a maximum payload of 10 tons, and providing a maximum no-load acceleration of 25 m/s^2 and full-load acceleration of 10 m/s^2 in one horizontal direction. The hydraulic actuator can produce a stroke of ±12.7 cm, and the operation frequency ranges from 0.1 to 50 Hz.

A 1/4 scale 3-story steel–concrete hybrid structure was employed as the test specimen. The experimental model was one span of the top three stories of a high-rise building. Because it was a destructive experiment, the model design had considered the capacity and size of the shaking table and the maximum control force of the MR dampers. As a result, the scale factor for the span was 1/4 to fit onto the shaking table, and the scale factor for the member cross-sections were much smaller to ensure that the test specimen would be damaged at the full capacity of the shaking table. The ground motion magnitude considered in the specimen design was degree 8 (0.3*g*) in the Chinese seismic code, and the corresponding PGA values for small, medium and strong earthquake were 0.1*g*, 0.2*g* and 0.4*g*.

The specimen dimension was 1.555 m long by 1.2 m wide in plan, and 2.4 m high in elevation, as shown in Fig. 4. Six steel boxes with additional weights were welded to the steel beams connecting the RC columns and the steel frames, with a total mass of

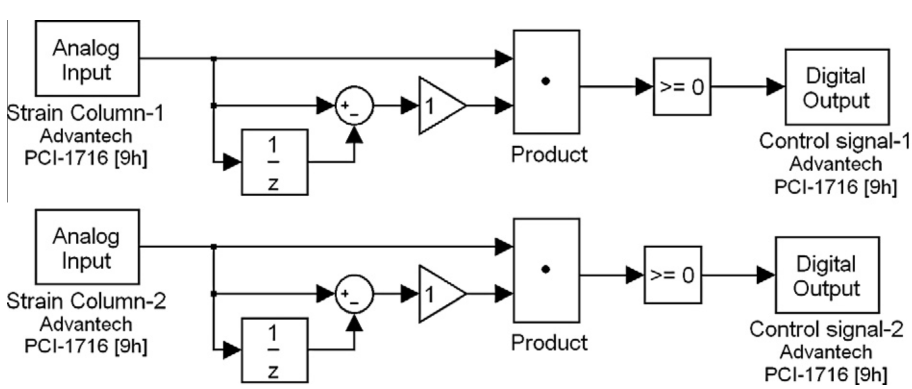

Fig. 1. Diagram of the control procedure.