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Shaking Table Test of Controlled Rocking Reinforced Concrete Frames

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ABSTRACT

The controlled rocking reinforced concrete frame (CR-RCF) is a new type of seismic structure system with resilient rocking columns and column-beam joints. The effects of earthquakes on this type of structure are reduced by weakening the overall stiffness of the structure, and the lateral displacement is controlled by energy-dissipation dampers. Two types of CR-RCF are proposed, one with beam-end-hinge joints and the other with column-end-hinge joints. The seismic performance of the CR-RCFs was comparatively studied against a conventional frame by a shaking table test. The rocking mechanism and construction details of rocking joints are introduced, and the design of the three 1/3 scale 3-story-3-span models is also outlined. The dynamic characteristics and seismic responses of the three models are analyzed and compared. The test results indicate that the main bodies of the CR-RCF remaining intact under the major earthquake test, and the inter-story drifts could be effectively controlled by adding metallic dampers. Based on the test results, a conclusion can be reached that the CR-RCF is a damage-free structure system with an excellent self-centering capability during earthquakes.

KEYWORDS: *controlled rocking RC frame, post-tensioned tendon, seismic performance, shaking table test*

1. INTRODUCTION

The concept of the *rocking structure* was proposed by G. W. Housner [1]. After decades of development, the rocking structure has been transformed into the way by which a structure restores its original position through prestressing forces other than its self-weight. Unbonded post-tensioned (PT) prestressing tendons are used to provide the elastic restoring force of rocking joints, which enables the kinetic energy of the structure to be converted into the potential energy of prestressing tendons during an earthquake [2]. In recent years, an increasing number of studies have considered the seismic performance of the overall rocking structure. The research has focused on reinforced concrete and steel frames, and several shaking table tests of large-scale rocking structure models have been conducted [3-6].

Based on a series of studies on the rocking structures, the authors of the current study proposed a new type of energy-dissipation structure system: the Controlled Rocking Reinforced Concrete Frame (CR-RCF) [7]. Several types of CR-RCF structural forms were conceived. In this paper, shaking table tests for two types of CR-RCF models are introduced; the two CR-RCF models are CR-RCFb (CR-RCF with Beam-end-hinge joints) and CR-RCFc (CR-RCF with Column-end-hinge joints). The main difference between these two models is in the configurations of the beam-column joints. The main structural features of CR-RCF are as follows: (1) all beam-column joints are hinge joints, and component-embedded post-tensioned tendons are used to provide the restoring forces of the joints; and (2) inter-story dampers are installed to dissipate the earthquake energy and control the displacement response of the structure.

For comparative study, a shaking table test of a conventional Reinforced Concrete Frame (RCF) was performed simultaneously. The anti-seismic performance of CR-RCF was verified through the shaking table tests. The performance of CR-RCF in terms of seismic behaviors was evaluated by comparative analysis of the dynamic characteristics, acceleration and displacement responses of the test models.

2. DESIGN OF THE SHAKING TABLE TEST MODELS

2.1. Model Overview

Because 3D structure models are complicated in an exploration study, all models for the shaking table test were 2D frame models. Two 1/3 scale CR-RCF models and one 1/3 scale RCF model were designed with the same overall dimensions and component cross-section dimensions [8]. The general overview of the prototype and the models are shown in Table 2.1, and the model similitude ratios are shown in Table 2.2.

Table 2.1 Design parameters of the 1/3 scale shaking table models

Item	Prototype	1/3 scaled model
Number of stories	3	3
Floor height	3.6 m	1.2 m
Total height	10.8 m	3.6 m
Plane dimension	13.5 m × 5.4 m	4.5 m × 1.8 m
Cross section of the beam	300 mm × 450 mm	100 mm × 150 mm
Cross section of the column	450 mm × 450 mm	150 mm × 150 mm
Concrete strength	19.1 MPa	19.1 MPa

Table 2.2 Dynamic similitude relationships of the shaking table test (Model/Prototype)

Physical properties	Parameters	Similitude Relationship	Similitude ratios	Remarks
Geometry	Length	S_l	1/3	Size control
Material	Strain	$S_\varepsilon=1$	1	
	Modulus of elasticity	S_E	1	
	Stress	$S_\sigma=S_E$	1	
	Mass density	$S_\rho=\frac{S_E}{S_a S_l}$	3/2	
Load	Concentrated force	$S_p=S_\sigma S_l^2$	1/9	
	Moment	$S_{Mb}=S_\sigma S_l^3$	1/27	
Dynamics	Stiffness	$S_K=S_\sigma S_l$	1/3	
	Time	$S_t=\sqrt{S_l/S_a}$	$1/\sqrt{6}$	
	Damping	$S_c=\frac{S_\sigma S_l^{1.5}}{\sqrt{S_a}}$	$1/\sqrt{54}$	
	Acceleration	S_a	2	Test control

The three 1/3 scale models of CR-RCFc, CR-RCFb and RCF had the same concrete strengths. The initial controlled stress of the post-tensioned tendons was 0.35 f_{ptk} (f_{ptk} is the standard value of the ultimate strength). The section area of the prestressed tendons in the components, which is a critical parameter for the lateral stiffness of the CR-RCF structures, was adopted based on the literature [9]. The shaking table test models are shown in Fig. 2.1.

2.2. Joint Design of CR-RCF Models

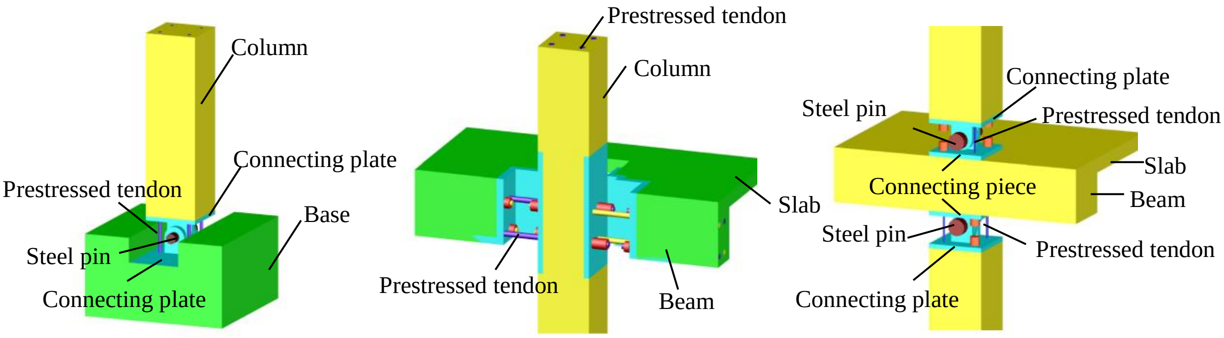
Unlike conventional frame joints, CR-RCF structure nodes have a designated rotational stiffness. A schematic drawing of the column base is shown in Fig. 2.2(a).

The joint configurations of CR-RCFb and CR-RCFc were different. For the CR-RCFb model, four ducts were reserved for prestressing tendons or wires through each column and beam, unbonded post-tensioned tendons were clamped by single-hole anchors in the column, and two prestressing wires were arranged diagonally in the beam; Fig. 2.2(b) shows the details. For the CR-RCFc model, four ducts were reserved for unbonded prestressing steel wires through each column, the diagonally arranged prestressing wires were anchored at both the column end and the floor slab, and there were no prestressed wires in any beam; the details are shown in Fig. 2.2(c).

(a) CR-RCFb (b) CR-RCFc (c) RCF

Figure 2.1 Shaking table test models

The foundation, column, beam and slab formed a whole CR-RCF structure through prestressing. The structure of CR-RCF would rock in moderate and large earthquakes. The prestressed tendons would restore the structure to its initial position, the main load-bearing components would remain intact, and the prestressed tendons would always be in an elastic state.



(a) Column-base (b) CR-RCFb (c) CR-RCFc

Figure 2.2 Details of CR-RCF joints

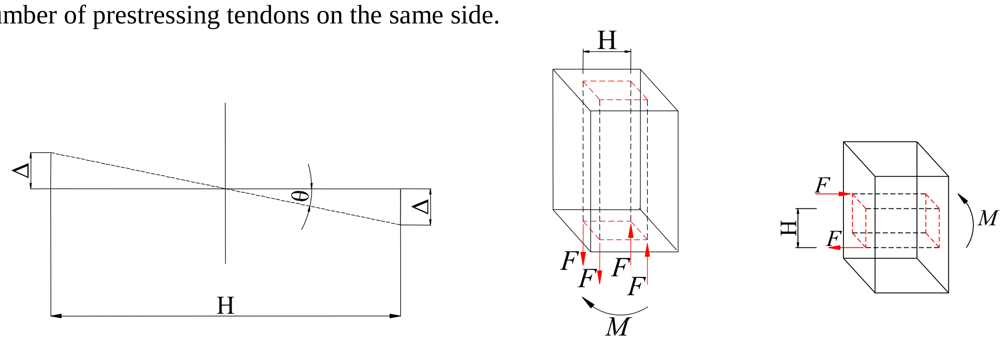
Joint rotational stiffness determines the overall lateral resistance stiffness of the CR-RCF structure, so the selection of the appropriate node rotational stiffness is crucial to the seismic behavior of the CR-RCF. Based on the research results of the literature [9], the node rotational stiffness calculation is explained as follows.

By the plane cross-section assumption, the theoretical stiffness equation was derived, neglecting the frictional effect. In this process, it was also assumed that the prestressing tendons do not yield or exhibit zero stress, which may be avoided by reasonably controlling the initial effective prestress of the prestressing tendons. The rocking joints remain elastic, even under large displacements. Fig. 2.3(a) shows the geometric distortion of the rocking joints of the CR-RCF. The mechanical parameters of the prestressing tendons are expressed as Eq. 2.1. The force diagrams of the rocking joints are shown in Fig. 2.3 (b) and (c). The theoretical stiffness of each rocking joint is defined by Eq. 2.2.

$$\Delta = \frac{H\theta}{2}, \quad \varepsilon = \frac{\Delta}{L} \quad \text{and} \quad F = EA\varepsilon \tag{2.1}$$

$$K_R = \frac{M}{\theta} = \frac{nEAH^2}{2L} \tag{2.2}$$

where
H = distance over the depth of the column between the unbonded prestressing tendons;
L = effective length of the tendons;
θ = rotational angle;
Δ = variation of the length of one tendon, where ε is the strain of one tendon;
F = variation of the tensile force of one tendon, where A is the cross-sectional area of one tendon;
E = elastic modulus of the prestressing tendon; and
n = number of prestressing tendons on the same side.



(a) Geometric relationship (b) Column (c) Beam

Figure 2.3 Force diagram of the rocking joints

2.3. Design of Inter-story Dampers of CR-RCF

The overall stiffness of the CR-RCF structure is much smaller than that of the conventional RCF structure; therefore, the CR-RCF structure has a larger displacement response than the conventional RCF structure under the action of a moderate or large earthquake. To control the seismic displacement response of the CR-RCF structure and dissipate the seismic energy, the inter-story dampers were strategically placed between the floors of the CR-RCF structure. In the shaking table test, X-shaped mild steel dampers were used.

3. NUMERICAL MODELING OF THE CR-RCF

3.1. FEM Elements

The finite element program ABAQUS was used to perform the numerical modeling work. The connection element *Hinge* provided by ABAQUS was adopted to model the column-base joint and beam-column joint. The connection element *Rotation* was adopted to model the friction damping and was used to define the damping characteristic. The connection element *Cartesian* was adopted to model the X-shaped metallic damper. The beam, column and brace were modeled using the beam element *B31*. Schematic diagrams of the typical analytical models are presented in Fig. 3.1.

3.2. Overview of the Analytical Models

The software ABAQUS was used to simulate the three models (RCF, CR-RCFb and CR-RCFc) [10]. The overall dimensions and component section dimensions of the three models are shown in Table 2.1. In the longitudinal (X) direction, each model has two frames with a span of 4.5 m. In the transverse (Y) direction, each model has four frames with a span of 1.8 m. The cross sections and reinforcement of the RCF frame were designed to satisfy the *Chinese Code for Seismic Design of Buildings* [11].

The load and the action on the three models was the same, including live load, gravity load and earthquake action. The rotational stiffness of the rocking joint in the CR-RCF was determined by Eq. 2.2. For CR-RCFb, the stiffness of the column-base joint is $K_c = 4.124\times10^6$ N m/rad, and the stiffness of the beam-column joint is $K_b = 2.198\times10^6$ N m/rad. For CR-RCFc, the stiffness of the column-end joint is $K_c = 2.748\times10^6$ N m/rad [12].

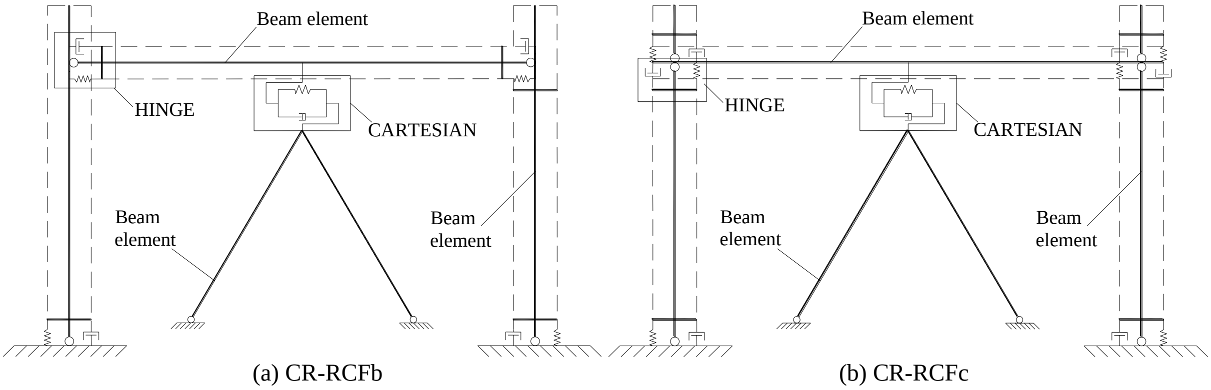


Figure 3.1 Schematic diagrams of the FEM for the CR-RCF

3.3. Time-history Analysis

The Taft-NS wave, El Centro-EW wave and Shanghai artificial wave (SH09-1) were selected to evaluate the seismic performance of the conventional frame and the CR-RCF by elasto-plastic time-history analysis. The seismic performance indices of displacement, inter-story drift, acceleration and inter-story shear under different level earthquake actions on the three models were calculated. Through calculation, many data were obtained. Owing to the limitation of the pages, they are given here only to validate that the modeling is correct and the accuracy can be guaranteed.

The shaking table test is a useful tool to investigate the seismic performance of structures. The El Centro wave, which is commonly used in shaking table tests, was chosen to simulate the earthquakes. As an example, the time history curves of the dynamic response of the third floor in CR-RCFb are shown in Fig. 3.3, and it can be observed that the time history curves of the inter-story drifts and accelerations obtained from the numerical analysis correspond well with the results obtained from the shaking table test. Furthermore, the finite element model with hinge joints, metallic dampers and the nonlinear analysis method were all verified to be suitable in the simulation of the CR-RCF structure.

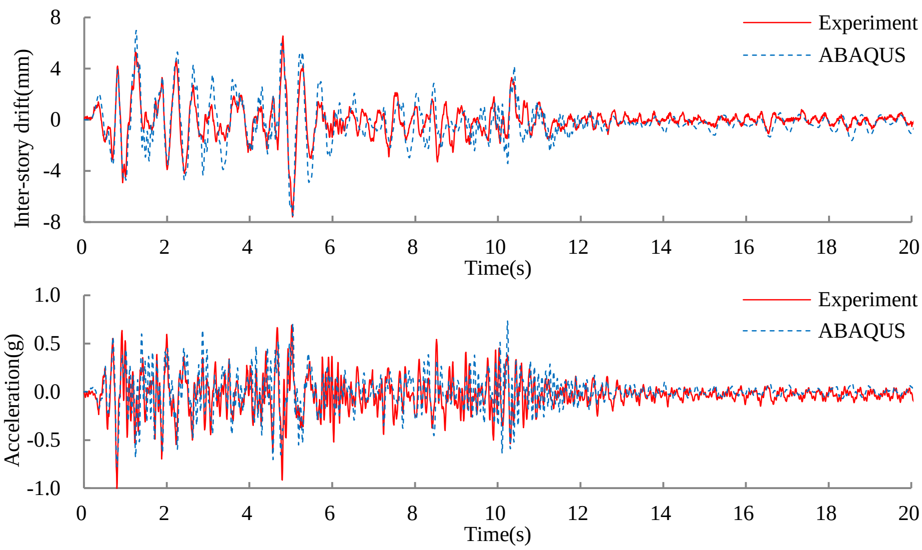


Figure 3.3 Dynamic response of the 3rd story drift and the roof acceleration (0.4 g El Centro, CR-RCFb)

4. SHAKING TABLE TEST

4.1. Test Method and Test Phenomenon

Because CR-RCF is a new energy dissipation seismic structure system, as a preliminary study, only one horizontal unidirectional earthquake wave was selected to be exerted on the models. According to the test plan, the El Centro EW earthquake record was chosen as the shaking table input, and the PGA of the input waves exerted on the models sequentially were 0.07 g, 0.14 g, 0.20 g, 0.40 g, 0.80 g, 1.24 g, 1.45 g, 1.65 g, 1.85 g and 2.00 g, respectively.

After the test model had been fixed on the shaking table, eight acceleration sensors and eight displacement meters were placed on the model, two for each floor and two for the base. These sensors were used to measure the acceleration and displacement responses of each floor and the base.

In the process of testing, the crack development of the components was recorded on the model by a marker pen after each run step. After the testing, the conventional RCF structure model was damaged seriously, and the damage is shown in Fig. 4.1. During the rare earthquake, the main components of the CR-RCF model remained intact, except that the dampers had some residual deformation, as shown in Fig. 4.2. The test is summarized as follows: (1) after experiencing the 1.45 g El Centro wave, the beam-column joints of the RCF model cracked seriously and formed some plastic hinges; the concrete crushed at the ends of the beam and column, and part of column reinforcement was exposed; the main components of the model were seriously damaged, and the structure could not meet the requirements of normal use; and (2) except for some residual deformations found in the dampers, the main bearing components of the CR-RCF model remained in good condition after the 2.00 g El Centro wave. The CR-RCF model showed superior damage-free performance during the shaking table test.

CR-RCFb CR-RCFc

Figure 4.1 Failure mode of RCF model

Figure 4.2 CR-RCF remained intact during the test

4.2. Dynamic Characteristics and Seismic Responses

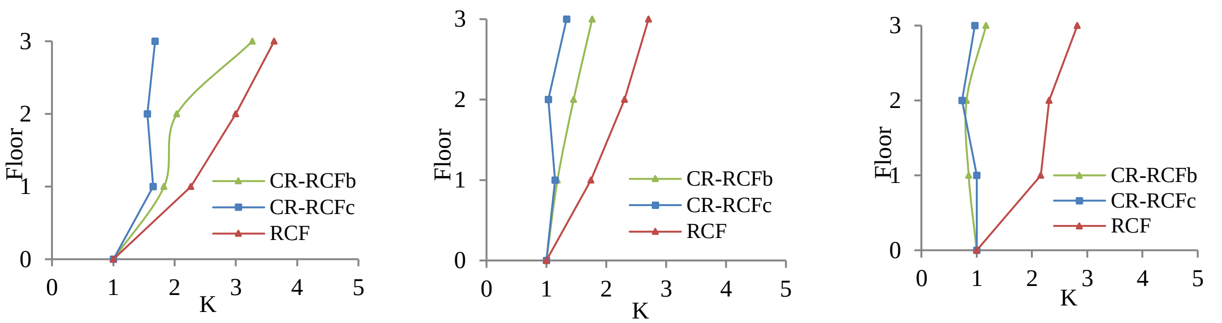
Before each earthquake wave exerting, white noise excitation tests were performed, and the initial natural vibration periods of the model were obtained. Because the models have three floors and have been excited in a single direction, only the first three orders of the natural vibration periods were measured. Table 4.1 shows the initial natural vibration periods of the CR-RCF and RCF models.

Table 4.1 shows that the initial first-order natural vibration periods of the two CR-RCF models are approximately 0.3 s; however, the dampers would enter the large deformation status, and the secant stiffness of the dampers would be much smaller than the initial stiffness when the CR-RCF structure encounters a large earthquake. Thus, CR-RCF would have a longer nominal first-order natural vibration period than 0.3 s. The first-order natural vibration period of the CR-RCFb prototype is close to 2.5 s, which was obtained from the test and calculated by the similitude ratio listed in Table 2.2. The predominant period of the El Centro-EW earthquake wave is less than 0.55 s; according to the seismic response spectrum theory, the floor acceleration response and inter-story shear response would become smaller when the vibration period of the structure is greater than the predominant period. This means that the CR-RCF structure performed better in terms of seismic resistance than the conventional RCF structure.

Table 4.1 Initial natural vibration periods of CR-RCF and RCF models (s)

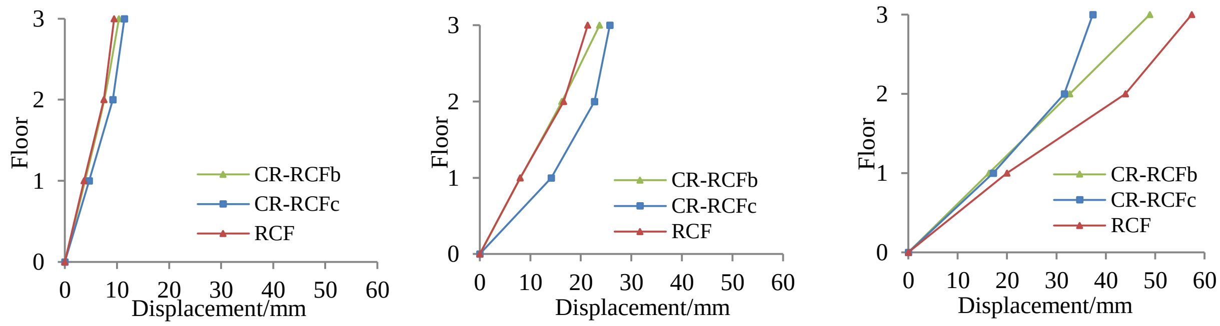
Period	RCF		CR-RCFb		CR-RCFc	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
1st mode	0.1739	0.1720	0.3077	0.3048	0.3200	0.3167
2nd mode	0.0506	0.0496	0.0702	0.0720	0.1212	0.1172
3rd mode	0.0291	0.0286	0.0273	0.0285	0.0833	0.0805

The envelope values of acceleration and displacement response of the three models were obtained from the shaking table test. The comparison of the envelope acceleration response between the CR-RCF structures and the RCF structure are shown in Fig. 4.3, and the dynamic amplification factor K is defined by the ratio of the maximum floor acceleration response over the base. The envelope values of the displacement response are shown in Fig. 4.4. Some conclusions can be drawn from Fig. 4.3 and Fig. 4.4:



(0.2 g) (0.4 g) (0.8 g)

Figure 4.3 Comparison of acceleration responses between CR-RCF and RCF



(0.2 g) (0.4 g) (0.8 g)

Figure 4.4 Comparison of maximum displacement responses between CR-RCF and RCF

(1) In the moderate and large earthquakes, the acceleration response of the CR-RCFc structure is obviously less than that of the RCF structure. The dynamic amplification factor K of each floor in the CR-RCF structures is approximately 1.0, and K for the RCF structure is between 2.0 and 3.0; thus, the CR-RCF structure acceleration response is significantly less than that of the RCF structure, indicating that the seismic performance of the CR-RCF structure is good.

(2) In the moderate earthquakes, CR-RCF and RCF displacement responses are roughly equal, indicating that the CR-RCF structure dampers were arranged reasonably, which can effectively control structural displacement. In large earthquakes, the stiffness of the RCF structure decreased seriously, and the displacement response increased significantly; therefore, the CR-RCF structural displacement response was less than that of the RCF structure, indicating that, at that time the control effect of the dampers on the lateral shift is still significant.

(3) The earthquake acceleration and displacement responses at different levels are comprehensively compared, indicating that the CR-RCF structure can control the structural displacement response and reduce the structural acceleration response significantly.

5. CONCLUSIONS

The CR-RCF is a new type of seismic structure; two types of CR-RCF models were proposed. Compared to the conventional RCF structure, the seismic performance of the CR-RCF was researched by the shaking table test. The results of the study are summarized as follows:

(1) The overall stiffness of the structure is significantly reduced via the rocking joint system using post-tensioned prestressing tendons. The CR-RCF effectively reduces the effects of the earthquake actions. The lateral displacement of the structure can be controlled effectively.

(2) The test results of the CR-RCF obtained from the shaking table test correspond well with the numerical analysis; therefore, the model building of the CR-RCF structure is verified to be efficient in terms of the finite element selection, the mechanical model of the joint connection, the parameters of the metallic damper and the method of nonlinear analysis.

(3) The removable metallic dampers yield to dissipate earthquake energy, whereas the components of the CR-RCF remain elastic under large earthquake actions. The structure can restore the original position by replacing the dampers after the earthquake. These results indicate that the CR-RCF satisfies the performance objective of reparability after a major earthquake, and the CR-RCF is a damage-free structure system.

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