NUMERICAL ANALYSIS STUDIES OF A FULL-SCALE FOUR-STORY REINFORCED CONCRETE TEST STRUCTURE

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1. Background and Objective

In the 1994 Northridge earthquake and 1995 Hyogo-Nanbu Earthquake, many older reinforced concrete(RC) structures suffered massive damages and some collapsed due to the failure in key structural elements. Although from the perspective of life safety and satisfying general code requirements, the buildings designed according to newer standards has performed well, as a result of nonlinear behavior producing large member cracks and residual deformations, hindrance to safety and continued use were observed. These damages have caused extremely high expenses owing to economic loss due to loss of use, and cost of repairs. As a result, Performance-based earthquake engineering (PBEE) design approaches were developed that focused on structural design criteria are expressed in terms of achieving a set of performance objective. Based on these lessons learned, as an approach towards investigating PBEE design procedures, a series of shaking table tests were conducted using the three-dimensional large-scale earthquake experiment facility (E-Defense) in order to clarify the damage process and enhance the seismic performance of RC structures.

In 2010, E-defense shake table testing program was conducted on four-story full-scale RC building designed using the latest code requirements and design recommendations available in both Japan and the U.S. To assess the performance of the structure in both moderate-intensity frequent earthquakes (service-level) and large-intensity very rare earthquakes (collapse-level), the building was subjected to increasing intensity shaking using the JMA-Kobe and Takatori records until a near-collapse state was reached.

In this research, the aforementioned four-story RC structure was modeled using modified Ibarra-Medina-Krawinkler(IMK) peak oriented hysteretic model and IMK pinching model. It was designed in accordance with the latest seismic design provisions of ACI 318-14 and ASCE/SEI 41-06 in order to investigate the implications and applicability of current US seismic design codes.

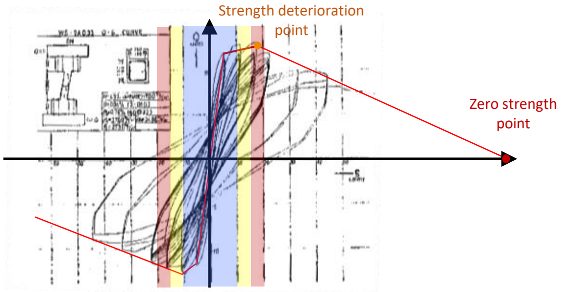


Figure 1 Backbone curve of IMK model

In the current practice of design, the negative slope of analysis curve that represents the deterioration of strength of building structural systems *(Figure 1)*, is rarely taken into consideration. But such real ultimate behaviors have a significant effect on the safety issue related to collapse of structures. Hence the main objectives of this study were: 1) to propose a methodology to assess the deterioration nature of building system by using static-cyclic loading frame analysis, 2) to verify assessing performance such as strength, deformation capacity and energy spectrum; 3) to draw a comparison between the wall modelling of IMK model and fiber model. (Kang, Sato, & Kajiwara, 2017)

2. E-defense specimen details

E-defense shaking table test was carried out for a full scale RC test structure with a moment-resisting frame in X direction and multistory shear-wall frame in Y direction. The height of each story is 3 m. the moment frame system has two spans of 7.2 m, and the shear-wall system with a wall section of 2.5 m width (thickness 250 mm) has one span of 7.2 m. *Figure 2* shows the plan and framing elevation of RC specimen. (Nagae, et al., 2015)

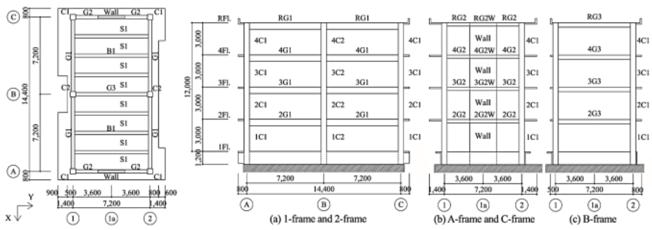


Figure 2 Configuration of RC test specimen

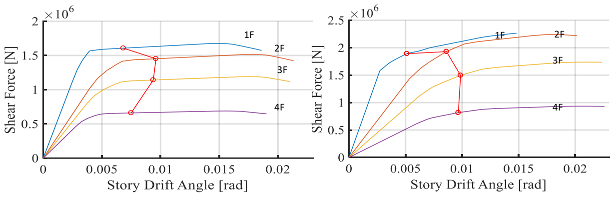
3. Numerical Analysis

Numerical models for the test structure was developed and analyzed using OpenSees (Open System for Earthquake Engineering Simulation). (PEER: Pacific Earthquake Engineering Research Center, 2018)

OpenSees is an object-oriented structural analysis framework developed at PEER (the Pacific Earthquake Engineering Research Center). Frame elements and wall elements consist of zero-length rotational spring located at the beam and column end, and modified Ibarra-Medina-Krawinkler(IMK) deterioration model with peak oriented hysteretic response is used to determine the rotational spring parameters simulating the experimental data.

The moment frame system and the shear wall system of the specimen were first subjected to nonlinear static analysis (Pushover) and the relation between the test and analysis results in the first mode response was compared to obtain the stiffness and strength modification factors. The stiffness factor and strength factor of the frame direction are 1.39 and

1.93 respectively. The wall direction has a stiffness factor of 2.48 and a strength factor of 1.85. These factors clarify the over-strengthening properties of the modeled specimen. The nonlinear static analysis of the modified model is carried under a uniform lateral force distribution for a maximum displacement of 1/50th of the roof drift. Lateral load-drift ratio response obtained for the frame direction and wall direction is shown in the *Figure 3*. Strength deterioration nature of the analytical model was verified by performing nonlinear cyclic analysis. Cyclic loading analysis exceeding the 0.04 rad of global drift angle was carried out keeping a constant lateral force distribution. The global drift angle was successfully controlled by the designated cyclic protocol as shown by *Figure 4*.



(a) Frame direction pushover (b) Wall direction pushover

Figure 3 Nonlinear Static Analysis Curves

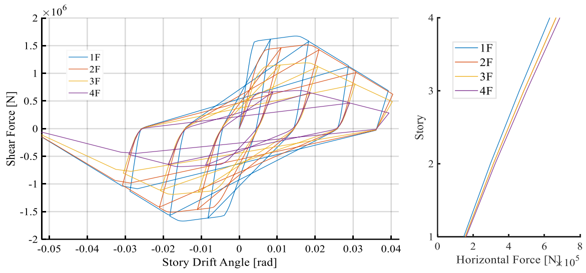
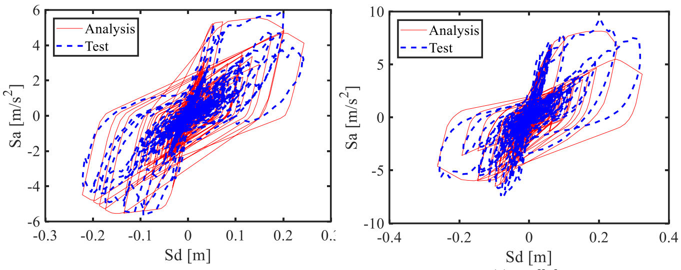


Figure 3 Nonlinear Cyclic Analysis curve and Force distribution curve

4. Comparison with test data

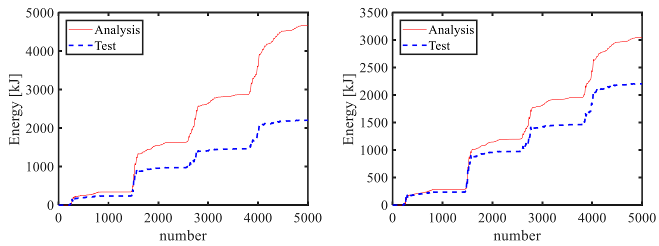
The loading test protocol of the 2010 test structure consists of white noise excitation and JMA-Kobe and JR-Takatori ground motions recorded from 1995 Hyogo-ken Nanbu earthquake. For the RC structure, the overall response of the test data and model data are represented through Equivalent-Single-Degree-of-Freedom (ESDOF) system. Since the height of the third floor could be considered as sufficiently close to the equivalent height value (H_{eq} 9 m), the global drift angle of the ESDOF system is calculated using the relative displacement and the third floor's height. As a result, the maximum global drift in the frame direction is 0.027 rad and in the wall direction is 0.036 rad. Comparison of overall global response of the test and analysis data is shown in the *Figure 5*. This results also verifies the cyclic deterioration of the model.

The energy dissipation spectrum of the frame direction RC structure is analyzed using the IMK peak oriented model and compared with the IMK pinching model (Yenidogan, et al., 2017) values. The maximum difference ratio of cumulative energies of RC test structure and the model structure is 2.1 with peak-oriented modelling, but with pinching model, the maximum difference ratio was reduced to 1.4, verifying that the slipping effects incorporated in IMK-pinching system is



(b) Frame direction (a) Wall direction

Figure 5 Comparison of the Global response



(a) IMK-Peak oriented (b) IMK-Pinching

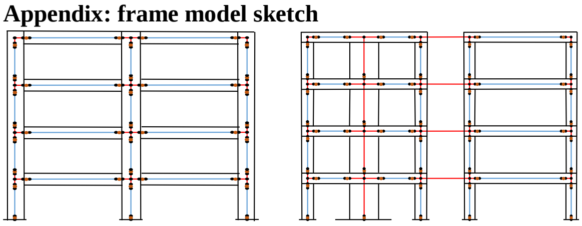
Figure 6 Comparison of Cumulative Energy Curves

more suitable to represent energy deterioration of modeled structure. *(Figure 6)*

5. Summary

Numerical simulations of static and cyclic behavior of a tested reinforced concrete structure with rotational hinges represented using IMK-Model are presented in this paper. This research focused on developing a 2D numerical model to analyze the reinforced concrete test structure of 2010 E-defense test and discuss the performance-based design approach by conducting nonlinear analysis and comparing the global response with the test data to verify the assessing performance such as strength, deformation and energy. Dynamic response of the IMK model and fiber base modelling for wall sections would be incorporated to expand this study further.

Appendix: frame model sketch



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