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Simulation Analysis of Shaking Table Tests of Full-Scale Six-Story RC Building using the Earth Simulator

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SUMMARY

This study was performed for purpose of developing a simulation analysis system for computing the collapse phenomenon of RC structure subjected to earthquakes. Earth Simulator belonging to JAMSTEC (Japan Agency for Marine-Earth Science and Technology) is a highly parallel vector supercomputer and could be utilized by Maebashi Institute of Technology in FY 2010 and 2011. A vast quantity of analytical data could be processed for modeling RC structure in detail by the finite element. Earthquake response analyses for the shaking table tests of the full-scale six-stories RC building executed at the E-defense were computed by using impact analysis code based on the explicit time integration. As a result, good simulation for the shaking table tests of the RC building was successfully realized. In addition, dynamic response characteristics of the RC building over the design input levels were determined by parametric studies due to several large input levels.

1. Introduction

A study[1] for establishing a simulation analysis method using the explicit finite element impact analysis code LS-DYNA[2] was conducted on the shaking table test of the full-scale six-story reinforced concrete (RC) building, which can analyze the behavior of RC buildings under strong seismic loading close to the near collapse of the building structure.

An analysis of the seismic response was conducted for a sophisticated model of the main wall-frame of the six-story RC building in a damage-free fresh condition, based on the experimental data of full-scale building structure tested on the shaking table at the Hyogo Earthquake Engineering Research Center (E-Defense) with input seismic waves (input acceleration factor of 100%) equivalent to those recorded during the 1995 Hanshin-Awaji earthquake. Displacement response of the analytical result was smaller than that recorded in the experiment. The authors considered that one of the causes that affected such a difference was the cumulative damage of the building under the test loads, which were performed by gradually increased shaking intensity (prior shaking) before application of the actually measured wave (100%). Accordingly, analyses that consider the cumulative damage caused by such prior shaking were conducted, and the results were in comparatively good agreement with the experimental results.

2. Outline of shaking table test of full-scale six-story RC building

The experiment analyzed was the shaking table test of the full-scale six-story RC building conducted in E-Defense. The data for the test conditions and the building used for the analysis were taken from the published paper[3]. The structure of the building used for the analysis was the six-story, three-dimensional wall-frame consisting of two spans in the x-direction and three spans in the y-direction, and each span had a dimension of 5,000mm, a floor-to-floor height of 2,500mm, and overall building height of 15,000mm. The test was conducted with seismic waves equivalent to those recorded at the Kobe Marine Observatory of the Japan Meteorological Agency during the 1995 Kobe-Awaji earthquake (corresponding to the seismic intensity of 6 upper) increasing the input acceleration factor in steps of 5%, 10%, 25%, 50%, and 100%, respectively, and finally 60%. Shaking was applied in three directions, horizontally the x- and y-directions and in the vertical direction, with the original seismic waves rotated 45 degrees, the N45W direction in the y-direction of the building under test, and the N45E direction in the x-direction. Based on such an application, the intention was that the ultimate fracture of the building would take place in the y-direction.

3. Analytical condition

3.1 Analytical model

Figures 1 through 4 show the outline of the model used in the FEM analysis. In the model, concrete was represented as solid elements, and reinforcing bars were represented as beam elements as they were in the actual state. The concrete and reinforcing bar elements have common nodes assuming full adhesion between them. The foundation of the building was not represented in the model but represented as shell elements where the bases of the columns were anchored. Input of the seismic waves was applied at

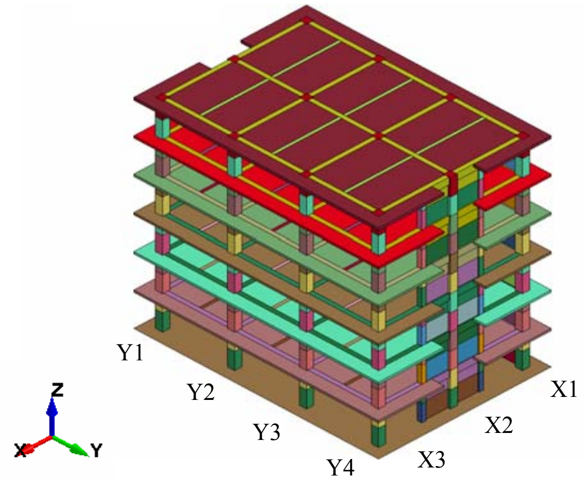


Fig. 1 View of the entire analytical model (Color-coded for input data layer recognition category)

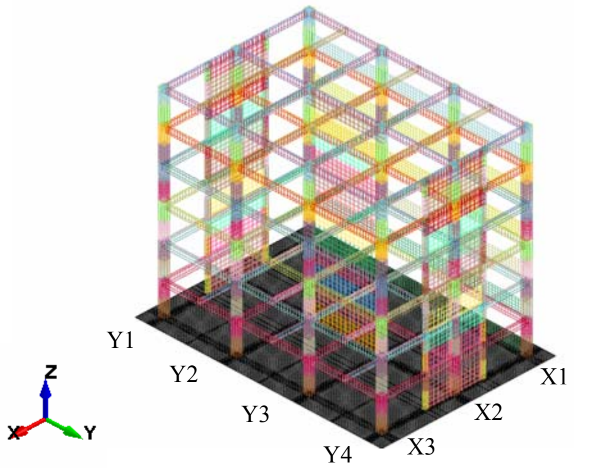


Fig. 2 Reinforcing bar model of the main frame

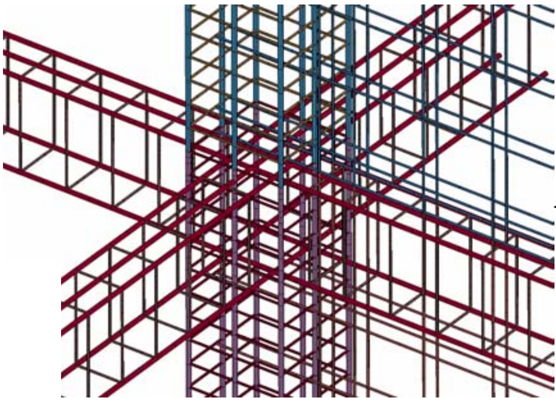


Fig. 3 Enlarged view of the reinforcing bar model of the main frame

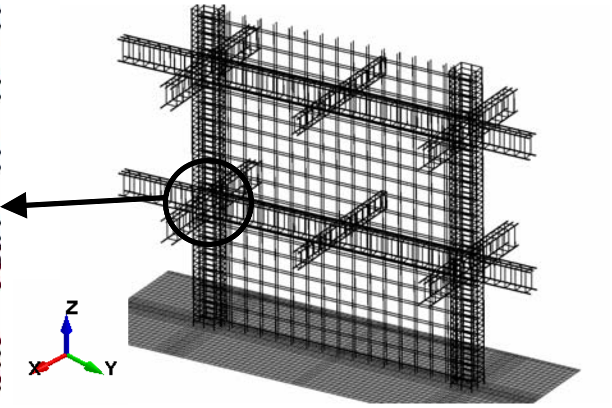
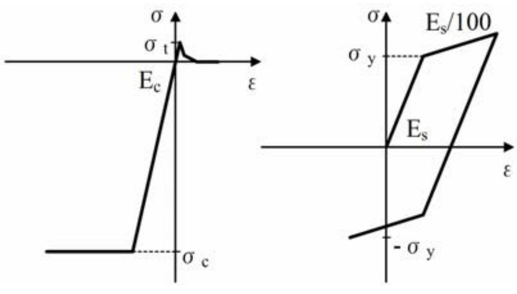


Fig. 4 Reinforcing bar model of the earthquake resistant wall

the shell elements in the analysis of the seismic response. The size of the analysis model was about 1.48 million elements for concrete, about 0.57 million elements for reinforcing bar, and about 30,000 elements for the shell for total of about 2.08 million elements, and the total number of nodes was about 1.79 million. The material model installed in LS-DYNA[4] was used. Figure 5 shows the stress (σ) and strain (ε) relationship of the material model used.



Concrete model Reinforcing bar model

Figure 5 Material model

For the concrete element, the material model[5,6] was used with characteristics of Ottosen's fracture criterion[7], smeared cracks, etc. in consideration of strain rate effect. Stress relaxation in tension was dependent on the fracture energy and the crack width. For the reinforcing bar element, an isotropic elastic-plastic model in consideration of kinetic hardening was used, which is a bi-linear type where the plastic hardening coefficient after the yield is 1/100 of the elastic modulus.

3.2. Structural characteristics of analytical model

Although no static loading experiment was conducted, a pushover analysis using an explicit dynamic analysis method was conducted to understand the structural characteristics of the analytical model. Horizontal force in the y-direction with the load distribution based on the Ai (Architectural Institute of Japan) was applied. Loading by the gravitational acceleration was taken into consideration by gradually increasing it from 0 m/s^2 to 9.8 m/s^2 within 0 to 0.6s, and at 0.6s horizontal force was applied. While loading was applied to the group of nodes near the slabs on each floor in path Y1 (Refer to Figure 1), increments of loading were applied gradually in this analysis to reduce vibration during loading because dynamic loading was used. The analysis was conducted with the column bases in the anchored condition by constraining displacement and rotation of the rigid shell elements located at the column bases on the first floor. Figure 6 shows the shear force and story drift relationship in the y-direction on each floor. The lower horizontal axis indicates story drift in millimeters, and the upper horizontal axis indicates story drift angle in radians, and the story height of the building analyzed was 2,500 mm throughout the first floor to the sixth floor. Figure 6 also shows the results on each floor when the story drift angles of the first floor reach 1/200, 1/100, and 1/50 radians and indicates base shear force (base shear coefficient). The displacement is the result obtained for the centers of the floor slab on each floor. In Figure 6, the results of each floor are connected by three lines when the story drift angles of the first floor(1F) reach 1/200, 1/100 and 1/50 respectively and values of base shear force with base shear coefficient are also indicated. The story drift angles from 1F to 6F are almost the same at 1/200 and 1/100 and on the other hand, at the 1/50 story drift angles from 2F to 6F are the value of about 70% of that of 1F, which shows remarkable progress in the story drift of 1F after 1/100. It is found from Figure 6 that nonlinear characteristics appears relatively early and the building has relatively large strength in view of the base shear coefficient of 1.00 and 1.16 greater than 1.0 at the story drift angle 1/200 and 1/100 respectively.

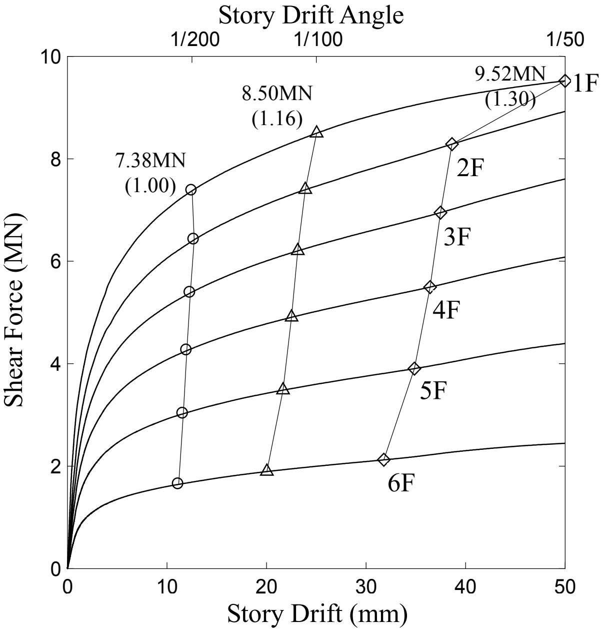


Figure 6 Result of pushover analysis (y-direction)

3.3 Conditions of seismic response analysis

In this analysis, an explicit dynamic finite element method was used. Consideration was given wherein the application of the load due to gravitational acceleration was increased gradually from 0 m/s^2 to 9.8 m/s^2 during the 0 to 0.6s before the application of the seismic waves, which started at 0.6s. Because of the large volume of data in the analysis of the six-story RC building, it took about 2 hours using 16 nodes (128 CPUs) of the Earth Simulator for calculation of the initial 1.0s. After 1.0s, it took about 3 hours for calculation of the next 1.0s possibly due to the increased computing task load in treating the plastic region and fracture of the materials. Because use of the Earth Simulator for one operation is restricted to 12 hours, an analysis for about 4.0s was possible with 16 nodes (128 CPUs) used in one operation (12 hours) in the case of the analysis of the six-story RC building. Restarting the analysis was made up to 4.6s in the case of no prior shaking and up to 13.6s in the case of application of prior shaking, which was the remaining computing task. Damping characteristics in proportion to the mass with damping coefficient of 3% was considered. Central difference time integration in the explicit finite element method was used, and the time interval of about 3.8 μ s (3.8×10^{-6}s) with the data output interval of 1.0ms (1.0×10^{-3}s) was used

4. Results of seismic response analysis

Figure 7 shows the analytical results of the time-history waveform of the story drift at the first floor in the y-direction as well as the input acceleration and the experimental results[1]. While the results of the analysis with seismic waves with 100% and 120% input acceleration factors are smaller than the results of the experiment, the result of the analysis with the 150% input acceleration factor is larger than the results of the experiment. This means that for seismic waves input into the fresh model that does not take cumulative damage into consideration, analysis with the input acceleration factor between 120% and 150% would correspond to the results of the experiment. When the results of the analysis for the fresh model (Figure 7) are compared with the results from the model taking cumulative damages into consideration (Case ⓔ) with input acceleration factor of 100%, the story drift for Case ⓔ is considerably greater than that of Case ⓐ and is close to the story drift measured in the experiment. By the way, cumulative damages occurred in the prior shaking were reproduced by the response due to seismic wave with 100% assumed to be equivalent to the total input effect due to 5%, 10%, 25%, 50%, before the actually measured wave 100% and therefore Case ⓔ is subjected to 100%-100% inputs.

Figure 8 shows the shear force and story drift relationship in the y-direction at the first floor with the results of the experiment. [3] In the experiment, the maximum story drift angle at the first floor was about 1/25 during 100% shaking causing close to sufficient damage to collapse the building, and at the final 60% shaking, the angle was about 1/17 with the building near collapse. When the seismic wave was applied to the fresh analytical model, the story drift angle showed 1/80 for ⓐ 100% input, 1/35 for ⓑ 120% input, 1/19 for ⓒ 150% input, and 1/16 for ⓓ 200% input. When the degree of damage in the analysis is evaluated with the results of the experiment as the reference, damage is close to collapse at ⓒ 150% input and is just before or already in the state of collapse at ⓓ 200% input. In the case of ⓔ 100%-100% input that took cumulative damage into consideration, the drift angle was about 1/33, which is greater than the value at ⓑ 120% input and is close to the result at 100% shaking in the experiment. The shear force in the analysis was calculated by multiplying response acceleration results at the center of gravity of the floor slab on each floor with the mass of each floor and by adding shear forces acting on the floors above the floor in question.

The stress conditions of the short columns with the spandrel walls and the foot of the earthquake resistant wall where damage occurred in the experiment was severe, the deformation condition of the concrete skeleton, and the deformation condition of the reinforcing bar are shown in Figure 9 in the magnified view of the deformation. Figure 9 (a), (b), and (d) through (f) are contour maps showing von Mises equivalent stress, where the stress increases from the cold colored area to the warm colored area. In Figure 9 (c), the main reinforcing bars of the short columns are resisting the seismic loads and swelling out a little under the constraints of the shear reinforcing bars. As shown in these diagrams, this analysis method allows flexible indication of conditions in detail of the building structure, such as the conditions of the reinforcements, stress conditions at any section of the structural elements, etc.

5. Conclusion

The time history seismic response analysis of the sophisticated FEM analysis model precisely representing concrete and reinforcing bars of the full-scale six-story RC building using the explicit finite element impact analysis method was conducted. The results of the simulation were consistent with the results of the experiment. The analysis method employed provides excellent features where the dynamic characteristics of the structure are automatically created by the material characteristics of the concrete and reinforcing bars, and by the arrangements, the dimensions etc. of each structural element. The evaluation of the elastic-plastic characteristics up to large deformation caused by large input acceleration is possible, and the conditions for damage or fracture can be visually presented as the computer animation. Because of the analysis method using explicit algorithms, verification of computational accuracy and analysis results are required, and the method can possibly be used for analysis of the large-scale model and large input acceleration. The authors consider the collection of analysis data for increasing the number of examples and verification of such analyses with the results of experiments so that shaking tests can be conducted in a simulation analysis program. When this is possible, the evaluation of shaking under extremely large input acceleration, which is severe seismic conditions as in the 2011 Great East Japan earthquake will become possible.

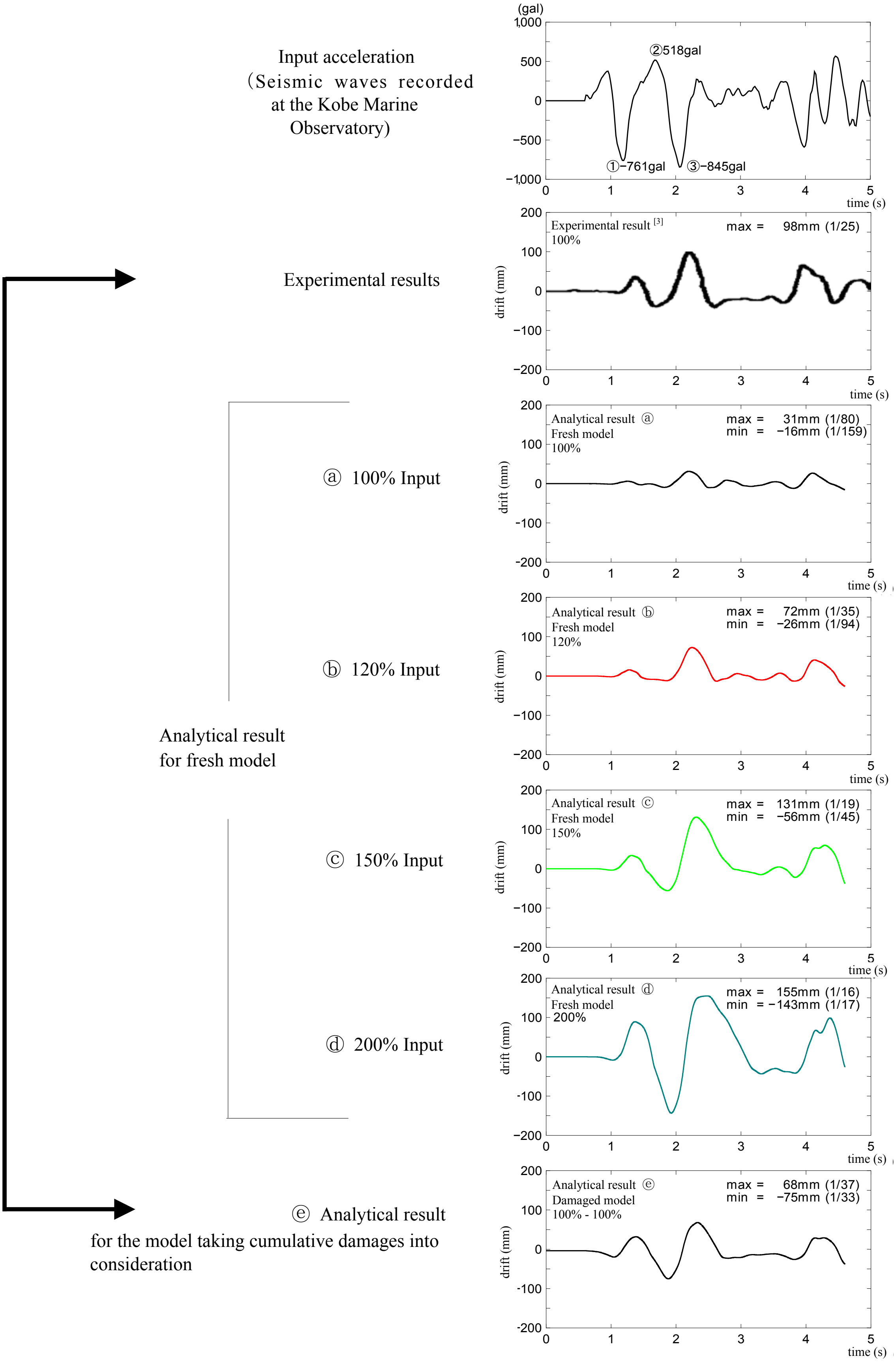


Figure 7 Story drift time history

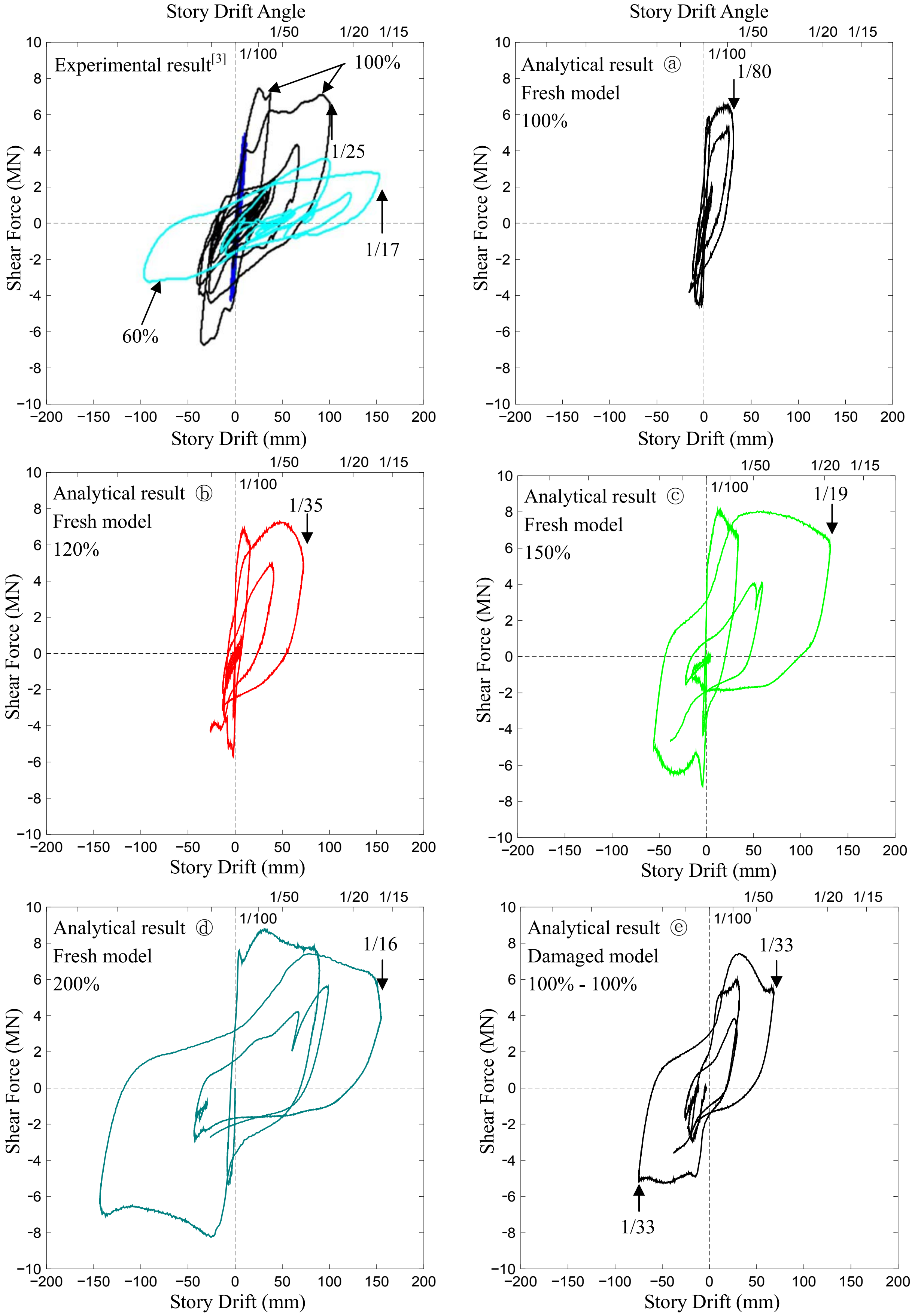
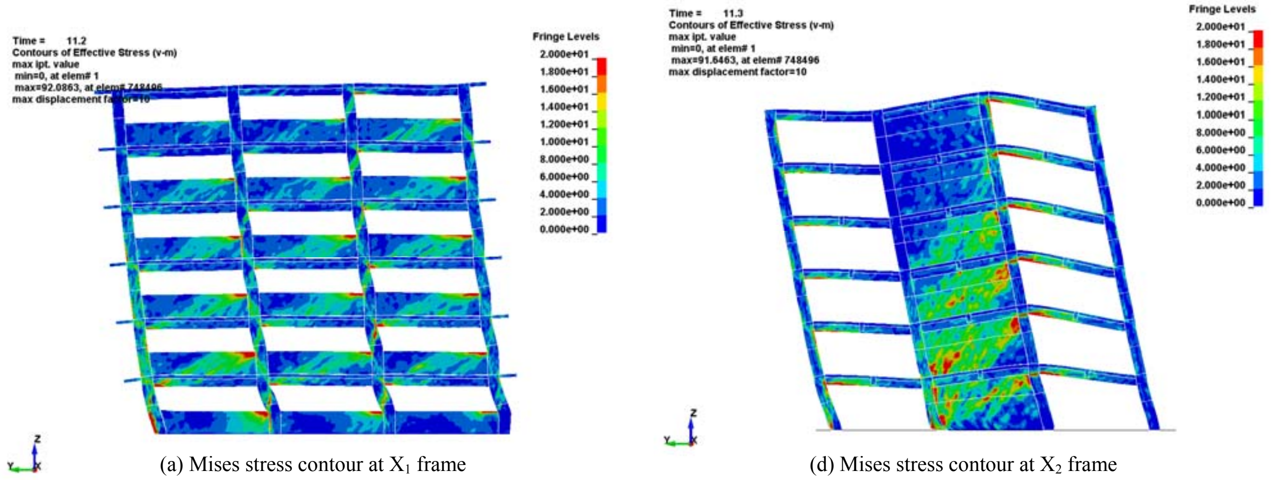
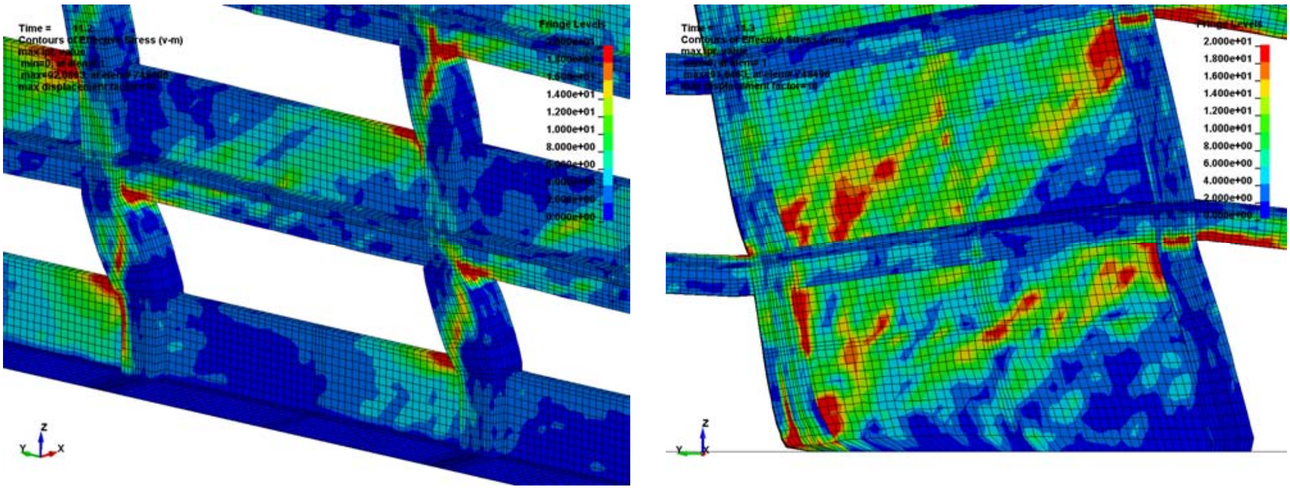


Figure 8 Relationship between shear force and story drift (y-direction, 1F)



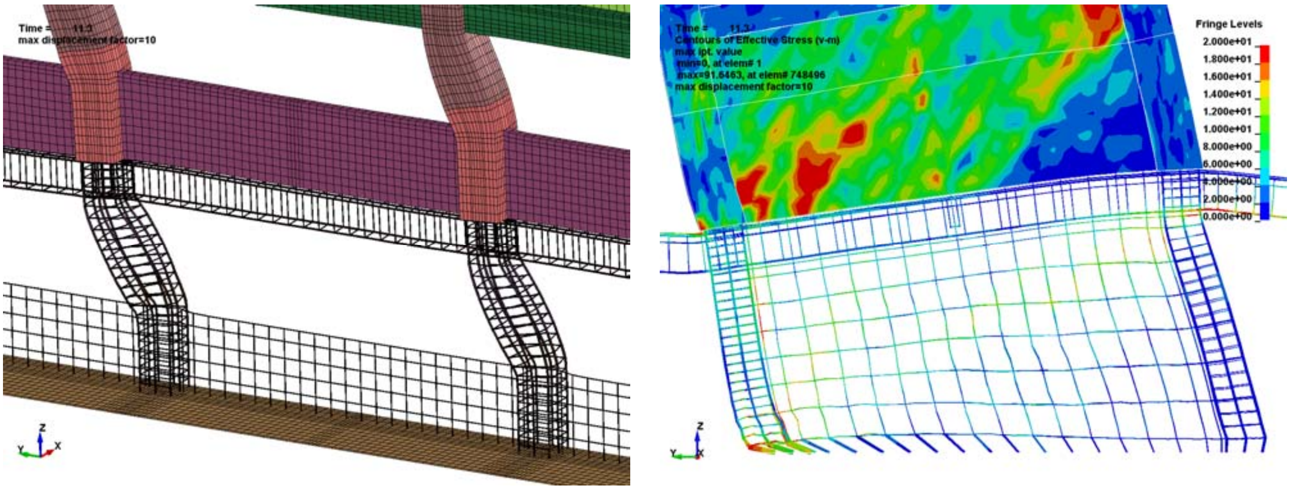
(a) Mises stress contour at X_1 frame

(d) Mises stress contour at X_2 frame



(b) Mises stress contour at X_1 frame (enlargement)

(e) Mises stress contour at X_2 frame (enlargement)



(c) Displacement at X_1 frame reinforcement bar

(f) Mises stress contour at X_2 frame (enlargement)

Figure 9　FEM simulation analytical result (displacement is enlarged by 10 times)

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