Development of Sophisticated Simulation Analysis Method of Actual Reinforced Concrete Building by Shaking Table Test-II

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The impact analysis code of the explicit method that demonstrates effectiveness in the collision analyses of automobiles etc. was applied to the seismic response analyses of buildings to study the methods enabling computer analyses of reinforced concrete building collapse phenomena that were frequently observed in the Hanshin Awaji Earthquake but not yet clarified. In this study, the authors performed simulation analyses of shaking table tests at the E-Defense in which the phenomenon close to collapse of a full-scale six-story RC building was found and the evaluation of effectiveness of seismic reinforcement, which is an issue of seismic design in recent years. In addition, the seismic response analyses considering collision with the retaining walls of a RC building subjected to long-period pulse earthquakes.

This study enabled elasto-plastic seismic response analyses by constracting huge number of approximately 4 million finite element model consisting of concrete and reinforcing bars as they are, and thus the prospect of the possibility of a reduction in the vast expense required by full-scale shaking table tests for various structures and the improvement in the effectiveness of such tests was obtained by using the sophisticated simulation analysis method (the numerical shaking table).

Keywords: Seismic response, Shaking table test, RC frame, Earth simulator, FEM, Base isolation, Seismic reinforcement

1. Introduction

The impact analysis code of the explicit method that demonstrates effectiveness in the collision analyses of automobiles etc. was applied to the seismic response analyses of buildings to study the methods enabling computer analyses of reinforced concrete (abbreviated as RC hereafter) building collapse phenomena that were frequently observed in the Hanshin Awaji Earthquake but not yet clarified. In this study, the authors performed simulation analyses of shaking table tests at the E-Defense in which the phenomenon close to collapse of a full-scale six-story RC building subjected to a seismic intensity of 6 upper. Specifically, precise and detailed simulation analyses were performed by applying the impact analysis program (LS-DYNA) for comparisons with test results to verify the analysis

method. Moreover, based on the afore-mentioned analysis system, the procedures for numerical shaking tests were developed.

The items of the study to be implemented in this fiscal year are shown below from the viewpoint of simulation and application:

(1) Improvement of the simulation analysis for the shaking table test of full-scale six-story RC building and the additional pushover analysis

(2) Applied seismic response analyses of various buildings by the verified sophisticated simulation analysis method (Numerical shaking table)

① Seismic response analysis of the full-scale six-story RC building built on ground considering building –soil

interaction effect (Applied analysis)

② Seismic response analysis of the full-scale three-story RC buildings with and without seismic reinforcement on the shaking table (Simulation Analysis)

③ Seismic response analysis of base-isolated RC building considering collision with retaining wall placed around the building (Applied analysis)

2. Simulation analysis of full-scale six-story RC building by shaking table

The analytical results of this test were shown in references [1] through [3]. The analyses were performed using the Finite Element model shown in Fig. 1. As for the mesh sizes, the analytical model was divided into approximately 2.08 million elements in total consisting of approximately 1.48 million elements of concrete and approximately 0.57 million elements
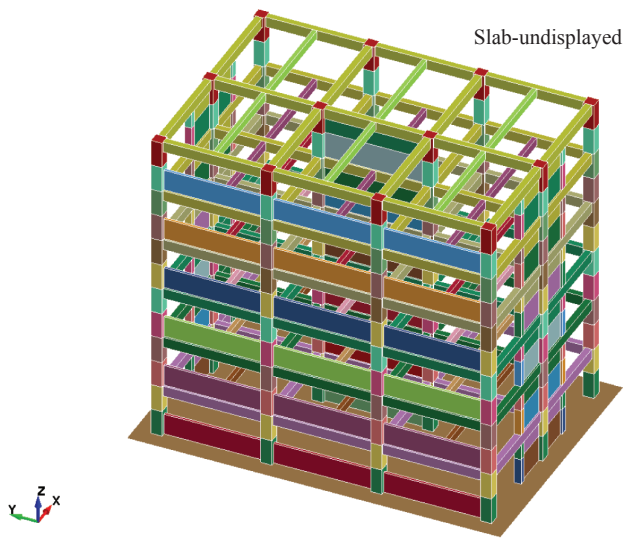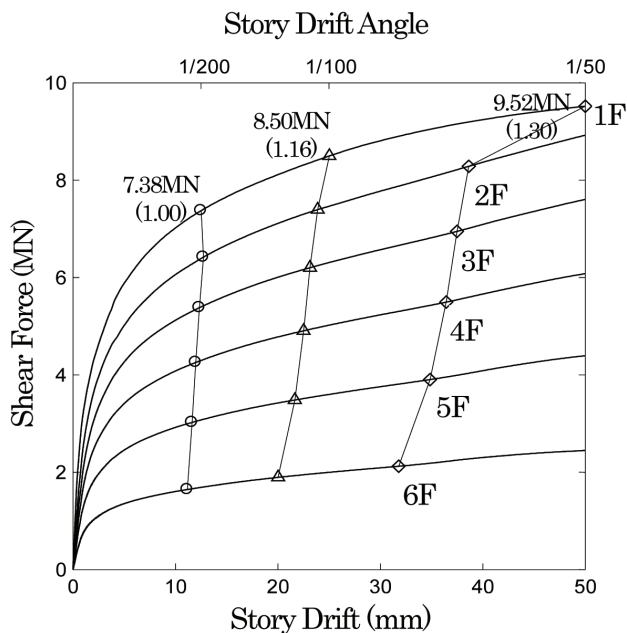
of reinforcing bars. According to the advice of the researcher who was in charge of the tests, the pushover analyses in which horizontal force distributing vertically similar to seismic force was stepwise increased were performed to calculate the relationship between the shear force and the story drift that is the basic structural characteristic of a building as shown in Fig. 2. This characteristic was not experimentally verified because a large size loading apparatus is required. However, these results are very important to identify the structural characteristics of a building, and it was found that determination by analysis is possible.

In the simulation analyses of shaking table tests, the consideration of shaking history provided the analysis results that can simulate the test results better as shown in Fig. 3. Furthermore, earthquakes with a input acceleration factor of 1.2, 1.5 and 2.0 that are impossible to load in the shaking tests were applied to the analytical model. Therefore, the authors found it is possible to verify that the building has seismic margin that shows no collapse by 1.5 times earthquake but possibly shows collapse by 2.0 times earthquake.
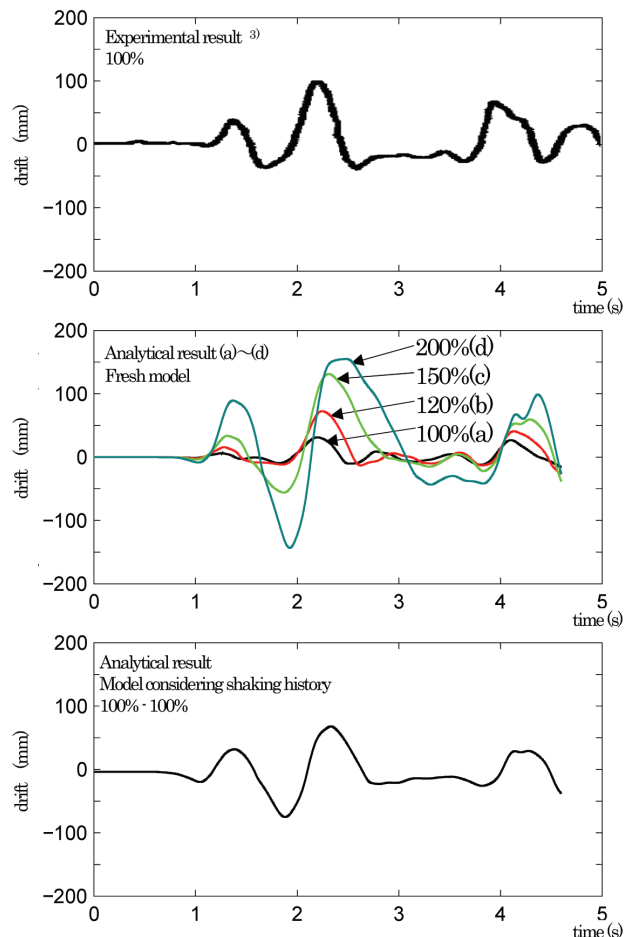

Fig. 1 FEM analytical model.

Fig. 2 Result of pushover analysis (y-direction).

Fig. 3 Story drift time history (y-direction,1F).

3. Seismic response analysis of full-scale six-story RC building placed on ground considering building –soil interaction effect (Applied analysis)

The aforementioned tests were performed under the condition of a divided foundation for the purpose of investigating properties of upper building nevertheless the foundation should primarily be integrated. In this study, a foundation was newly designed as shown in Fig. 5, modeling was performed to realize the condition that well simulates an actual building as shown
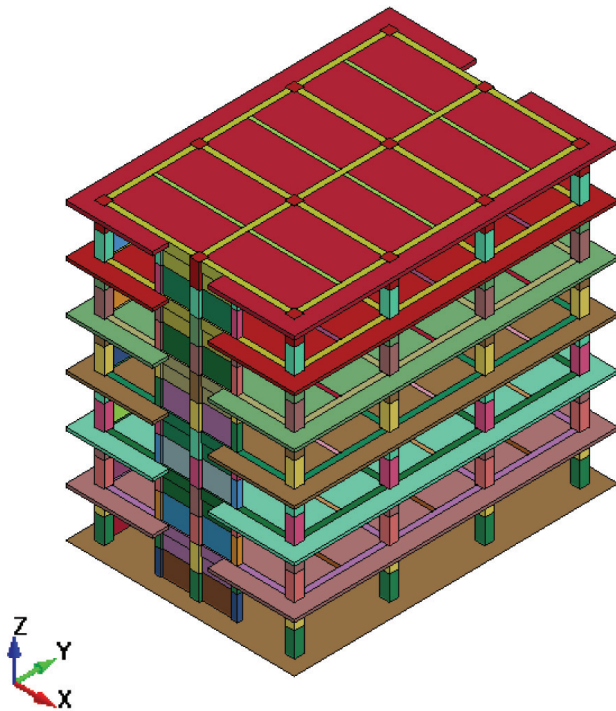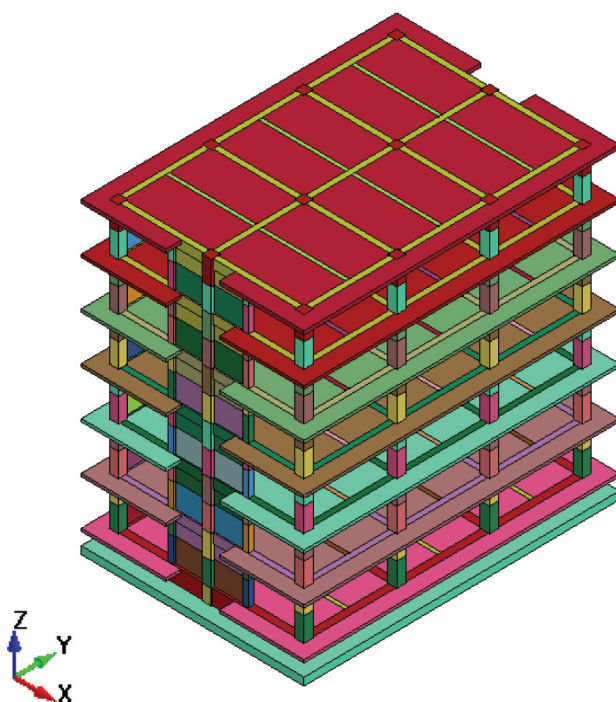
in Fig. 6 by considering the ground for bearing the building, detailed analyses [4] were performed in the three-dimensional elasto-plastic Finite Element Method, and the analytical results were compared with the model of only the upper structure with column bases fixed (Fig. 4) to examine the effects of the interaction of the building and the ground (soil) on the seismic response of the building. [4] As for the ground used for the analyses, the subsurface ground on the engineering basement was modeled by dividing into solid elements to make it elastic ground with a layer thickness of 10 m, a density ρ of 1.6 t/m^3, shear wave velocity of 200 m/s, and shear modulus G of 64 N/mm^2. In addition, the non-reflection boundary against shear wave was provided in the periphery of the ground model. The contact surface was defined without allowing share of nodal points between the building and the ground, assuming friction coefficient to be 0.3. This definition enables realization of slip, floating, etc. between the building and the ground, making it possible to perform analyses similar to the actual phenomena. As for the mesh sizes, the coupled model was divided into approximately 3.0 million elements in total after dividing the ground model into approximately 0.4 million elements. Damping was assumed to be 3% of mass proportion type. As shown in Fig. 7, the response of the building placed on the ground was about 30% smaller in comparison with the seismic response in the model of only the upper structure, that is, fixed column base model.
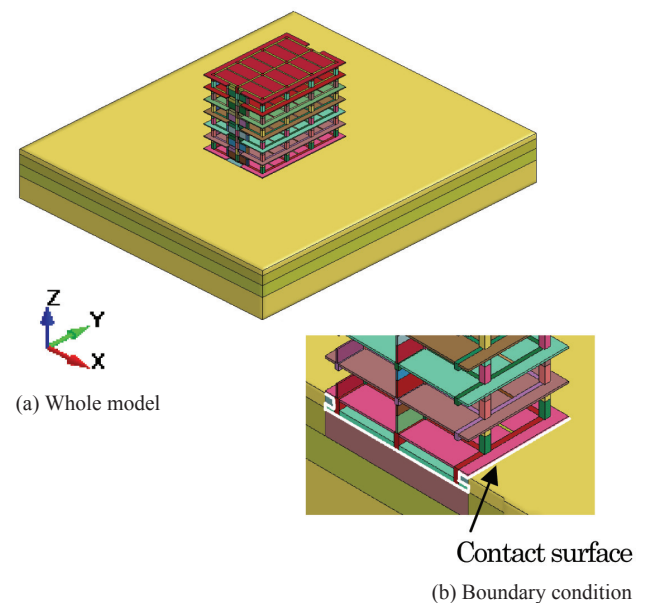

Fig. 4 Fixed column base model.

Fig. 5 Building model including foundation.

(a) Whole model

Contact surface

(b) Boundary condition

Fig. 6 Interaction model on ground.

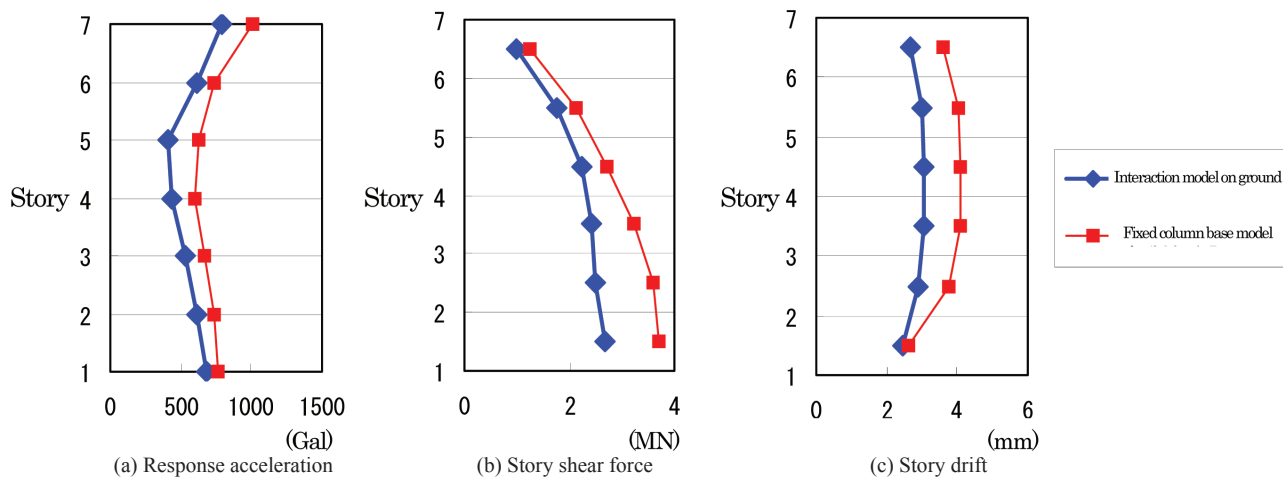(a) Response acceleration

(b) Story shear force

(c) Story drift

Fig. 7 Comparison of maximum response distribution.

4. Seismic response analysis of three-story RC buildings with and without seismic reinforcement on the shaking table (Simulation Analysis)

The objects to be analyzed [5] were assumed to be two specimens without and with seismic reinforcement as shown in Figs. 8 and 9 of a three-story RC building of which shaking table tests at the E-Defense were conducted. An analytical model was created by dividing concrete into solid elements and reinforcing bars into beam e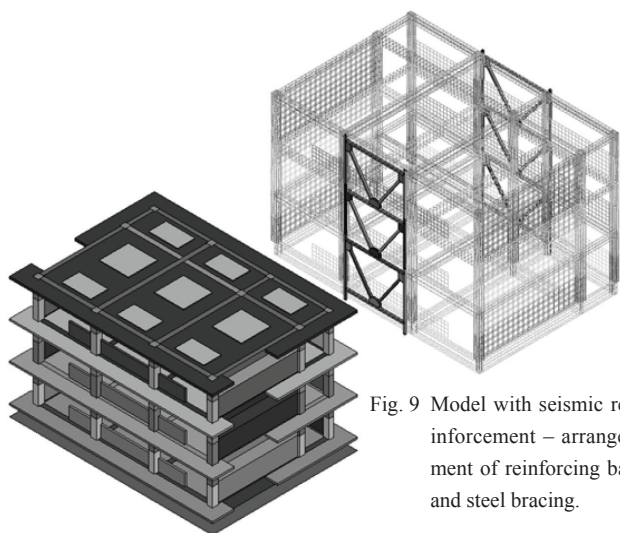lements and assuming nodal points between them to be completely bonded. Foundation section was divided into completely fixed rigid shell elements. As for the mesh size, the model of the specimen without seismic reinforcement was divided into approximately 0.84 million elements in total consisting of approximately 0.54 million elements of concrete, approximately 0.27 million elements of reinforcing bars and approximately 0.17 million elements of rigid shell. The model of the specimen with seismic reinforcement was divided into approximately 0.97 million elements in total consisting of approximately 0.67 million elements of concrete, approximately 0.28 million elements of reinforcing bars and approximately 0.02 million elements of rigid shell. Fig. 10 shows the relationship between the story shear coefficient of the first-story and the story drift angle obtained by the analysis. Although the maximum story shear coefficient showed almost no difference between the specimens without and with seismic reinforcement, the maximum story drift angle in the specimen with seismic reinforcement was found to be smaller, namely approximately 1/5 of that without seismic reinforcement. This result enables to say seismic performance of the building was improved by seismic reinforcement from the viewpoint of dynamic response during an earthquake.

Fig. 9 Model with seismic reinforcement – arrangement of reinforcing bar and steel bracing.

Fig. 8 Model without seismic reinforcement.

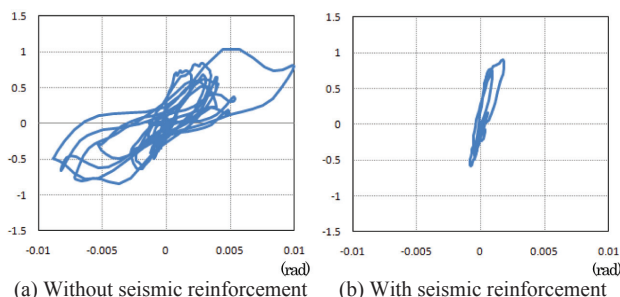## 5. Seismic response analysis of base-isolated RC building considering collision with retaining wall (Applied analysis)

Seismic response analyses [6, 7, 8] of a three-dimensional RC building model considering a collision with the retaining wall placed around the building by three-dimensional inputs in two horizontal directions and one vertical direction were performed concerning long-period pulse earthquakes that are observed in strong local earthquakes in recent years.

This analytical model was created by dividing the concrete of the upper structure, retaining walls and the backfill soil into solid elements and dividing the reinforcing bars into beam elements as they are shown in Fig. 11. The concrete and the reinforcing bars were made to share nodal points completely

(a) Without seismic reinforcement

(b) With seismic reinforcement

Fig. 10 Story shear coefficient – story drift angle. (Analytical results, 1F)

bonded. Backfill soil was modeled by dividing into rigid elements, and seismic wave at K-NET Kashiwazaki observation points of Niigataken Chuetsu-oki Earthquake in 2007 (NIG008) where a long-period pulse was observed was used. A model of base isolation system was created by replacing with horizontal and vertical spring elements. The analytical model was divided into approximately 3.9 million elements in total, and the primary natural period of the base isolation building was 2.79 s.

Among the analysis results, the orbit of horizontal displacement in a base isolation story is shown in Fig. 12. The

dotted line in the figure shows clearance between the building and the retaining wall (375 mm), and crossing over this line results in a collision. Fig. 13 shows the time history impact force waveform which shows the generation of collisions 5 times in total in 6.0 s. In addition, since there is a possibility that the collision of the building and the retaining walls results in behavior like sending and sweeping legs in judo, generating tensile force that reduce base isolation performance, and therefore some effective measures should be taken.

6. Conclusion

This study enabled elasto-plastic seismic response analyses by constracting huge number of approximately 4 million finite element model consisting of concrete and reinforcing bars as they are, and thus the prospect of the possibility of a reduction in the vast expense required by full-scale shaking table tests for various structures and the improvement in the effectiveness of such tests was obtained by using the sophisticated simulation analysis method (the numerical shaking table).
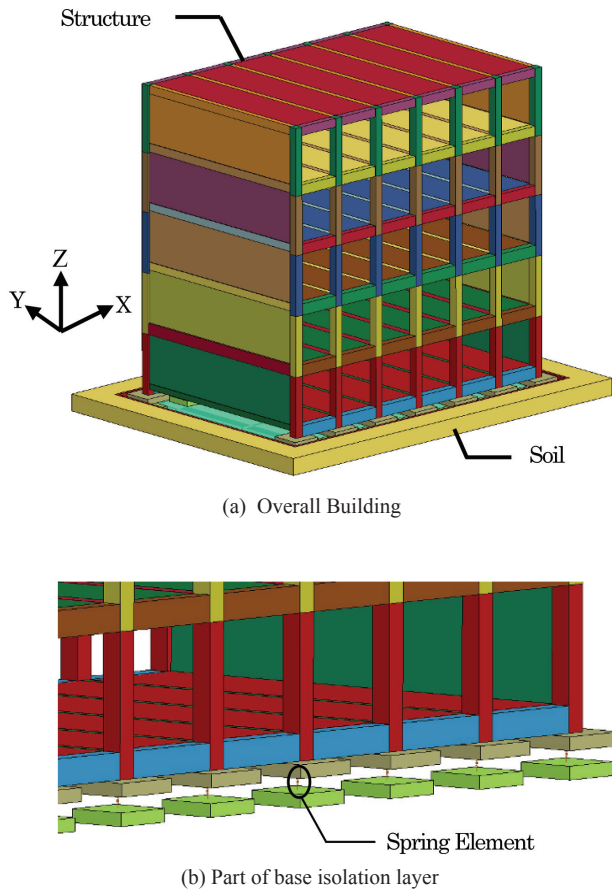

(a) Overall Building

(b) Part of base isolation layer

Fig. 11 Perspective View of Detailed FEM Model.

Fig. 12 Orbit of horizontal displacement.
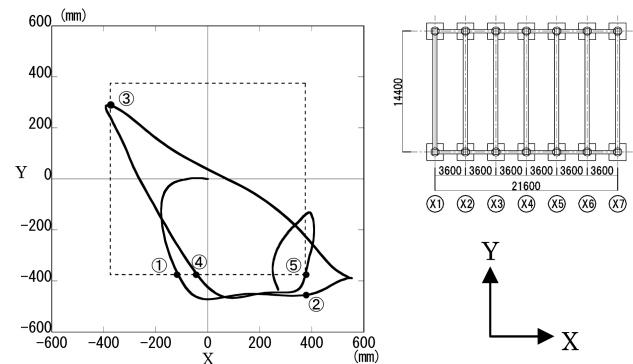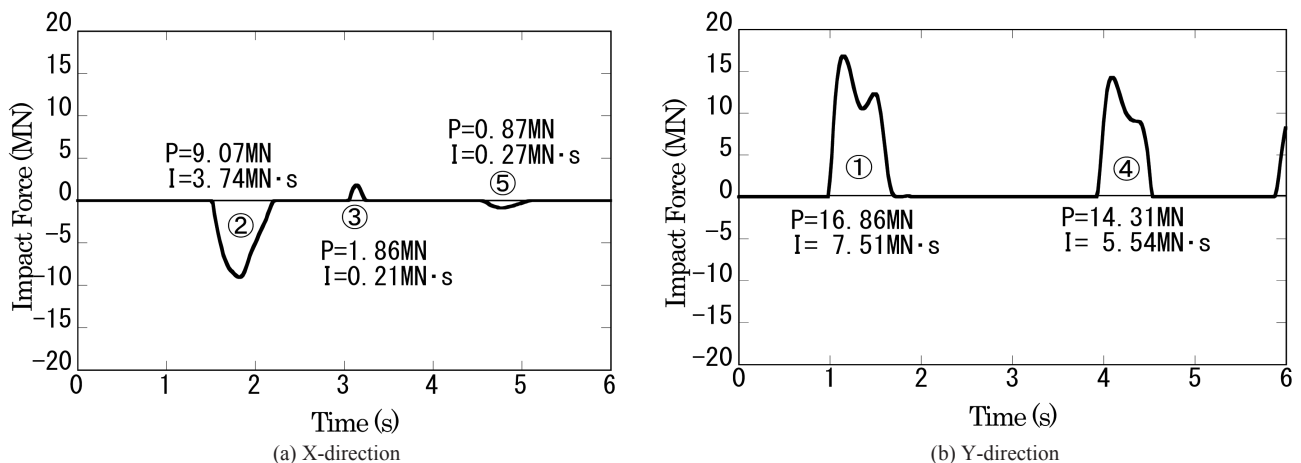

(a) X-direction

(b) Y-direction

Fig. 13 Impact force time history waveform (X, Y-direction).

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実大鉄筋コンクリート造建物の振動台実験の精密・詳細シミュレーション解析システムの開発 その2

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　自動車等の衝突解析に有効性を発揮している陽解法の衝撃解析コードを建物の地震応答解析に応用し、阪神淡路大震災で多発し未解明の鉄筋コンクリート建物の崩壊現象のコンピュータ解析を可能にする研究を行った。本年度は昨年度に引き続き、下記（1）に示すE－ディフェンスで行われた実大6階建て鉄筋コンクリート建物の崩壊に近い現象に至った振動台実験のシミュレーション解析の精度向上とその現象解釈に重要なプッシュオーバー解析（静的漸増解析）を行なった。

　更に振動台実験により検証を行なった「精密・詳細シミュレーション解析システム」の適用範囲の拡大と精度の検証増加の観点から下記（2）に示す解析を行なった。

（1）実大鉄筋コンクリート造6階建建物の振動台実験のシミュレーション解析の精度向上とその現象解釈に重要なプッシュオーバー解析　（静的漸増解析）

（2）「精密・詳細シミュレーション解析システム」（数値振動台）による各種建物の地震応答解析

　　①地盤上の実大鉄筋コンクリート造6階建物の地震応答解析（応用解析）

　　②耐震補強有・無の鉄筋コンクリート造3階建物振動台実験のシミュレーション解析

　　③長周期パルス地震に対する免震建物の周辺擁壁との衝突振動解析（応用解析）

　上記のような2年間の研究により、鉄筋やコンクリートをあるがままにモデル化した400万要素程度の有限要素による弾塑性地震応答解析が可能となり、数値振動台として各種構造物の実大振動台実験にかかる膨大な費用の軽減と効率化が可能となる目途を得ることができた。

キーワード：地震応答, 振動台実験, 鉄筋コンクリート骨組, 地球シミュレータ, FEM, 免震, 耐震補強