Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1450

ENGINEERING NONLINEAR STRUCTURAL RESPONSE IN RC PIERS: A COMPARISON BETWEEN FULL SCALE EXPERIMENTS AND FIBER ELEMENT MODEL ANALYSIS

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ABSTRACT

In response to severe damages during the 1995 Great Hanshin earthquake, specifications and standards for structures and bridges in Japan have since been modified. In order to better understand the effects of failure mechanisms and the scale of the damage of structures during earthquakes, a series of experiments have been performed using a shake table (E-Defense) at the nonprofit National Research Institute for Science and Disaster Prevention (NIED).

A C1-2 pier that was designed in the 1970's and is still used now was one of a series of experiment bridge piers. A blind contest accompanied the experiment and was held to improve the analysis technology. This team developed a program called UC-win/FRAME(3D), participated in the contest, and was awarded the fiber model section prize.

This paper introduces the experiment and analysis model and then presents a comparison of the experiment results and analysis results for displacements and forces.

Introduction

The 1995 Hyogoken Nanbu Earthquake caused a great deal of damage to bridge structures. As a result, the Japan Road Association's Specifications for Highway Bridges was modified the following year. Modifications included the introduction of the stress-strain relationship in concrete and changes to the calculation method for the horizontal force-displacement relationship in RC piers. At the same time, the stress-strain relationship of concrete was introduced in consideration of the confinement effects of tie reinforcements. Moreover, in order to improve ductile properties, the details of reinforcement arrangement were coded and the shear resistance was revaluated to take dimensional effects into consideration.

Even though several experiments were carried out on small-scaled models, the large-scaled model's experimental data was necessary to make safety judgments on the bridge design.

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E-Defense, the world's largest shake table experiment facility, is owned by the NIED, a non-profit organization, and was constructed to help clarify damage mechanisms of structures affected by the Hyogoken Nanbu Earthquake. Since many of the damage phenomena have not been understood, several experiments were performed.

This paper reviews the completed C1-2 experiments and introduces a results comparison of the analysis model and the experiment in the anticipation of blind analysis contest. The modeling tool and model validity is also verified.

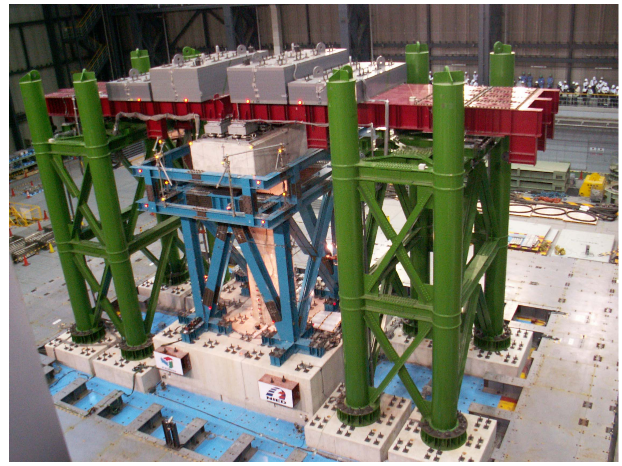


Figure 1. C1-2 Experiment Set

Experimental Summary

Shape and Materials

Figure 1 shows the C1-2 experiment set and Figure 2 shows the dimension and reinforcement arrangement of the pier.

The C1-2 height from the pier base to the cap beam upper position is 7.5m and its diameter is 1.8m. All main reinforcements are D32, and their arrangements are 2.5 layers from the pier base to 1.87m, 2 layers from 1.87m to 3.87m, and 1 layer from 3.87m to the pier top. The tie reinforcements are D13 with 300mm intervals for the internal, middle, and outside layers. But the outer layer tie at the part from the base to 0.95m and from 4.85 to the top is condensed with interval 150mm. The reinforcement material is SD345 and its tension strength based test is 372MPa. Test points were also set on the concrete surface at a position 3.0m from the pier base. The concrete strength on the test day according to tabular tests was 33.1MPa for the lower part and 28.4MPa for the upper part.

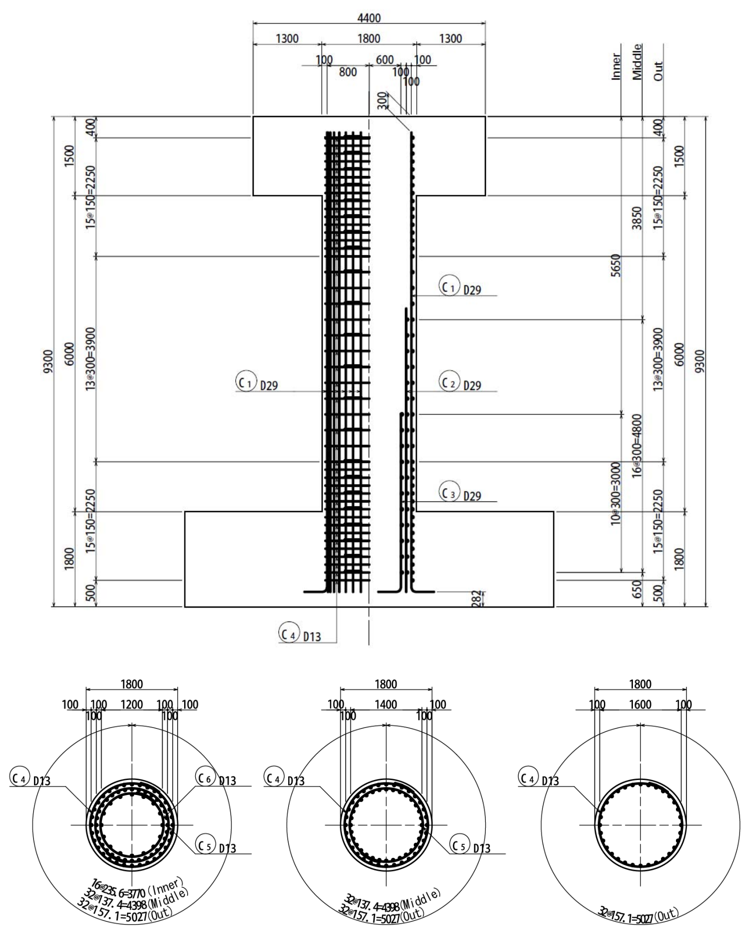


Figure 2. The Pier Sketch (C1-2)

Loads

The experimental body of the RC pier is about 310t. Moreover, superstructure girder weight with the bearings totaled 307t. Additionally, if the two side frame piers and protecting frame are summed together, the weight on the vibration table for loading was about 1030t.

The input acceleration was the observed waves at JR Takatori station in the Hyogoken Nanbu Earthquake as shown in Figure 3. The three direction components (two horizontal directions and one vertical direction) are input simultaneously. Because of the interaction between the soil and structures, the used acceleration is 80% of the original recorded ones.

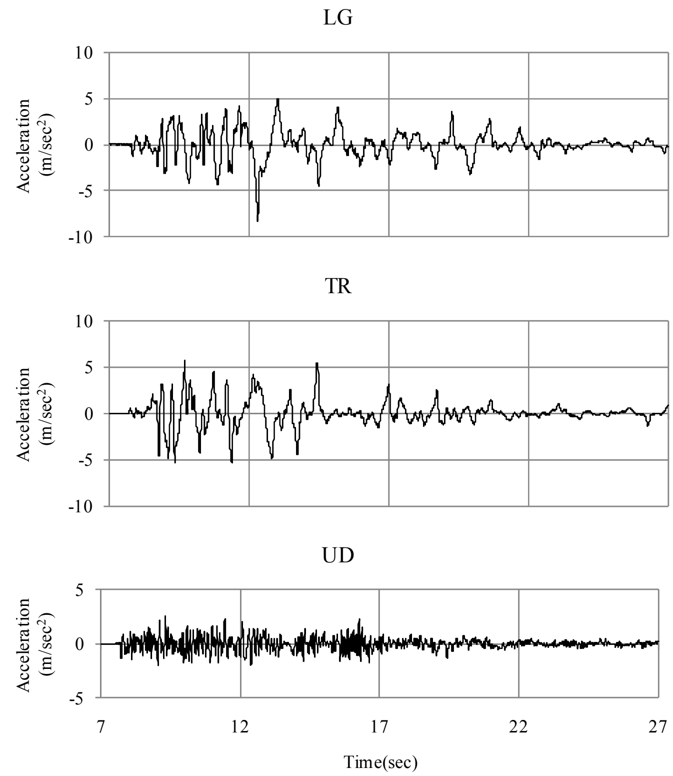


Figure 3. The input earthquake waves

Blind Analysis

Purpose of the Blind Analysis

In order to improve the numerical analysis technology to forecast the response and damage behavior of RC structures during earthquakes, the NIED executed a blind analysis contest against the experimental C1-2 pier. The analysis was performed in the following two stages:

Stage 1) Analysis before experiments: Forecast the damage behavior corresponding to the seismic ground motion (target waves) input to the shake table.

Stage 2) Analysis after experiments: Forecast the damage behavior with the same model as Stage 1 and analyze methods corresponding to the seismic ground motion (observed waves) input to the shake table.

This paper describes the results of Stage 2. The contest was held in the following two sections:

Section A) FEM model analysis section: Use the finite element method to analyze reinforcement concrete by solid elements.

Section B) Fiber model analysis section: Use the fiber model to analyze reinforcement concrete by beam elements.

We employed an analytical tool, UC-win/FRAME(3D), which is an all-purpose analysis program for the spatial frames. The program was used to create a fiber model simulation to predict the Section B contest.

Available Materials

Among the materials for the analysis, the following five items were opened to the contest participants. They were downloadable from the NIED server.

(1) Shape of structure: Details such as plane drawing, spatial drawing, member sections and bearings

(2) Weight distribution: Details of each member, parts and spindles, and bearing conditions

(3) Material: basic properties and strain-stress relationship of used materials, and concrete composition

(4) Input earthquake waves

(5) Photographs of experimental sample

Analysis Methods

Analysis Conditions

・Analysis tool: UC-win/FRAME(3D) Ver.3.00.02 developed by FORUM8 Co., Ltd.

・Integration method: Newmark β Method (β=1/4)

・Integration interval of time: ΔT=0.005 second

・Input acceleration: Two horizontal directions and vertical direction input simultaneously, observed wave (acceleration) to shake table

・Geometrical consideration: Large displacement analysis (Compatibility Condition: Nonlinear)

Analysis Model

Figure 4 shows an analytical model with 585 nodes, 735 elastic elements, 8 spring elements, and 6 fiber elements for the pier column. As for the bearing conditions, only the bearing on the top of the pier is fixed, and the side ones are movable. However, the friction of slipping is considered.

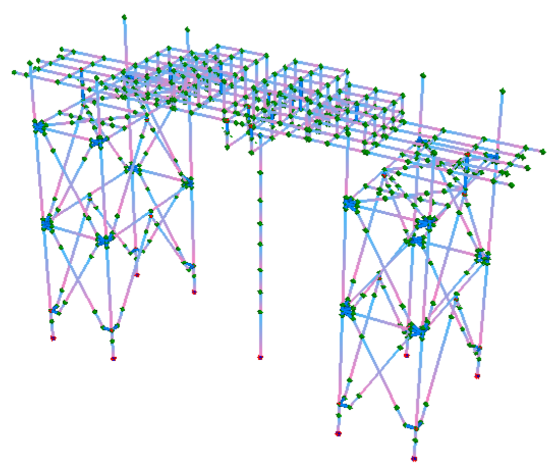


Figure 4. The analysis model

The pier where the fiber element is used is described in detail. The cap beam and the footing are assumed to be elastic. As described before, concrete was casted in three phases that included (a) footing, (b) column base part, and (c) column upper part and cap beam. The strength of those materials was published and reproduced. The length of fiber elements is set to the half of section diameter, D=1.8m.

The fiber element sections are finely divided and the stress-strain relationship of each cell is defined respectively. Figure 6(c) shows the division chart of the section. Because large stress occurs at a position away from a neutral axis, the cover concrete is divided more finely than the core concrete. As a result, the number of cells in the section becomes 1400.

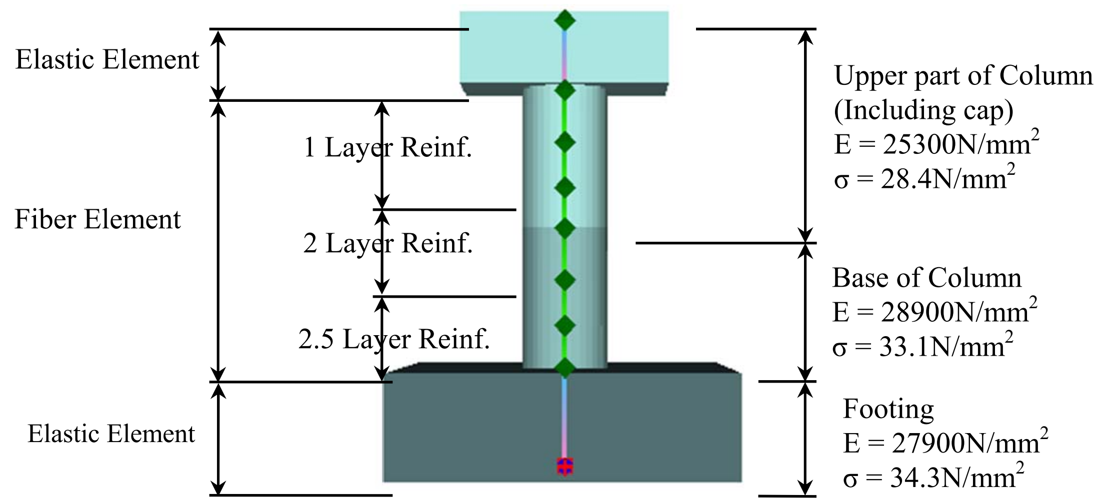
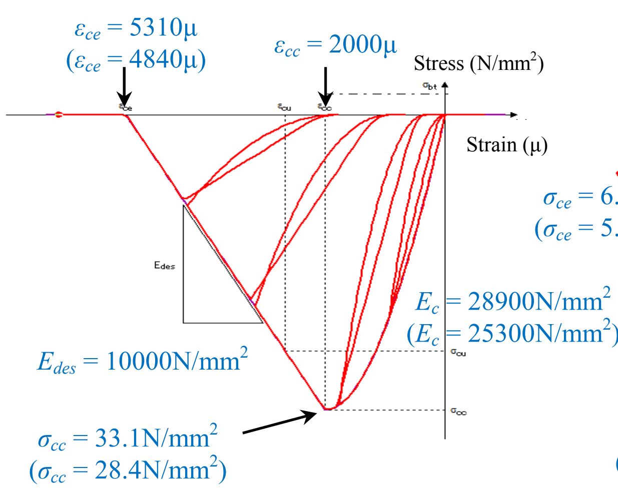
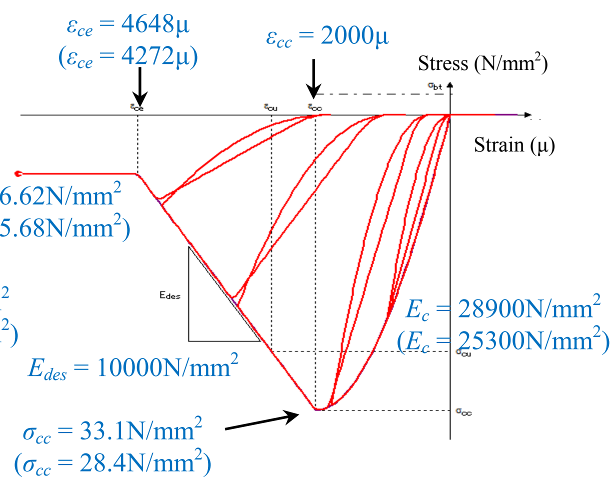


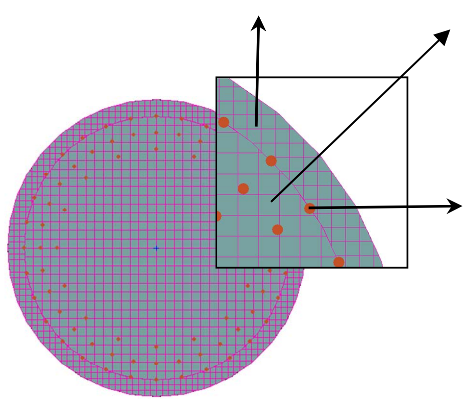
Figure 5. The Pier



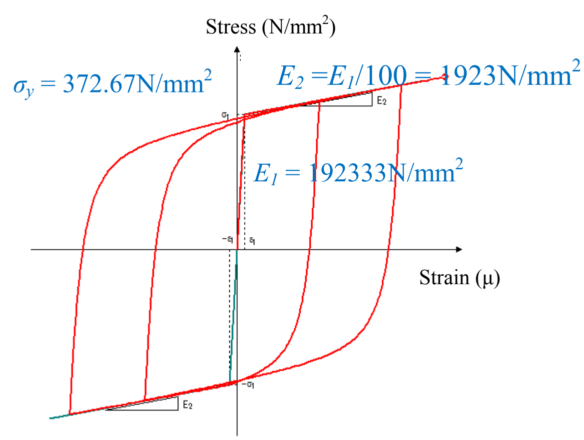
(a) Cover Concrete



(b) Core Concrete



(c) Section cell division



(d) Reinforceme

Figure 6. Cell Division of Section and Hysteresis

The hysteresis of the reinforcement employed is a bilinear type in the bone frame; its inner loop is the modified Menegotto-Pinto model.

Concrete hysteresis is defined differently for cover concrete and core concrete.

The numerical value in Figures 6(a), (b) and (d) is concrete of pier base parts and the value in brackets is a parameter for the upper part concrete.

Three kinds of springs that modeled bearings were defined as shown in the Figure 7. Fixed bearings (represented as circles) were set up at the top of the pier, and falling-prevention bearings (represented as triangles) were set on both sides of the circles in the transverse direction. Movable bearings (represented as rectangles) by spring elements were set to consider the friction on the sides in the longitudal direction.

The damping matrix was taken as the proportion type depending on elements. The viscous damping constant of each element was set as follows.

・Girder: 2%

・Concrete (elastic): 5%

・Rigid member and bearing: 0%

Moreover, the viscous damping constant for the fiber element used for the pier column was assumed as zero so that hysteresis damping only was considered automatically.

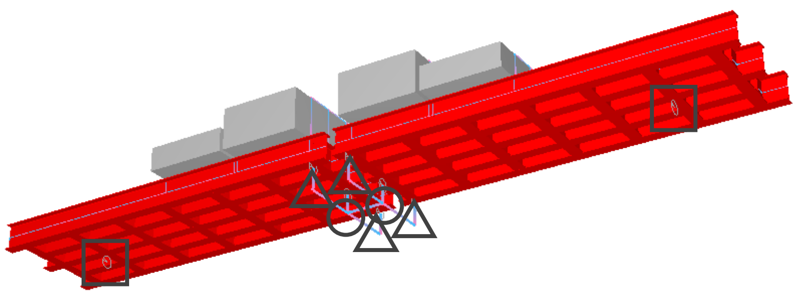


Figure 7. Bearing Conditions

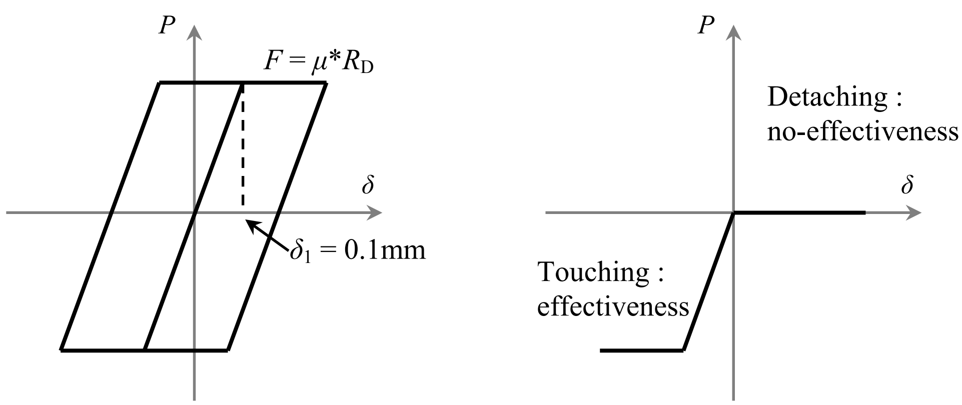


Figure 8. Bearing Spring *(Left: movable bearing in longitudal direction, Right: fall-prevention bearing in the longitudal direction)*

Comparison of Analysis and Experiment

Eigen Analysis Results

The eigen analysis was first completed to understand the vibration properties ahead of the time response analysis. The graphs in Figure 9 show the first mode (left) and second mode (right); the dominant vibration is along the transverse direction and the longitudinal direction. The difference between their periods is not very apparent at about 0.37 seconds.

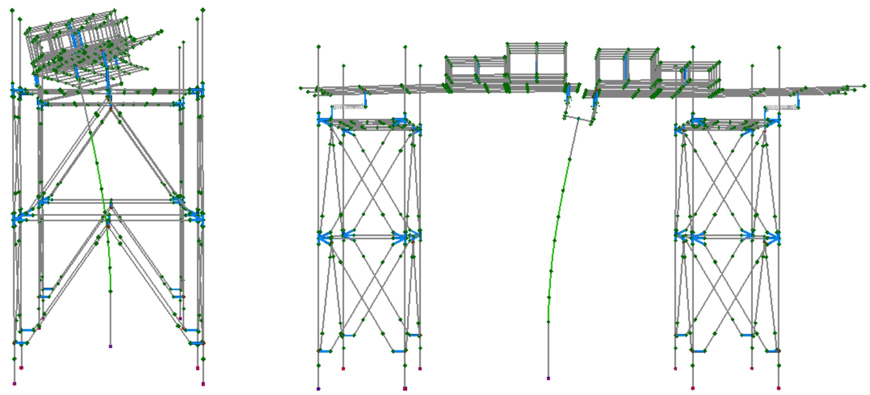


Figure 9. Mode Figure (Left: 1st mode T = 0.377sec, Right: 2nd mode T = 0.372sec)

Displacement Histories of Pier Top

Figure 10 shows the displacement history of the top of the pier. It can be concluded that both amplitudes and the period of the experiment could be reproduced well.

Moreover, the tracks of displacement are shown in Figure 11. The height from the pier base to the upper surface of the cap beam is 7.5m. The outcome of the experiment can be traced to about 150mm which is about twice the design allowance value. Because the superstructure has collided with the falling prevention hedge after 12.5 seconds, the analytical results deviated from the experiment results. Thus the comparable part between the analytical result and the experiment result was only for the first 12.5 seconds. The results after 12.5 second are shown in the dotted line.

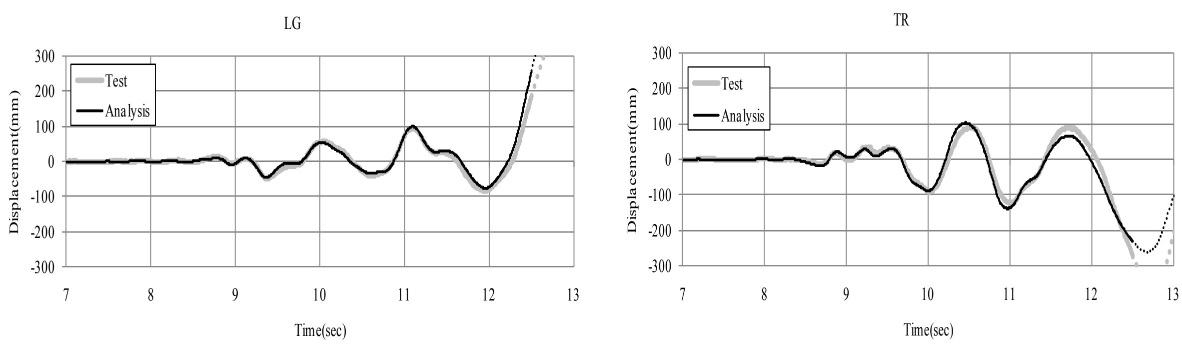


Figure 10. Displacement histories of pier top (Left: longitudal direction, Right: transverse direction)

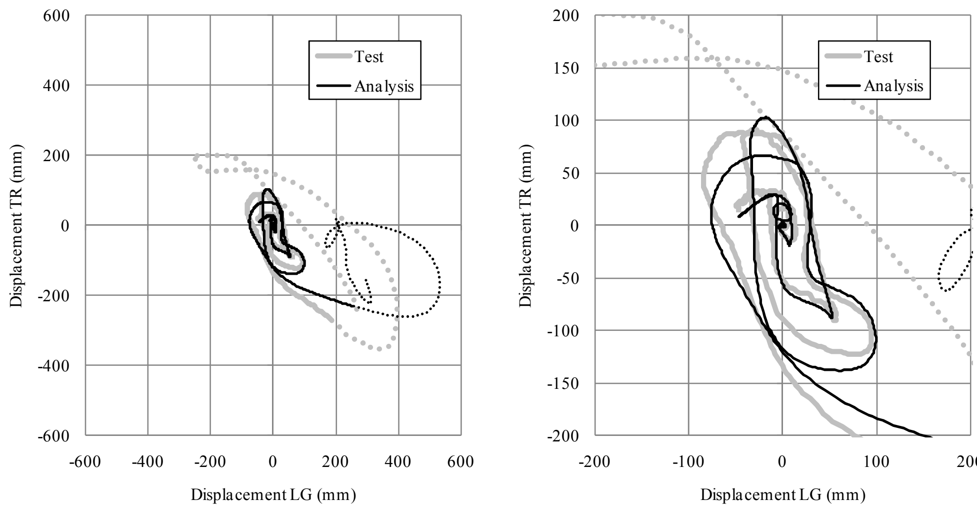


Figure 11. Displacement trace of pier top (Left: full scale, Right: magnified)

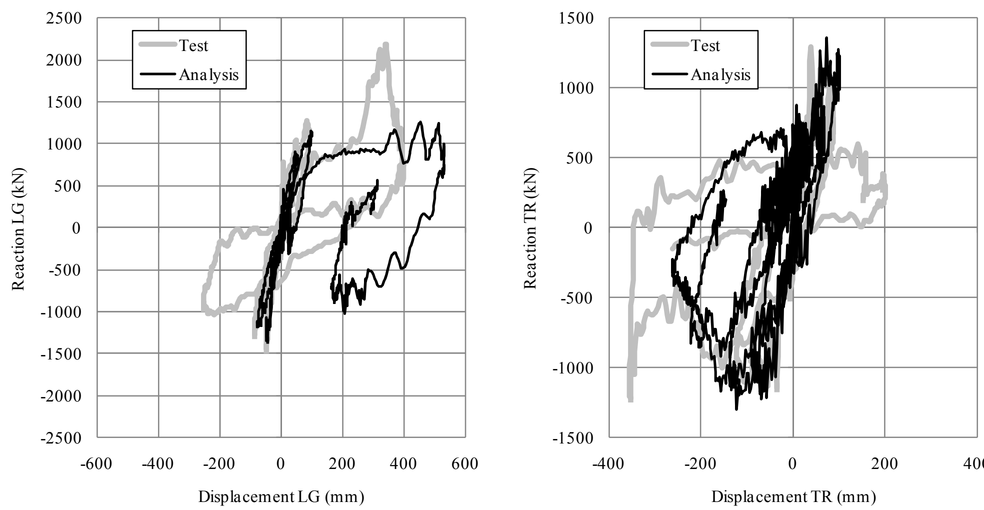


Figure 12. Force-Displacement relationship of pier top (Left: full scale, Right: magnified)

Force-Displacement Relationship

The relation between the load and the displacement generated at the fixed bearing position on a central pier is shown in Figure12. The outcome of the experiment and the analytical results correspond within about 200mm as does the comparison of displacements.

Distribution of Curvature and Strain

Reinforcement Yield of Base Part (T=9.305 Second)

Figure 13 shows the strain distribution and the curvature distribution at 9.305 seconds, the time of main reinforcement yielding. The curvature of cut-off part at the upper part of the column (H=3.9m) becomes somewhat larger but the maximum curvature appears at the base of the pier because of locating in the elastic range.

Concrete Ultimate of Cut-off Part (T=10.895 Second)

It is the step that the ultimate state occurred, the curvature and strain at the H=3.9m experienced the maximum. As shown in Figure 14, it can be concluded that the damage at the cut-off part had occurred in the experiment.

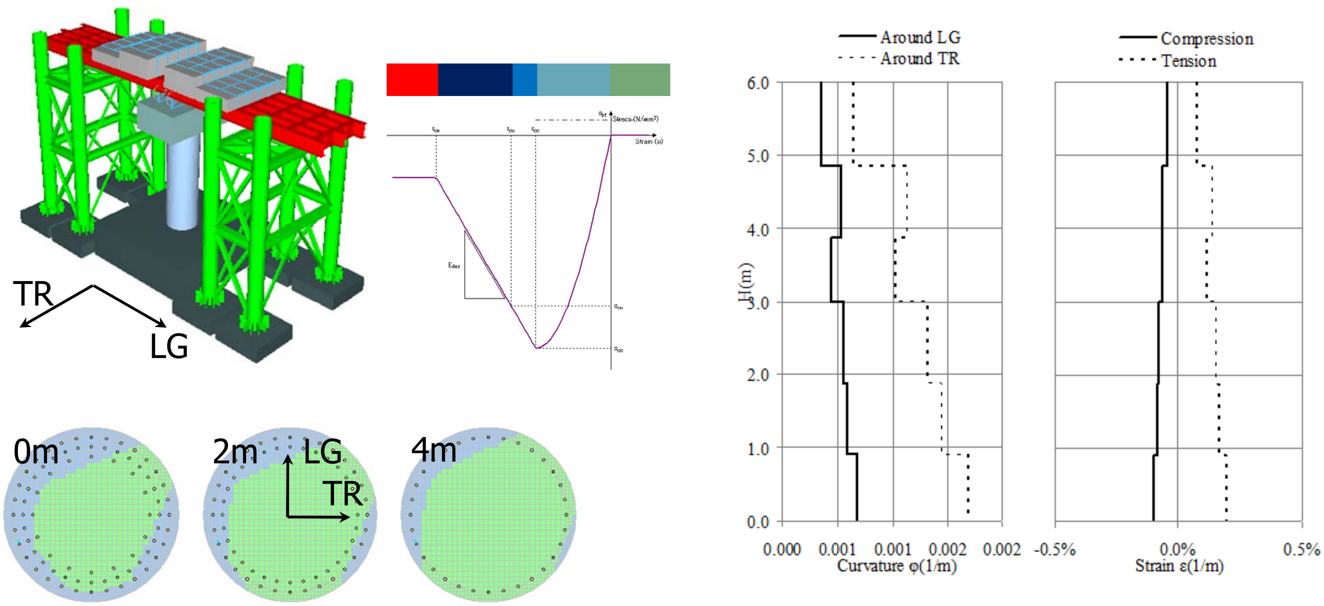


Figure 13. Maximum compression strain distribution (when the main reinforcement yields at base)

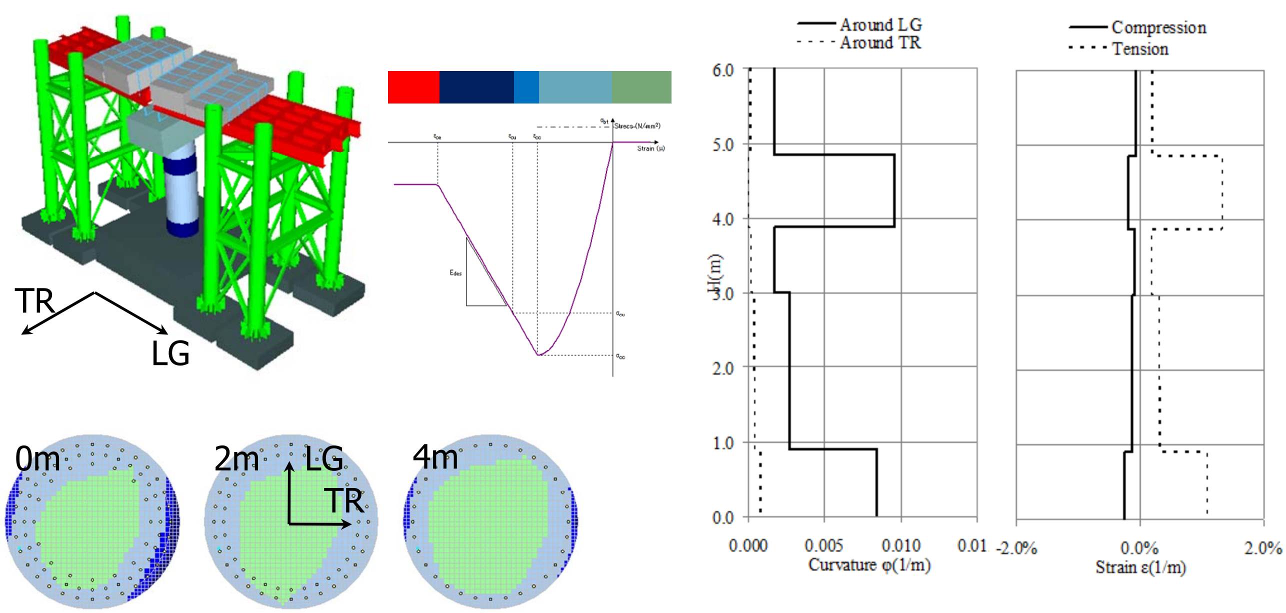


Figure 14. Maximum compression strain distribution (when concrete ultimate of cut-off parts)

Conclusions

・Response analysis of time history was executed for the real large experiment body which has a cut-off reinforcement. A comparison between the experiment and analysis was conducted.
・The displacements and forces in the experiment were reproduced very well in macro level of the model analysis.
・A verification on the micro level is planned. This will examine more detailed results between the experiment and analysis according to the materials available from the NIED.

Acknowledgments

We very much appreciate the NIED's permission to publish materials related to the C1-2 experiment.

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