STUDY ON RESTORING FORCE CHARACTERISTICS AND DEFORMATION CAPACITIES OF THE FLEXIBLE REINFORCED CONCRETE PIER WITH I-SHAPE CROSS SECTION UNDER HORIZONTAL LOAD

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ABSTRACT

Flexible reinforced concrete pier with I-shape cross section (FRCP-I) is originally designed in Japan, and is used as the high pier of expressway in mountainous area. The FRCP-I consists of the side columns and the shear wall. Therefore, the FRCP-I is expected to absorb more earthquake energy than the other types of piers. In this study, based on the horizontal loading tests, it is found that the failure type of the FRCP-I is the flexural shear compression failure instead of the brittle shear failure. Moreover, the restoring force characteristics and the deformation capacities are clarified. Deformation capacities of this pier obtained by finite element (FE) analysis coincide with the experimental results.

Keywords: RC frame pier with shear wall, horizontal loading tests, finite element analysis.

1. INTRODUCTION

Flexible in longitudinal direction reinforced concrete pier with I-shape cross section (FRCP-I) as shown in **Photo 1** is originally designed in Japan, and is used as the high pier of expressway in mountainous area. The FRCP-I consists of two side columns and a shear wall. The FRCP-I is rigid in the transverse direction, and is expected to absorb more earthquake energy than the other types of piers. However, the large deformation potential of the FRCP-I member is neglected in the seismic design for bridge piers because

Photo 1: Overview of the FRCP-I

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the horizontal load-carrying capacity and damage process of the FRCP-I member have not been sufficiently clarified yet. This paper describes the results of experiments and finite element (FE) analysis on the restoring force characteristics and the deformation capacities of FRCP-I specimens subjected to the horizontal loading, the specific objectives of this research are the following: (1) to experimentally assess the deformation capacity and damage process of FRCP-I specimens under the horizontal load; (2) to define the restoring force characteristic of FRCP-I specimens corresponding to the damage condition; and (3) to provide an evaluation method for the toughness of FRCP-I based on the FE analysis.

2. EXPERIMENTAL PROCEDURES

2.1. Test Specimens

The material properties of each specimen are summarized in **Table 1**. The size of each specimen is summarized in **Table 2**. Moreover, the details of each specimen are shown in **Figure 1**. The height of the shear wall is 1,900 mm, the width of the pier is 1,000 mm, and the height of the reinforced concrete footings is 500 mm in all of the FRCP-I pier specimens. The sectional size of the side columns is 250 mm×200 mm, the sectional size of the shear wall is 500 mm×60 mm, and the sectional size of the reinforced concrete footings are 2,000 mm×900 mm in all of the FRCP-I pier specimens. In this study, Specimen No. 1 is defined as the standard specimen, Specimen No. 2 and Specimen No. 3 had an increased volume of tie hoop of the side columns. Additionally, Specimen No. 4 had an increased volume of lateral reinforcement of the shear wall, and Specimen No. 5 had a reduced volume of lateral reinforcement of the shear wall.

Table 1 Material properties of the FRCP-I specimens

	Longitudinal reinforcement of side column						Ties of side column		
Specimen	Diameter (mm)	Number	Yield strength (MPa)	Diameter (mm)	Number	Yield strength (MPa)	Diameter (mm)	Spacing (mm)	Yield strength (MPa)
No. 1	16	6	385	10	2	363	6	120	409
No. 2	16	6	385	10	2	363	6	60	409
No. 3	16	6	385	10	2	363	6	40	409
No. 4	16	6	385	10	2	363	6	120	409
No. 5	16	6	385	10	2	363	6	120	409

	Longitudinal reinforcement of shear wall			Lateral reinforcement of shear wall			Concrete
Specimen	Diameter (mm)	Number	Yield strength (MPa)	Diameter (mm)	Spacing (mm)	Yield strength (MPa)	Strength of each specimen (MPa)
No. 1	10	5	363	13	120	345	34.4
No. 2	10	5	363	13	120	345	36.7
No. 3	10	5	363	13	120	345	31.5
No. 4	10	5	363	13	60	345	35.7
No. 5	10	5	363	10	120	363	30.3

Table 2: Size of the FRCP-I specimen

	Height of the shear wall (mm)	Width of the pier (mm)	Sectional size of the side column (mm)	Sectional size of the shear wall (mm)	Reinforced concrete footing	
					Height (mm)	Sectional size (mm)
Each specimen	1,900	1,000	250×200	500×60	500	2,000×900

2.2. Test Setup

The test setup is shown in **Figure 1**. The horizontal load was applied to the center of the lateral beam as shown in **Figure 1**. The horizontal force was applied monotonically by displacement control using the hydraulic jack.

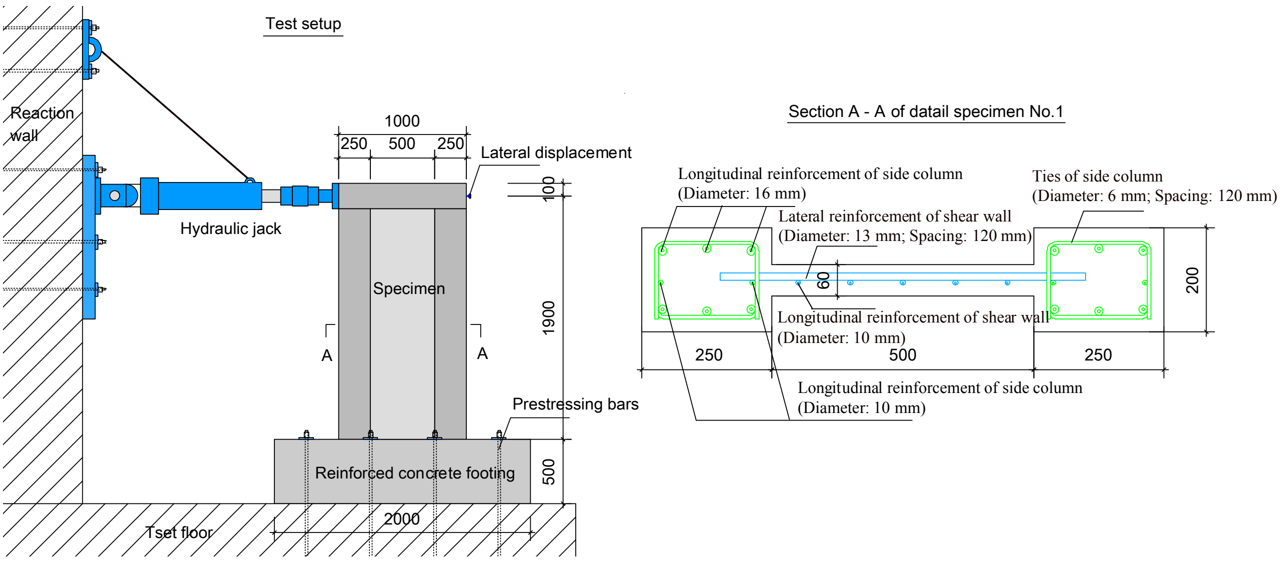

Figure 1: Test setup and cross section view of the specimen

2.3. Test Results

The damage process in the case of Specimen No. 1 is shown in **Photo 2**. The load-displacement relationships of the FRCP-I specimens are shown in **Figure 2**. In **Figure 2**, it is found that the load doesn't fall largely after the maximum load in all cases. According to the results of the horizontal loading test, the damage process of the FRCP-I specimens is commonly described as follows: the horizontal flexural crack, the diagonal shear crack, the yielding of the longitudinal reinforcement bar, the deterioration of the concrete cover, the failure of concrete on compressive column, the buckling of the longitudinal reinforcement bar, and the bulging of tie hoop in compressive column.

In this study, the damage process of specimens has been divided into three damage condition. The damage condition 1 is the condition until the longitudinal reinforcement bars yield. The damage condition 2 is the condition until the concrete cover is deteriorated. This means the damage condition is defined as from the yield of bar to the maximum load in the load-displacement curve. The damage condition 3 is the diagonal shear cracks in the shear wall and compressional column broadened. Then those cracks resulted in the compression failure of concrete on the compressional column’s base, and the buckling of the longitudinal reinforcement bars. Furthermore tie hoops protruded out of the column, and finally the column and the wall lost the proof stress and crushed because of flexural shear compression failure. At the end of damage condition 3 is ultimate displacement.

Damage condition 1 Damage condition 2 Damage condition 3

Photo 2: Damage condition (Specimen No. 1)

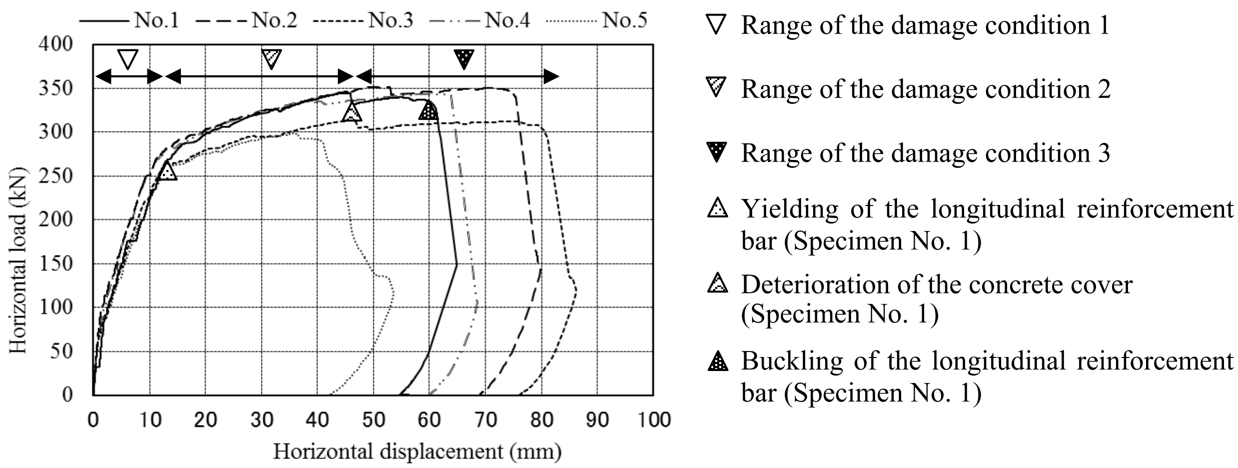

Figure 2: Load-displacement curves

3. SIMULATION ANALYSIS

3.1. Analytical Model

The FRCP-I specimens were modeled and analyzed by using the finite-element (FE) program FINAL (CTC 2010). The analytical model and the material structures are shown in **Figure 3**. In this study, the model is the two-dimensional model. In this model, the modified Ahmad (Naganuma 1995) stress-strain relationship model was used to simulate the concrete stress-strain curve in compression. To imitate the behavior of concrete under condition of tension the Izumo (Izumo et al. 1987) model was used. Moreover, the A1-Mahaidi (A1-Mahaidi et al. 1979) model was used to model the shear transmission characteristic after concrete cracked.

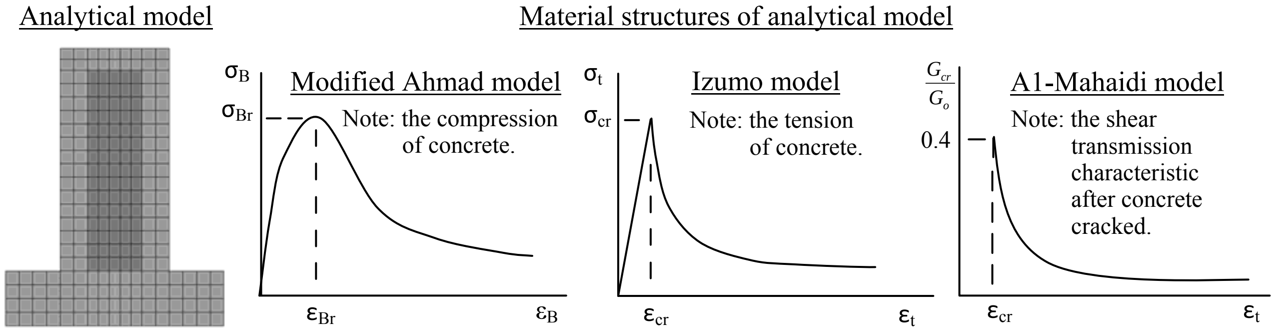

Figure 3: Analytical model and the material structures

3.2. Analysis Results

Analysis results of load-displacement curve are shown in **Figure 4**. As shown in **Figure 4**, the load-displacement curve from FINAL is in good agreement with the test result. Moreover, the boundary point of the damage condition 1 and damage condition 2 (yield displacement), and the limiting point of damage condition 3 (ultimate displacement) are shown in **Figure 4**. As shown in the analysis results of FINAL, the yield displacements of Specimen No. 1, No. 2, No. 4 were tended to be underestimated and those of Specimen No. 3, No. 5 were opposite; while the yield loads of all the specimens were overestimated considering the test result. In addition, the ultimate displacement using FINAL was in good evaluation with the test result.

4. CONCLUSIONS

In this study, the horizontal loading tests of the FRCP-I specimens were carried out. In addition, the test results were simulated by FE analysis. The key observations from these tests and analyses are as follows: (1) the failure type of the FRCP-I member was flexural shear compression failure with large flexural toughness; (2) associating the damage process with the restoring force characteristic of the bridge pier, it is found that the damage process could be separated into three steps; and (3) the test results can be reappeared well by using FE analysis.

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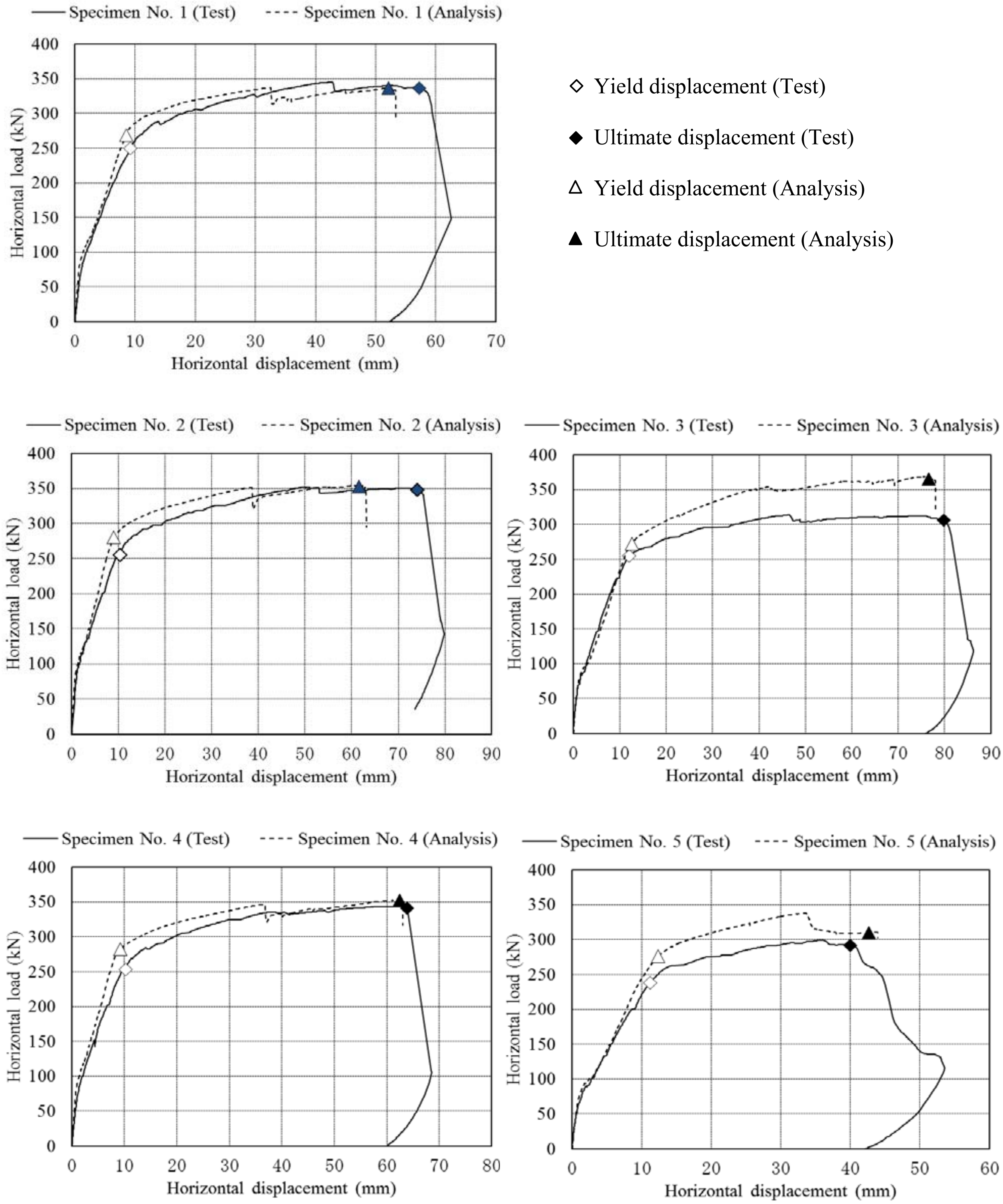

Figure 4: Comparison of load-displacement curve between experiment and analysis