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ANALYTICAL SIMULATION ON EXPERIMENTAL SEISMIC RESPONSE OF HEADED ANCHORS EMBEDDED IN REINFORCED CONCRETE

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Abstract. This paper deal with a series of dynamic response analyses, carried out to give numerical correlation of hysteretic behavior of cast-in-place anchorages obtained by the static loading and shake table tests. Specimens for the analyses are reinforced concrete rectangular blocks with embedded headed anchors. Failure modes expected are the steel bolt failure and the concrete cone failure, associated with the respective embedment depth. Initial flexural cracks presumed seismic damage on the concrete block is developed with bending loading. In the analytical model, nonlinear hysteretic behavior of the anchorage is idealized by translational and rotational springs in which properties estimated from the hysteretic loops of the static loading tests. It was shown that the overall force and displacement performance under dynamic loads are well simulated based on the analytical models presented herein.

Keywords: Dynamic response analyses, headed anchor bolt, nonlinear hysteretic behavior.

1. Introduction

Design and construction of seismically resilient reinforced concrete (hereinafter, RC) structures will contribute toward the sustainable society in an earthquake prone country like Japan. Structural resiliency for a RC structure supporting industrial equipment can be attributed to its global as well as local behavior. For instance, in RC structures of the cooling system facilities at the thermal or nuclear power plants, the equipment and piping are generally installed on the RC members using anchors [1], [2]. In the meantime, the current seismic design allows RC structures to sustain partial damage such as cracks of concrete and yielding of reinforcements, unless they exceed the ultimate state [3]. However, if such seismic damage develops around the anchors, it is necessary to evaluate the seismic safety of the RC structure as well as the effect of the crack on the anchorage strength. From such background, the authors have carried out a series of the experiments related to the strength and the hysteretic behavior of the cast-in-place headed anchor bolts during an earthquake event considering the effects of the flexural cracks [4, 5].

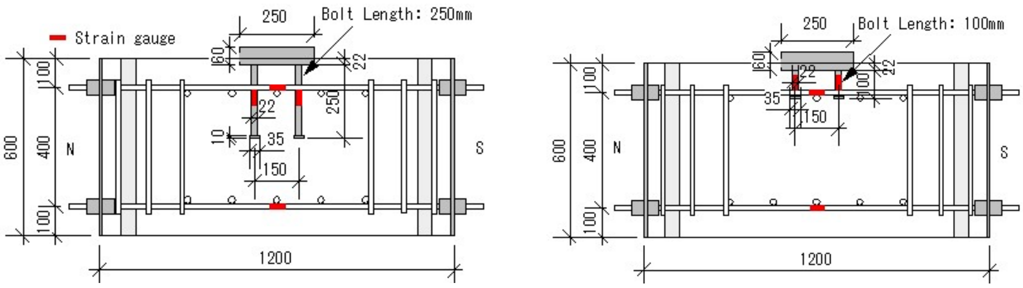
In the present paper, the dynamic response analyses are performed to give numerical correlation of the nonlinear hysteretic behavior of the anchorages obtained by the past experiments (the static loading and the shake table tests). In the analyses, the hysteretic behavior of the anchorage is idealized as translational and rotational springs. The properties of the springs such as stiffness and damping ratio are identified based on the static loading tests results. Then the dynamic response analyses are conducted to simulate the force and displacement hysteresis obtained by the shake table tests.

2. Experimental conditions and results

2.1. Experimental conditions

The test specimens and test cases for this analytical study are presented in Figure 1 and Table 1, respectively. The specimens are RC rectangular brocks with four headed anchors welded to a baseplate. The material properties of the anchors and reinforcing bars are listed in Table 2. The experimental methods for assessing the strength and the hysteretic behavior are the static loading tests and shake table tests. The main parameters of these tests are the failure modes of the anchorages and the initial flexural cracking around the anchors in the RC blocks. The failure modes expected in the anchorages are the steel bolt yielding and the concrete cone failure (hereinafter, bolt yield type and concrete failure type, respectively), associated with the bolt length (250 mm and 100 mm respectively). The initial flexural cracks presumed seismic damage on the concrete block is developed by bending test preliminary conducted as illustrated in Figure 2. The bending moment is applied until the main reinforcing bars yield and the maximum residual crack width exceeds 2.0 mm.

Figure 3 presents the experimental condition and the loading pattern in the static loading test. In these tests, a steel support and a weight (20 kN) are attached on the RC specimen, and a horizontal load



(a) Bolt yield type (b) Concrete failure type

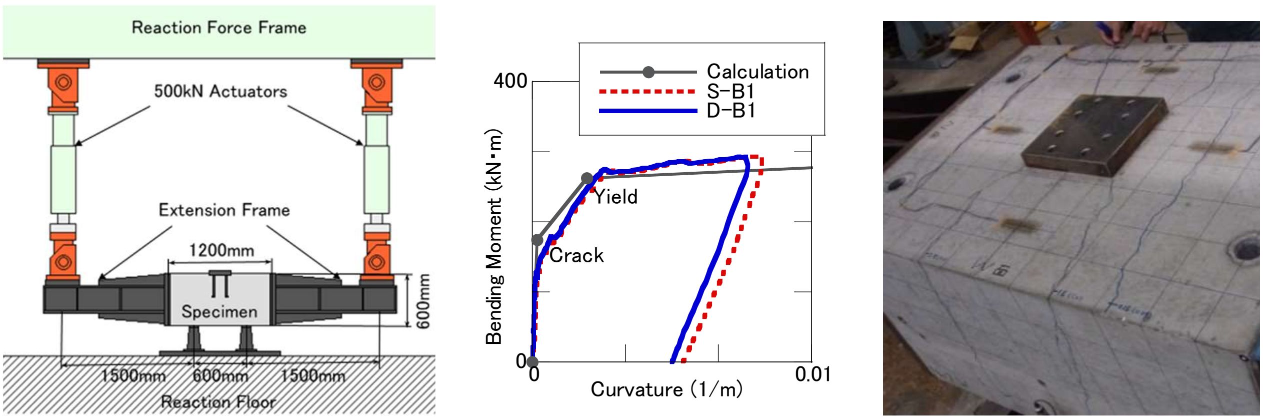
Figure 1. Test specimens (Unit: mm).

Specimen	Failure mode	Bolt length [mm]	Initial cracks	Test method	Strength of concrete [N/mm^2]
S-B0	Bolt yield	250	Without	Static loading test	39.1
S-C0	Concrete failure	100	Without	Static loading test	39.2
S-B1	Bolt yield	250	With	Static loading test	39.6
D-B0	Bolt yield	250	Without	Shake table test	42.5
D-C0	Concrete failure	100	Without	Shake table test	42.6
D-B1	Bolt yield	250	With	Shake table test	43.1

Table 1. Test cases.

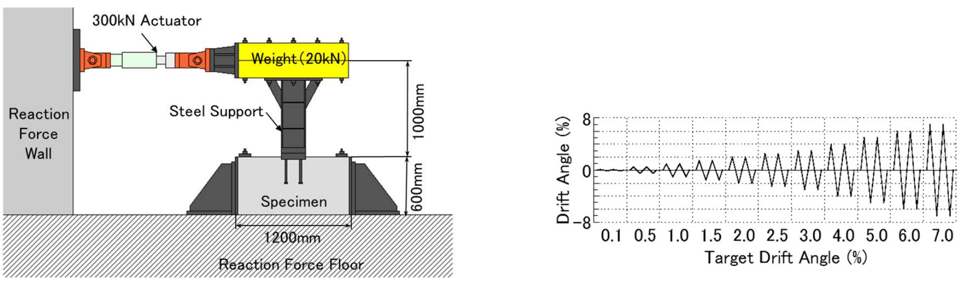
	Diameter [mm]	Young's modulus [kN/mm^2]	Yield strength [N/mm^2]	Tensile strength [N/mm^2]
Anchor bolt	22	208.5	330.2	464.1
Reinforcing bar	19	190.7	401.9	582.9

Table 2. Development of initial flexural cracks.



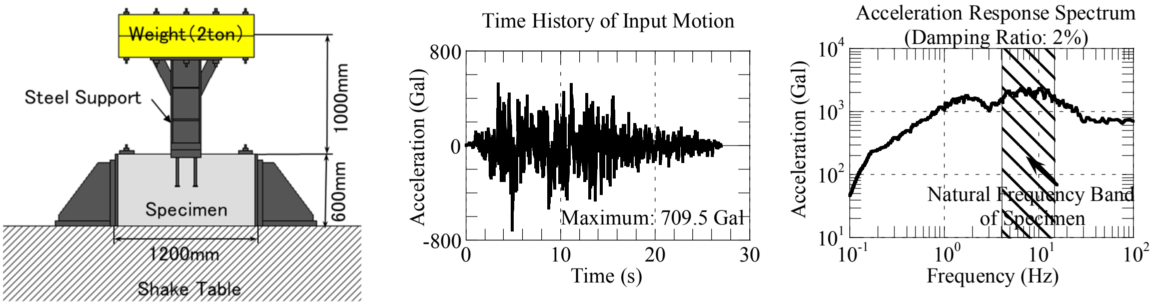
(a) Loading condition (b) Moment and curvature relation (c) Flexural cracks (S-B1)

Figure 2. Development of initial flexural cracks.



(a) Experimental condition (b) Loading pattern

Figure 3. Loading conditions in the static loading test.

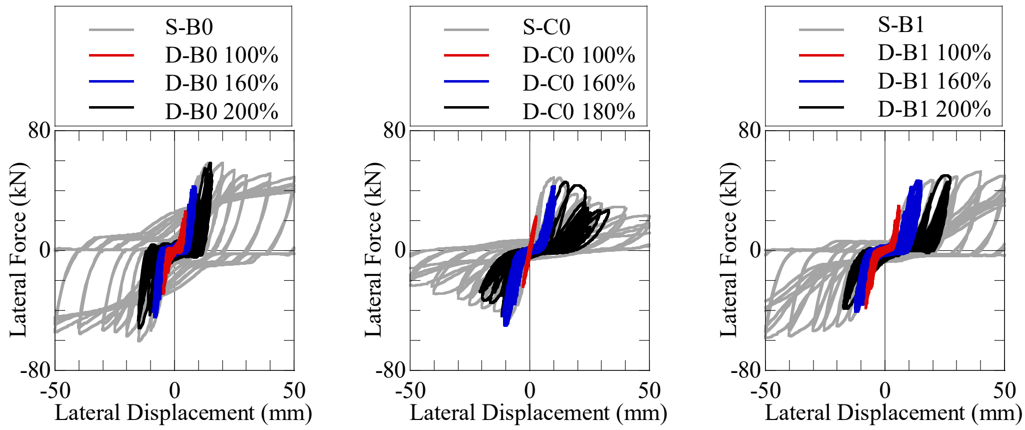


(a) Experimental Condition (b) Input wave

Figure 4. Loading conditions in the shake table test.

Specimen	Magnification of input Motions [%]									
D−A0	20	40	60	80	100	120	140	160	180	200
D−C0	20	40	60	80	100	120	140	160	180	–
D−A1	20	40	60	80	100	120	140	160	180	200

Table 3. Magnification of input wave in the shake table tests.



(a) S-B0 and D-B0 (b) S-C0 and D-C0 (c) S-B1 and D-B1

Figure 5. Lateral force and lateral displacement relationships based on the static and dynamic tests.

is applied to the gravity center of the weight. The lateral displacement is stepwisely increased until the specimen will suffer from significant damage. In the shake table test, the RC specimen is set on the horizontal uniaxial shake table, and then the steel supports and weights are attached on the specimen (see Figure 4). The floor response acceleration is used as an input wave, obtained through the seismic response analysis on the RC head race (duct) equipped with seawater pipes [2]. As shown in Table 3, the input magnification is initiated with 20 % and then it is increased by 20 % increment until the shaking table capacity (200 %).

2.2. Experimental results

Figure 5 compares the hysteresis curves associated with the lateral force and displacement derived from the static loading as well as the shake table tests. The lateral force in the shaking table test was calculated by multiplying the measured lateral acceleration with the mass of the superstructure. In the case of the bolt yield type without the initial crack (S−B0 and D−B0), the restoring force in the post peak region keeps stable forces compared to the concrete failure types (S−C0 and D−C0). The effect of the initial flexural cracks on the anchorage strength appears insignificant in both bolt yield type specimens (S−B1 and D−B1). These results clearly show that the nonlinear hysteretic loops under the shake table tests well cover the ones under the static loading test.

3. Analytical conditions and results

3.1. Analytical conditions

In this study, numerical analyses are performed with respect to an equivalent linear analysis and a step-by-step nonlinear analysis. The analytical model for the

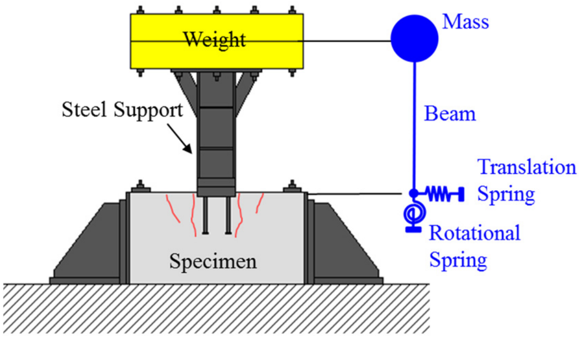


Figure 6. Analytical idealization for the specimen.

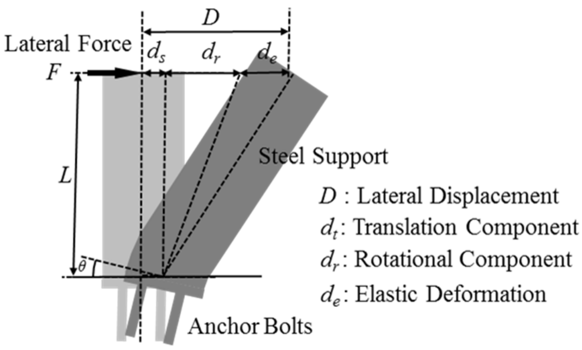


Figure 7. Components in lateral displacement.

test specimen is shown in Figure 6. The steel weight, the steel support and the anchorage part of the RC specimen are idealized as the lumped mass, the beam element and the spring element (translation and rotation), respectively. To evaluate the stiffness and the damping ratio required in the spring elements, the lateral displacement of the static test is decomposed into the translation and the rotation components as shown in Figure 7. The equivalent stiffness and the equivalent damping ratio, defined in Figure 8, are identified for the equivalent linear analysis, while the nonlinear slip model (see Figure 9) is used for the nonlinear analysis.

Figure 10 shows the equivalent stiffness of the translational and rotational components based on the static loading tests. The equivalent stiffness decreased as the lateral displacement increase and the equivalent stiffness decreased in accordance with the degree of initial damage. In all the specimens, the equivalent stiffness of the translation component is some ten times higher than that of the rotation component. This indicates that the lateral displacement during the experiments is mainly caused by the rotation component at the anchoring. The nonlinear hysteresis model is introduced to the rotational spring because of relatively larger deformation appeared in the rotation component.

The equivalent damping ratios based on the lateral force and displacement loops of the static loading tests are presented in Figure 11. These damping ratios of the concrete failure type tend to be slightly lower than that of the bolt yield type. The initial

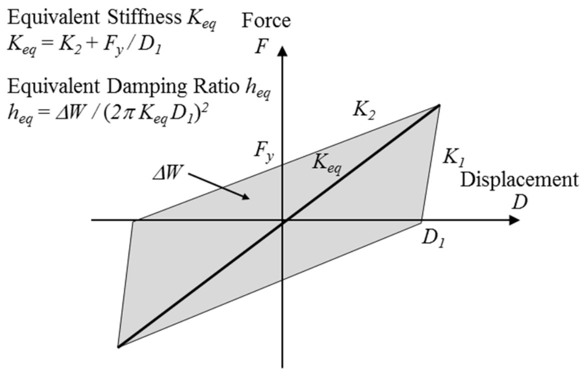


Figure 8. Equivalent stiffness and damping ratio.

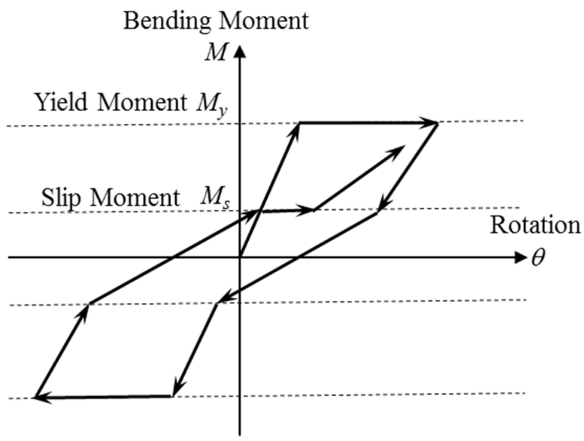


Figure 9. Nonlinear model for rotational spring [6].

damage may bring slightly lower equivalent damping ratio. In the both equivalent linear and nonlinear analysis, the stiffness-proportional damping is applied and the damping ratio is assigned to the natural frequency obtained based on the eigenvalue analysis for each model.

3.2. Analytical results

Figure 12 shows the analytical results of the shake table test based on the linear model, comparing with the experimental results. In the specimen D-B0 (the bolt yield type without the initial damage), The numerical analyses well simulate the dynamic behaviours associated with restoring forces as well as displacement response under considerably large nonlinearity states brought by input magnification.

On the other hand, a good numerical correlation is observed on the specimen D-C0 (concrete failure type without initial damage) up to the 160 % input. However, this correlation deteriorates under the 180 % input where the significant nonlinearity appears due to significant concrete damage. The equivalent analysis, which employs equivalent stiffness and damping ratio based on the static loading hysteresis, demonstrates a well numerical correlation on the overall dynamic hysteresis behaviour on the bolt yielding type (the specimen D-B1) that involves the effect of initial flexural cracks nonlinearity.

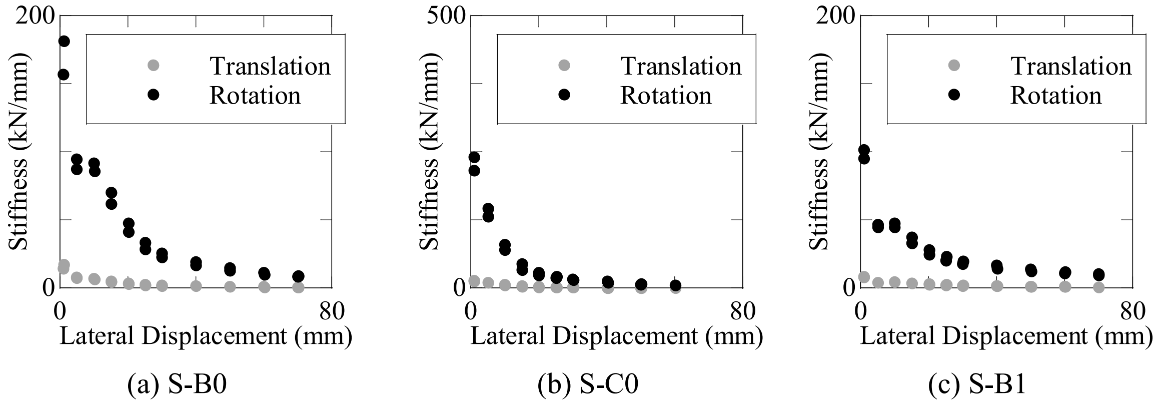


Figure 10. Equivalent stiffness based on the static loading tests.

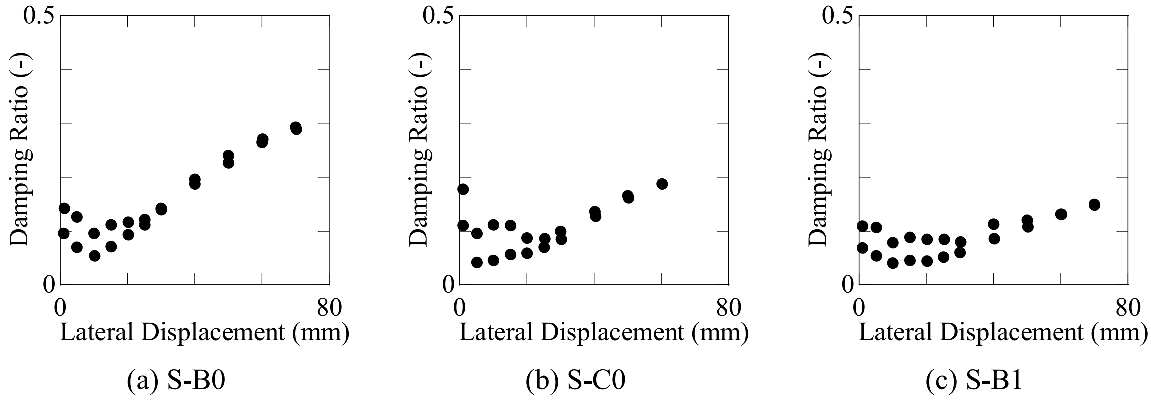


Figure 11. Equivalent damping ratios based on the static loading tests.

As discussed previously, the nonlinear hysteresis model (Figure 9) is introduced to the rotational spring because of relatively larger deformation appeared in the rotation component. Then, the numerical analysis for the shake table test using this model is performed, resulting in hysteresis curves as plotted in Figure 13. These analysis and experiment curves demonstrated that use of the nonlinear hysteretic model improves the degree of numerical correlations, especially in strong nonlinearity observed in the specimen D-C0 and D-B1.

4. Conclusions

In this paper, the dynamic response analyses on the cast-in-place headed anchor bolts are conducted to simulate the lateral force and displacement performance under the shake table tests. The main parameters are the failure modes of the anchorage and the initial flexural cracks in the RC brock. In the analytical model, the hysteretic behavior of the anchorage is idealized as translational and rotational springs whose mechanical properties are identified based on the static loading tests. Based on these analytical simulations conducted herein, the hysteretic behavior under dynamic loads simulate well to those under the static loads. Insignificant nonlinear response of the anchors allows to employ the equivalent linear stiffness and damping ratio in the simulations. On the other hand, significant nonlinearity on the anchorage under relatively excessive seismic loads will require the nonlinear hysteretic model for the anchorage to provide more narrow numerical correlations.

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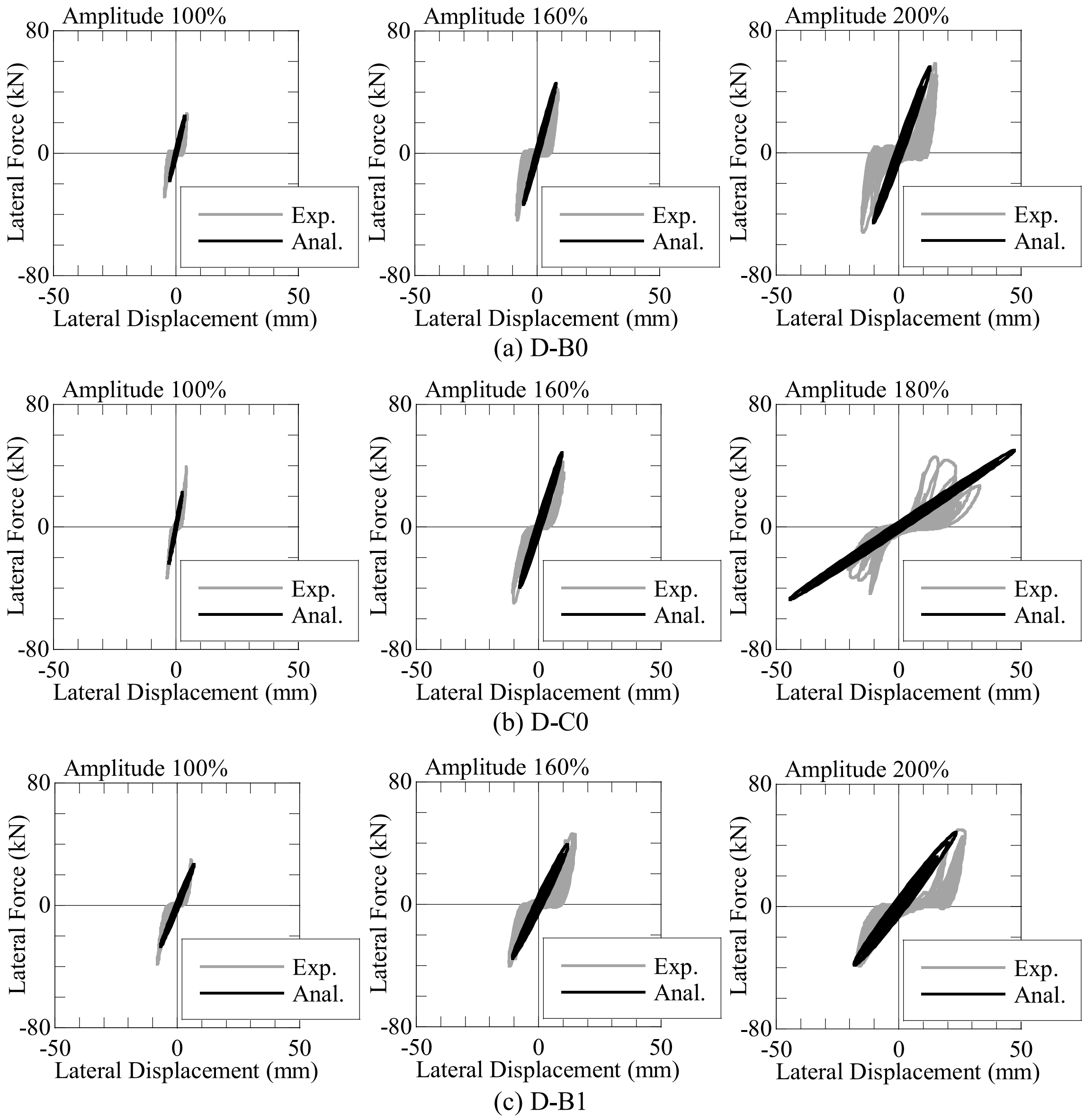

Figure 12. Analytical results based on the linear model.

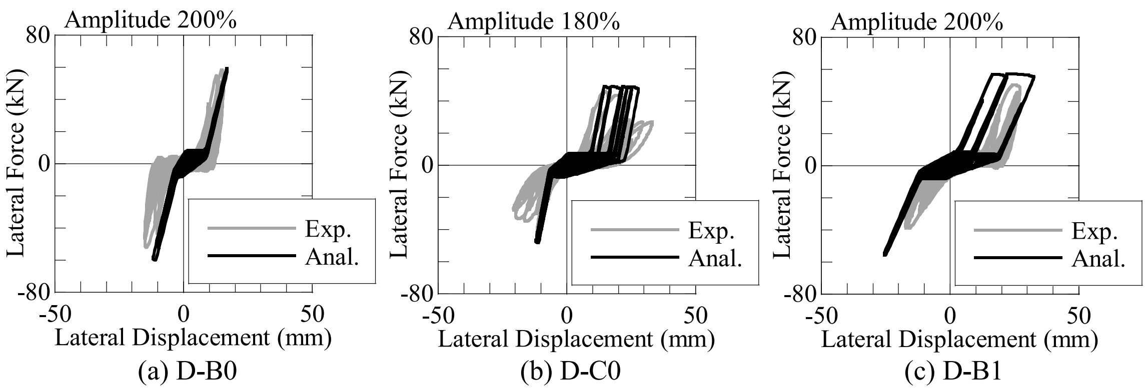

Figure 13. Analytical results based on the nonlinear model.

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