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PROPOSAL AND VERIFICATION OF COLLISION ANALYSIS METHOD USING IMPULSE EXTERNAL FORCE.

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Abstract: *Base isolation can effectively reduce seismic damage to a building and allow it to maintain functionality after an earthquake. The response accelerations and displacements of the superstructure can be minimized by absorbing seismic-input energy in the isolated story. However, when the deformation of the isolated story exceeds the design considerations under extreme ground motions, there are concerns about the collision between the superstructure and the surrounding retaining wall. Previous research has revealed that the response increase of the superstructure during the collision can be determined by the amount of impulse input to the base-isolated building. And, unique collision analysis method that applying the time history of the Impact force measured by load cell to the first floor or location of collision of lumped-mass model simulating the base-Isolated building proposed. As a result of comparing the experimental results and the analytical results, it was clarified that the proposed time-history analytical method using the impulse input to the first-floor mass of the lumped-mass model can simulate the behavior of the superstructure precisely. Moreover, impulse input that the time history of the Impact force measured by load cell to the first-floor mass could be transformed into simple simulated wave. The integrated value of the simulated wave has the same area of impulse according to the collision condition. This analysis method using simple simulated wave was also proposed to reproduce the measured responses during the collision. The response of the superstructure during a collision can be appropriately reproduced without using the numerical analysis model including the collision spring. Authors showed that the proposed collision analysis method can reproduce the response of the superstructure during the collision without complicated modeling such as back soil and retaining walls. This unique analysis method is considered a useful and practical structural design tool to predict the response of a superstructure during collision.*

1. Introduction

Base isolation can effectively reduce seismic damage to a building and allow it to maintain functionality after an earthquake. The response accelerations and displacements of the superstructure can be minimized by absorbing seismic-input energy in the isolated story. However, when the deformation of the isolated story exceeds the design considerations under extreme ground motions, there are concerns about the collision between the superstructure and the surrounding retaining wall.

In Japan, a 300 mm deformation was observed in the isolated story of the building in Kushiro City during the 2003 Tokachi-Oki Earthquake; the building had a design deformation clearance of 500 mm. Recently, a 460 mm deformation was observed in a hospital in a base-isolated building in Aso City, Kumamoto Prefecture during the 2016 Kumamoto Earthquake; this building had a design deformation clearance of 550 mm. In the US, only one case regarding the collision of a base-isolated building in Los Angeles has been reported, and it occurred during the 1994 Northridge Earthquake [Nagarajaiah and Sun (2001)]. This is because this the collision was considered to be caused by the poor construction of the clearance around the building entrance that that resulted in the slight collision with an obstruction that reduced the intended clearance. Collisions between base-isolated buildings and a retaining wall have not been reported previously. However, there is a high possibility of severe earthquakes in the future, which comprise pulse waves of strong ground velocity in the vicinity of an active fault or long-period ground motions close to natural periods of base-isolated buildings. Because collision between the base-isolated building and its surrounding retaining walls cannot be avoided during these severe earthquakes, an adverse effect on the base-isolators or the superstructure should be considered as a potential risk accompanying the collision of base-isolated buildings. Therefore, a clear understanding of the behavior of a superstructure when a base-isolated building collides with a retaining wall is necessary to secure the safety and performance of the base-isolated building under strong ground motions. [Mavronicola and Polycarpou (2017)], [Polycarpou and Komodoromos (2013)]

Recently, collision experiments were performed using full-scale base-isolated buildings. Miwada et al. (2011) performed full-scale collision tests against a retaining wall with an actual existing base-isolated building. A collision test on the E-Defense shaking table was carried out to investigate the two-dimensional behavior of the test specimen of a full-scale base-isolated building with four stories. [Fukui (2015)] In the US, Masroor et al. (2013) examined the effects of collisions for various cases of retaining-wall materials and clearances of an isolated story in shaking table tests using a three-stories 1/4 scale base-isolated building model. These past experiments required excessive planning and construction to conduct the collision experiment on a practical scale as it is necessary to employ very large-scale instruments and a full-scale building specimen. These tests are not feasible when attempting to repeat the experiment as it is difficult to obtain sufficient samples to examine the plastic deformation of the building and the retaining wall under various conditions. Analytical studies have therefore been conducted to evaluate the structural response during collisions of base-isolated buildings. Kashiwa et al. (2005) proposed a method for predicting the maximum inter-story displacement caused by collision based on the time-history analysis in a non-collision state. Yasumoto et al. (2014) predicted the maximum displacements of the superstructure during a collision using equivalent external force to represent the colliding force on a retaining wall. However, it is necessary to improve the preciseness of the response evaluations because these analytical methods are not validated by comparing sufficient experimental case studies including variations in the stiffness of retaining walls, the difference in collision velocity, and other factors.

The authors have previously conducted collision experiments using a shaking table, and by varying the input waves and rigidity of retaining wall, the story shear force and the floor response acceleration of superstructure depend on the collision velocity at the time of collision. Further, the analysis result of Impact forces measured by load cell revealed that the floor acceleration of the superstructure depends on the maximum impact force input into the building, and the relative story displacement depends on the impulse. [Fukui and Fujitani (2018)]

In this study, collision analysis using a lumped-mass model was conducted, and the responses of the base-isolated building during a collision were simulated. The analysis results were compared with the experimental results to validate the numerical model for collision analysis. The influence of the impulse induced by the collision on the structural responses was evaluated. Assuming that the impulse occurs in the first floor during a collision and by applying an impulse load to the lumped-mass model, a time-history analysis was executed. The behavior of the superstructure during the collision can be simulated to a considerable extent by introducing the proposed method using an impulse. This unique analysis method is considered a useful and practical structural design tool to predict the response of a superstructure during collision.

2. Outline of collision tests

2.1. Test specimen

The dimensions and component configuration of the experimental testing system used in this study are shown in Figure 1. Each floor was supported by roller bearings, and coil springs provided the restoring force. A push spring is attached to the superstructure, and a push/pull spring is attached to the base-isolated story. the coil spring of testing model gives restoring force to each story was judged to have linear characteristics within the movable range. Free vibration tests were performed on this test model while a certain single story was free and the other stories were fixed. Figure 2 shows the relations of the deformation of each story and the sum of the inertial forces supported by that story (calculated by the mass of the upper stories and the floor acceleration). In this study, the damping coefficient of each story was considered for only inherent structural damping, and no additional damping equipment was installed to supplement energy dissipation during the collision. The friction forces of the roller bearings were not considered because the coefficient of the maximum static friction force (=μ) was identified as ~0.0037.

In this study, the natural period of the test model is close to that of the actual base-isolated building, so similarity rule is not considered.

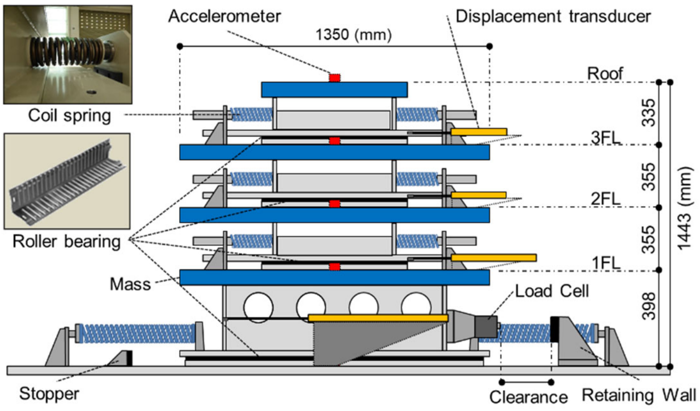


Figure 1. Figure of test specimen.

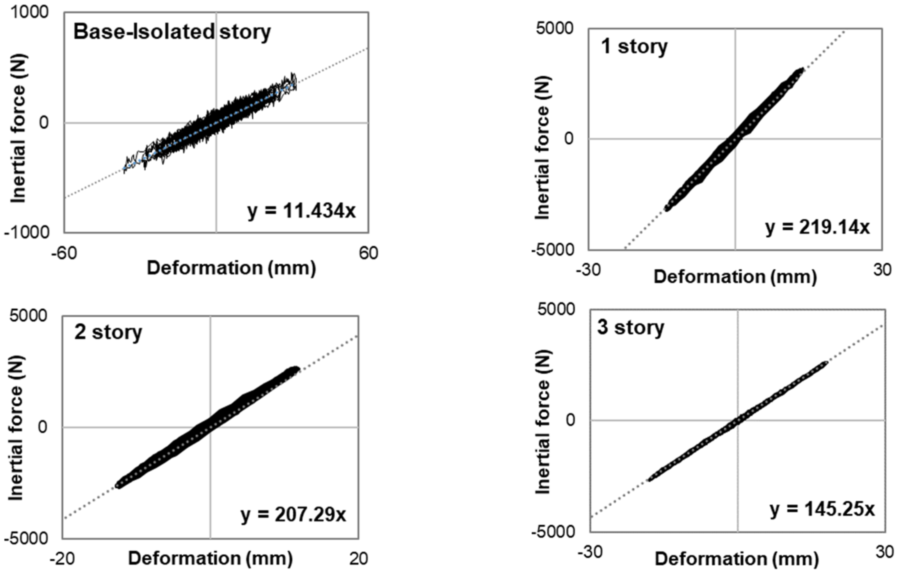


Figure 2. Restoring force characteristics of coil springs.

2.2. Test overview

The testing model was excited by the shaking table, and the load cell attached at the first floor collided with a retaining wall installed with a clearance gap of about 120 mm (On the other side, a stopper was installed with a clearance gap of about 200 mm). (Figure 3) The acceleration of each floor, relative story displacement of each story, and the impact force of the first floor were measured by a sampling of 1 kHz (sampling time dt=0.001 s). In cases without collisions, the retaining wall was removed. In this study, even if there were multiple collisions, only the first collision is reported. To examine the effect on the superstructure while varying the rigidity of the retaining wall, nitrile rubber (NBR) attached with retaining wall were changed from the hardness of 50º, 70º and 90º. A compression test was performed on the rubber members based on the measurement method described in the JIS standard (JIS K6254; 2010 5.1 compression test method A), and compressive force-deformation curves were obtained. Table 1 summarizes the young's modulus (*E*) calculated from the material test results and rigidities (*Kr*) for each rubber member calculated from the equation (a).

$$K_r = \frac{EA}{L}(kN/mm) \qquad \text{(a)}$$

K_r= Rigidity of the rubber member, *E*= Young's modulus of the rubber member

A= Area of the rubber member at colliding part (Equivalent to load cell surface area)

L= Thickness of rubber member

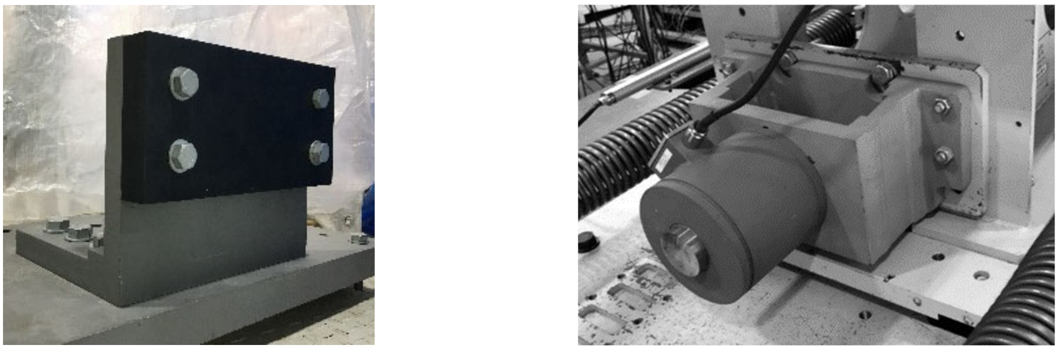

(a) Retaining wall *(b) Load cell*

Figure 3. Photo of devices at colliding position

Table 1 Young's modulus and rigidity of rubber member

	Young's modulus : *E* (MPa)	**Rigidity : K_r (kN/m)**
Hardness 50°	3.69	292.23
Hardness 70°	6.82	540.11
Hardness 90°	25.99	2058.26

2.3. Identification method of specifications of the test specimen

The characteristics of the test specimen (natural frequency ω, damping factor h, stiffness k) were calculated using the curve fitting method after determining the transfer function of each story. After confirming the consistency of the H1 and H2 estimate methods and confirming their validity using the coherence function, it was determined that it would be appropriate to conduct the study using the value of the transfer function from H1 estimate method. (Figure 4 (a) (b)) To identify the vibration characteristics, the theoretical formula for the transfer function proposed by Kasai et al. (2011) was used. (Equation (1))

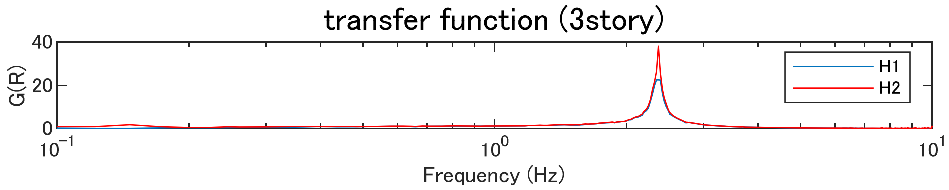
$$G_{k,j}(\omega) \approx \beta_j \varphi_{nj} \left(\frac{\omega^2}{\omega_j^2 - \omega^2 + 2ih_j\omega_j\omega} + 1 \right) \qquad (1)$$

$$\left(\begin{array}{c} \beta_j\varphi_{nj} = j_{th}\ \mathit{participation\ function\ at}\ n_{th}\ \mathit{order},\quad \omega_j = \ : j_{th}\ \mathit{natural\ circular\ frequency}, \\ i = \mathit{imaginary\ unit},\quad h_j = j_{th}\ \mathit{danmping\ factor} \end{array}\right)$$

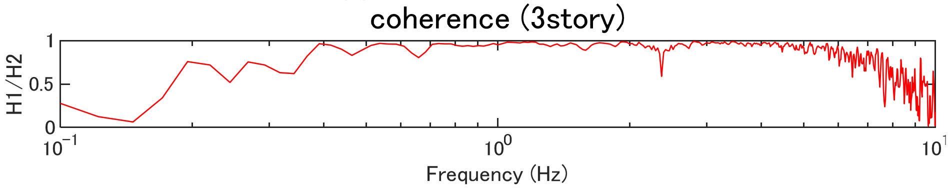
Regarding the identification method, the nonlinear least squares method is applied to the transfer function obtained by random wave excitation to find the natural circular frequency ω_j, damping factor h_j and participation coefficient β_j that minimize the difference from the theoretical formula in equation (1). Figure 5 shows the H1 estimate value, the curve fitting line obtained by the least squares method, and the identified natural circular frequencies ω_{ident} of each story. Note that curve fitting is applied within the range of the vertical lines in the figures. Table 2 also shows the damping coefficient c, stiffness k, and mass m of each story obtained using equations (2) and (3) below. However, in equations (2) and (3), M_n represents the sum of the masses of the n or more floors.

$$c_n = 2h\sqrt{m_n k_n} \tag{2}$$

$$k_n = m_n {\omega_{ident}}^2 \tag{3}$$



(a) Transfer function



(b) Coherence function

Figure 4. Transfer function and coherence function for third story.

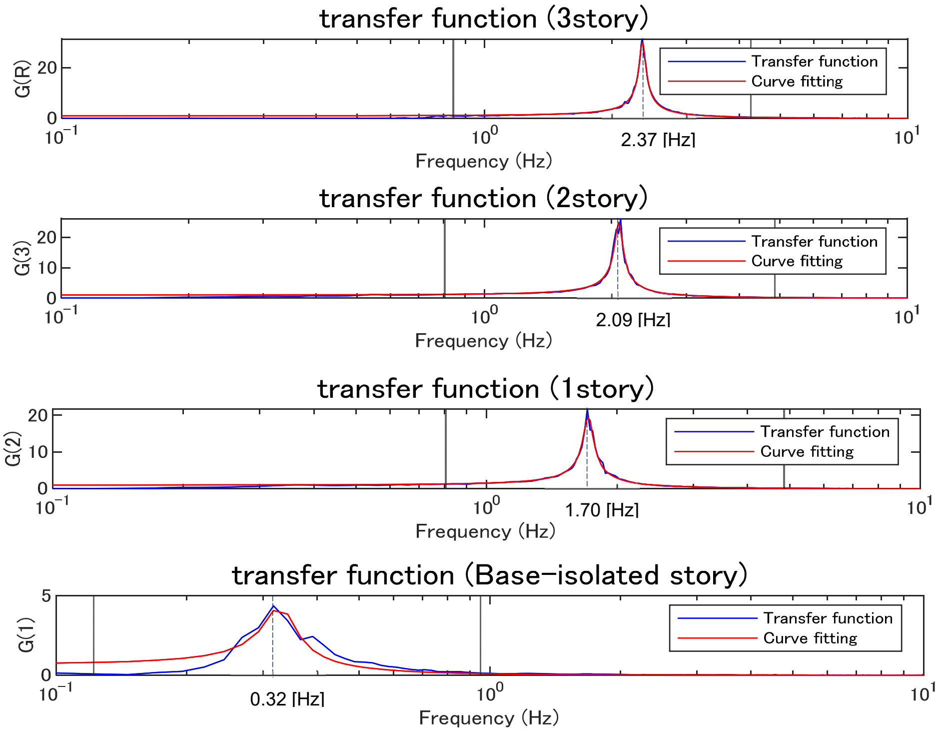


Figure 5. Comparison between transfer function and curve fitting for each story.

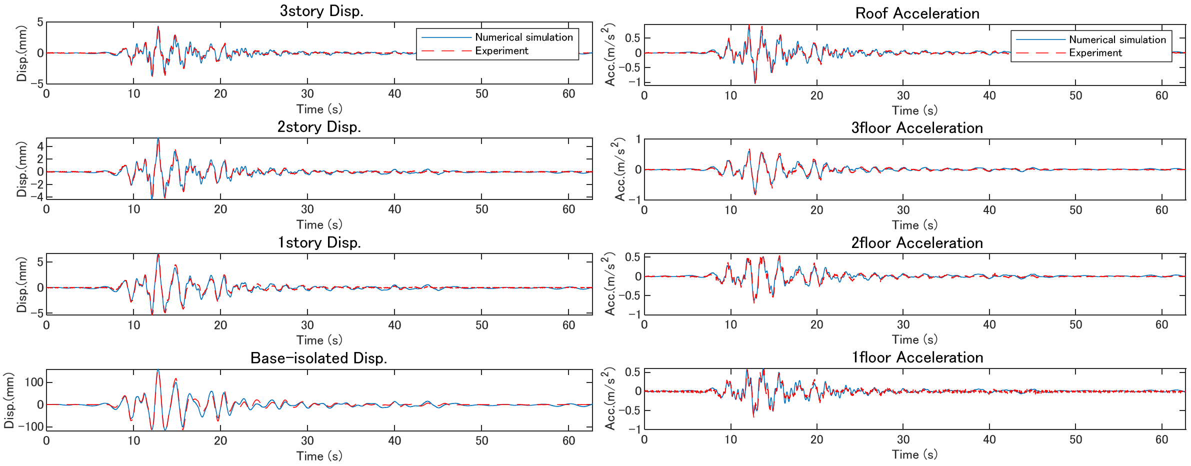
Table 2 The specification of test specimen

Floor	Mass (kg)	Story	Stiffness (N/mm)	Damping coefficient (N・s/m)	Natural circular frequency (Hz)	Damping factor (%)
Roof	611.3 (=m_4)	**Third**	145.2 (=k_3)	414.6 (=c_3)	14.8	2.2
3FL	611.3 (=m_3)	**Second**	207.3 (=k_2)	668.6 (=c_2)	13.0	2.1
2FL	611.3 (=m_2)	**First**	219.1 (=k_1)	1000.2 (=c_1)	10.8	2.5
1FL	713.2 (=m_1)	**Base-isolated**	11.4 (=k_b)	231.1 (=c_b)	2.1	2.2

3. Collision Analysis

3.1. Analysis model and its validity

In this section, a base-isolated building model for collision analysis is proposed, and the validity of the simulation model is verified by comparing the results of the collision analysis and the collision tests. To simulate the collision behavior of the base-isolated test model, an analytical structural model is developed in the MATLAB Simulink environment for the time-history analysis. Floors are considered as the lumped mass, and every story including the isolated story is modeled by shear springs. The simulation model consists of four-degrees-of-freedom (4DOF). The values of the floor mass m_j (j = 1, 2, 3, 4), story stiffness K_n (n = b, 1, 2, 3), and damping coefficient C_n (n = b, 1, 2, 3) for each floor is listed in Table 2. The time interval of the numerical simulation integration time step is 0.001 s, and it corresponds to the measurement sampling time of the experiment. Figure 6 shows the relative story displacement and the floor acceleration of each story. The time-histories of the analytical results and the experimental results under the NS component of the ground motion observed at the JR Takatori Railway Station during the South Hyogo Prefecture Earthquake in 1995 (labeled Takatori) with the input factor scaled 46% are compared. The fourth-order Runge-Kutta method is used for numerical integration. As seen in Figure 6, the analysis results can accurately reproduce the experimental results for the duration of the time-history, and it can be concluded that the specification of test specimen identified in section 2.3 are generally valid.

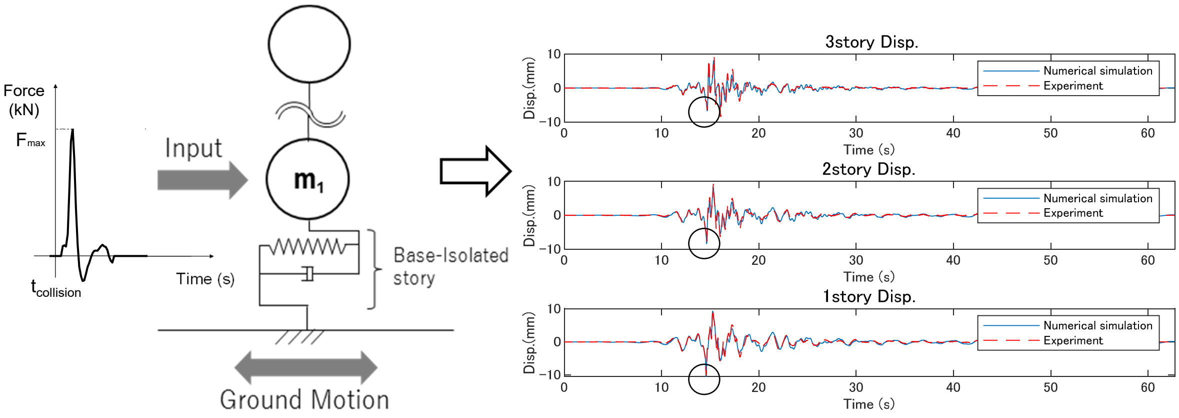


(a) Relative story displacement *(b) Floor acceleration*

Figure 6. Comparison of relative story displacements and floor accelerations between the experimental and analytical results (Takatori 46%, Without collision)

3.2. Collision analysis model

In this section, the novel analysis method was proposed. Figure 7 shows a schematic of the impulse analysis. To reproduce the behavior of the superstructure during a collision, A time-history analysis was performed, and impact force measured by load cell was applied to the first-floor mass of the 4DOF model (m_1) at the time when the response of base-isolated story displacement exceeds the design clearance.

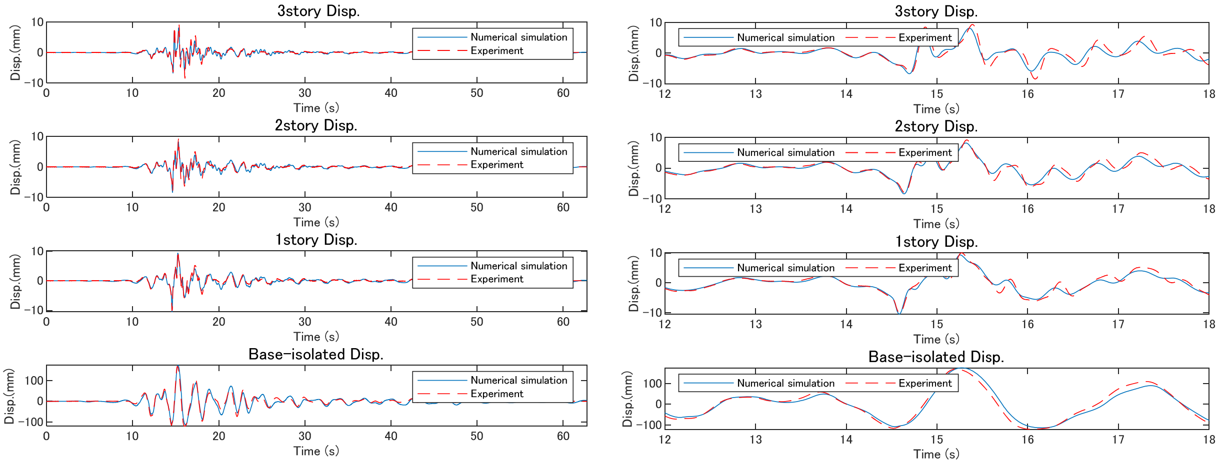


(a) Simulation model *(b) Time-history of relative story displacement*

Figure 7. Schematic of impulse analysis and comparison of relative story displacement between the experimental and analytical results (Takatori 46%, With collision, Hardness 70°)

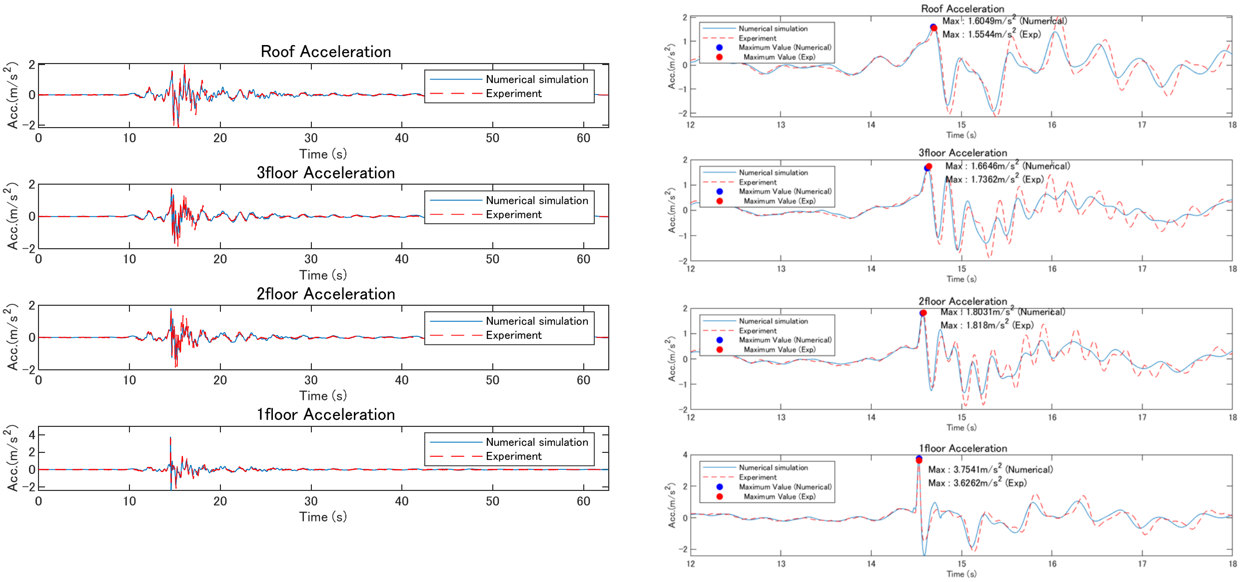
3.3. Comparison between experimental and analytical results

Figure 8 shows the time-history of relative story displacement of all stories and the floor accelerations of all floors comparing the analytical results and the experimental results for a case with collision to the retaining wall of hardness 70° under 46% Takatori. Figure 8 confirms that the analytical and experimental results compare well through all ranges of the time-history. As seen in Figure 13, the maximum story displacements of the superstructure and the maximum accelerations of every floor showed good agreement between the analytical and experimental results. The maximum floor acceleration values shown in Figure 8 also confirm that the analytical results can accurately simulate the experimental results. From the above verification results, it is possible to simulate the collision phenomenon of base-isolated building by applying the impact force to the 1FL floor using the MDOF model and performing time-history analysis, and to reproduce the maximum response value of base-isolated superstructure. This analysis method is considered to be a very simple analysis method in that there is no need to model the retaining wall stiffness which have complicated factor and only a structural model is required.



(a) Overall view *(b) Closed view(13-18s)*

(A) Relative story displacement



(a) Overall view *(b) Closed view(13-18s)*

(B) Floor acceleration

Figure 8. Comparison of relative story displacements and floor accelerations between the experimental and analytical results (Takatori 46%, collision, hardness70°)

4. Conclusion

In this paper, numerical simulation model that reproduce the response of superstructure of base-isolated building during a collision was conducted. A time-history analysis was performed, and impact force measured by load cell was applied to the first-floor mass of the 4DOF model at the time when the response of base-isolated story displacement exceeds the design clearance. The validity of the proposed collision analysis model was confirmed by comparing and verifying the experimental data obtained from the collision experiment of a base-isolated test specimen using a shaking table. Verification through comparison of experimental and analytical results revealed that the proposed analysis method is effective method compared to other collision analysis using collision springs, as it can accurately reproduce the maximum floor acceleration and relative story displacement. This unique method is considered to be simple and easy to analyze.

In addition, since the purpose of this study was to confirm the validity of the analysis method, the impact force measured by load cell in this collision experiment was used as the external force input to the first-floor mass. It is expected that by using a design wave that simulates impact force, it will be possible to predict the response of superstructure during a collision.

Acknowledgments

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