Modeling and Simulation of Collision-Causing Derailment to Design the Derailment Containment Provision Using a Simplified Vehicle Model

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Abstract: As the operating speed of a train increases, there is a growing interest in reducing damage caused by derailment and collision accidents. Since a collision with the surrounding structure after a derailment accident causes a great damage, protective facilities like a barrier wall or derailment containment provision (DCP) are installed to reduce the damage due to the secondary collision accident. However, the criteria to design a protective facility such as locations and design loads are not clear because of difficulties in predicting post-derailment behaviors. In this paper, we derived a simplified frame model that can predict post derailment behaviors in the design phase of the protective facilities. The proposed vehicle model can simplify for various frames to reduce the computation time. Also, the actual derailment tests were conducted on a real test track to verify the reliability of the model. The simulation results of the proposed model showed reasonable agreement to the test results.

Keywords: DCP (Derailment Containment Provisions); derailment; simplified vehicle model; protective facility

1. Introduction

As train speeds increase, safety becomes increasingly significant. Railway accidents are reported around the world every day. In particular, derailment accidents cause a lot of casualties and property damage. Derailment accidents have occurred frequently in Korea. Some coaches of the Korean high-speed train were recently derailed due to an error in the operation of a turnout. The derailment accident damaged rails, PC sleepers, the turnout and coaches although it did not cause any casualties as shown in Figure 1a [1]. In the United States, a derailment accident in a curve due to over-speed, as shown in Figure 1b, caused more than 170 dead or injured and property loss of $9 million [2].

Secondary collision accidents following derailment result in greater damage than derailment itself due to collision with surrounding structures or bridges falling down when wheels deviate from the tracks. For these reasons, a protective facility is usually installed to minimize damage due to secondary collision or falling [3,4].

In Korea, it is a requirement to install protective facility in a sharp curve area and a bridge of over 18 (m) or other areas with high derailment risk. In the UK, the RSSB assume that, after a train is derailed, the inner wheel will be guided by the outer rail before wheels collide against the barrier walls. Based on this assumption, they suggested that the barrier wall height should be at least 350 (mm) from
the head of rails, and the distance of the barrier wall must be greater than 1500 (mm). In Germany, guard-rails are usually applied to passenger and freight train lines. In the case of a high-speed train line, it is assumed that derailed wheels would be guided by rails. Therefore, the barrier walls must be kept from the running wheel-sets by a distance avoiding a collision against the walls. The height of the barrier walls is designed no higher than the rail head [5].

![Derailment accidents](image)

Figure 1. (a) The derailment accident of the high-speed train in Korea (02.2011); (b) the derailment accident in America (12. 2013).

Even though barrier walls are installed on bridges or in curves to reduce damage after derailment for high-speed trains, the criteria for their locations and design loads are not clear, and studies on railway protective facilities are insufficient. In order to determine the construction locations and design loads of the protective facility, it is important to know the derailment behaviors of trains. Although it is ideal to check post-derailment behaviors through actual derailment tests, many research works generally simulate these using multi-body dynamics programs because of practical difficulties such as high cost and construction of a test facility.

Jerry Evans and Mats Berg [6] discussed appropriate modelling choices for suspension components, wheel/rail contact conditions and modeling input. Dmitry Pogorelov and Viasdislav [7] considered a technique referred to as the ‘Train 3D method’ for simulation of trains as coupled derailed spatial and simplified one-dimensional models of rail vehicles to evaluate safety factors with dependence on the train operation regime. R.Kovalev and V.N Yazykov [8] presented nonstiff method for computing the nonelliptical contact problem that can apply to the wheel rail contact problem. Hyung-Suk Han and Jeong-Seo Koo [9] studied high-speed train crashes in three dimensions using multi-body dynamics to predict the crash behavior of trains. Hyun-Woong Bae [10,11] studied the impact forces in the case of a collision with a barrier wall using a three-dimensional finite element model of the KTX (Korean High Speed Train). Xingwen Wu [12,13] developed a half-car test specimen of a vehicle and analyzed its derailment behaviors through experiments in the laboratory. In addition, they predicted the derailment behaviors of a derailed high-speed train using dynamic simulations. Lirong Guo [14] conducted a series of low-speed derailment test under different test conditions for a Chinese train. This study confirmed that gearbox of train plays an important role in restricting the lateral motions of the derailed vehicle, and also the other influence factors such as speed, weight and track were considered. Liang Ling [15] studied the efficacy of the guard rail system (GRS) to minimize the derailment of potential of trains laterally colliding by a heavy vehicle, and the sensitivities of parameters of the guard rail system such as the flange way width, and reported the installation height. Dan Brabie [16,17] studied the effects on derailment behaviors according to the bogie frame and the damage degree of concrete sleepers based on derailment accidents in Europe. Hirsch [18] studied the height of the barrier wall according to overturning moment considering the center of gravity of trains and impact acceleration.

In this study, a simplified frame model is developed that can be used in simulation for design of the protective facility. The reliability of the suggested model is verified through the actual derailment
tests. In addition, the deviation prevention effects by installation of a derailment containment provision (DCP), which is one of the barrier types, are verified through the derailment tests.

2. Wheel-Rail Contact

To simulate wheel/rail contact, solid elements for wheels and shell elements for rails are used. The basic contact method of Ls-Dyna is the penalty method [19]. The concept is that when a slave node penetrates a master surface, the contact force is calculated from the amount of penetration and the contact stiffness. The contact force also increases in proportion to the increase of the amount of penetration.

In Figure 2, \( t \) represents the position vector of the slave node \( n_s \), and the master segment surface \( s_i \) is related to \( n_s \). If \( n_s \) penetrates \( s_i \), the contact point coordinates \((\xi_c, \eta_c)\) must satisfy Equation (1).

\[
\frac{\partial r}{\partial \xi}(\xi_c, \eta_c) \cdot [t - r(\xi_c, \eta_c)] = 0, \quad \frac{\partial r}{\partial \eta}(\xi_c, \eta_c) \cdot [t - r(\xi_c, \eta_c)] = 0
\]

The initial values are estimated through a least-squares projection iteration,

\[
\xi_0 = 0, \quad \eta_0 = 0
\]

\[
\begin{bmatrix}
  r_{,\xi} \\
  r_{,\eta}
\end{bmatrix}
\begin{bmatrix}
  \Delta \xi \\
  \Delta \eta
\end{bmatrix}
= \begin{bmatrix}
  r_{,\xi} \\
  r_{,\eta}
\end{bmatrix} [r(\xi_i, \eta_i) - t],
\]

\[
\xi_{i+1} = \xi_i + \Delta \xi, \quad \eta_{i+1} = \eta_i + \Delta \eta
\]

From the Newton–Raphson iteration, the amount of penetration on the penetration coordinate can be calculated as (3).

\[
[H]\begin{bmatrix}
  \Delta \xi \\
  \Delta \eta
\end{bmatrix} = -\begin{bmatrix}
  r_{,\xi} \\
  r_{,\eta}
\end{bmatrix} [r(\xi_i, \eta_i) - t],
\]

\[
[H] = \begin{bmatrix}
  r_{,\xi} & r_{,\eta} \\
  r_{,\eta} & 0
\end{bmatrix}
\]

\[
\xi_{i+1} = \xi_i + \Delta \xi, \quad \eta_{i+1} = \eta_i + \Delta \eta
\]

When the amount of the slave node coordinate penetrates into the master surface, Equation (4) is obtained.

\[
l = \eta_i \times [t - r(\xi_c, \eta_c)] < 0
\]

At this point, the normal vector of the master surface at the contact point is:

\[
n_i = n_i(\xi_c, \eta_c)
\]

If the slave node penetrates the master surface, the contact force vector becomes Equation (6).

\[
f_s = -lk_i \eta_i \text{ if } l < 0
\]

In addition, considering the degree of freedom of \( \eta_s \), the contact force is given by Equation (7).

\[
f_{s,\eta} = \phi_i(\xi_c, \eta_c) f_s \text{ if } l < 0
\]

The master segment consists of four nodes \( i = 1, 2, 3, 4 \), and the contact force \( k_i \) consists of the bulk modulus \( K_i \) and the surface area \( A_i \) of the master segment.

The contact force obtained in the master segment is calculated as follows:

\[
k_i = \frac{f_s K_i A_i}{\text{max (shell diagonal)}}
\]

Generally, contact search methods of one-way and two-way are useful for handling contact problems. The two-way contact method calculates the contact force between a master surface and a
slave node at each calculation cycle. The one-way contact method shows good results in the dynamic stabilization of the vertical contact force, but it does not accurately simulate the contact between a flange and a rail. Therefore, a two-way contact method which can simulate the contact between a flange and a rail was applied [20]. Depending on the relative distance between the wheel and rail, large oscillations could occur because of the penalty method. The dynamic relaxation time was saved by appropriately adjusting the distance between the wheel and the rail before contact analysis.

![Figure 2](image1)

**Figure 2.** Location of contact point when $n_s$ lies on master segment.

Another important factor in rolling contact simulation is to reduce vibration generated by wheel/rail contact between elements. To minimize vibration, wheel tread and flange are finely modeled as shown in Figure 3. For simulation of wheel/rail contact, friction coefficient between wheel and rail is applied as 0.3 and CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword which is two way contact method is used to simulate flange and rail contact.

![Figure 3](image2)

**Figure 3.** Finite element of wheel tread and flange.

Figures 4 and 5 show the contact force and vertical displacement between wheel/rail. Oscillation occurs due to the rolling contact of the finite elements and it is confirmed that in a rough mesh wheel model large vertical displacement occurred because the wheel angle and mean contact force of fine mesh model is 5.4 kN which is the same as the theoretical force. Figure 6 for a fine mesh model shows the vertical displacement of the wheel and the displacement oscillated within 0.06 mm.
3. Simplified Frame Model

For railway vehicle simulations, various modeling techniques can be used depending on their purposes and performances. Simplification is not essential when simulating derailment for only one car. However, simulation for a multiple-unit train would take a tremendous computing time, therefore simplification is necessary.

In this study, analyses were carried out using commercial finite element (FE) software, Ls-Dyna. It is ideal to create the finite element model of the actual shape, but if the shape of the model is changed, additional modeling work would be required, and the number of elements which is related to a longer analysis time would increase. So in many cases of dynamic analysis a model is simplified to a level that does not significantly affect the results.

A Comparison of Behaviors between the Real Model and the Simplified Model

It is necessary to verify that the simplified model has less computation time than the detailed model. Therefore, each model was evaluated under the same conditions. Tables 1 and 2 show the parameters and performances. Simplification is not essential when simulating derailment for only one car. However, simulation for a multiple-unit train would take a tremendous computing time, therefore simplification is necessary.

The frame mass and moment of inertia are assigned to the node at the center of gravity using CONSTRAINED_NODAL_RIGID_BODY_INERTIA in Ls-Dyna [21]. To assemble these parts, supplementary materials.

The specification of 3-piece bogie frame [21].

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![Figure 4. Contact force between wheel and rail.](image)

![Figure 5. (a) Vertical displacement between wheel and rail (fine mesh model) and (b) Vertical displacement between wheel and rail (rough mesh model).](image)

![Figure 6. Examples of simplified bogie.](image)
The frame mass and moment of inertia are assigned to the node at the center of gravity using CONSTRAINED NODAL RIGID BODY INERTIA in Ls-Dyna [21]. Simplified models have each node located at the center of gravity and at each suspension. The position of the nodes can be changed easily. Therefore, this can be changed into various other models by modifying or adding the location of nodes.

The number of elements in wheelset is exactly the same because of using the same wheelset to simulate the wheel–rail interface in FE analyses. The number of elements of frames is significantly reduced by using the simplified model. As for railway vehicles, two bogies are usually installed per a vehicle. If the number of vehicles increases, the effect of the frame simplification could be greater in numerical simulations. Figure 6 shows examples of a simplified bogie model including secondary suspensions.

A Comparison of Behaviors between the Real Model and the Simplified Model

It is necessary to verify that the simplified model has less computation time than the detailed real model. Therefore, each model was evaluated under the same conditions. Tables 1 and 2 show the specifications and the number of elements [22,23]. Additional specifications of bogie are referred in supplementary materials.

| Table 1. The specification of 3-piece bogie frame [21]. |
|---------------------------------------------------------|
| **Parameters** | **Values** |
| Gauge (mm) | 1435 |
| Wheelbase (mm) | 1676 |
| Wheel Size (mm) | 860 |
| Length (mm) | 2600 |
| Width (mm) | 2350 |
| Weight (kg) | 3800 |
| Frame Weight (kg) | 1585 |
| Frame Ixx (Kg·m²) | 1420.6 |
| Frame Iyy (Kg·m²) | 493.6 |
| Frame Izz (Kg·m²) | 1812.2 |

| Table 2. The comparison of elements of the 3-piece bogie. |
|----------------------------------------------------------|
| **Part** | **Real Model** | **Simplified Model** |
| Wheelset (Solid element) | 150,880 | 150,880 |
| Bogie Frame (Solid element) | 818,164 | 1 (1D element) |
| Total Elements | 969,044 | 150,881 |
| Primary suspension stiffness | 160 kN/mm | 160 kN/mm |

Since the model does not take into account the damage of the frame, rigid properties (Mat 20) have been assigned to the main frames. The real frame model consists of four main components. Bolster, side frame, journal box, spring plate. To assemble these parts, CONSTRAINED_RIGED_BODIES and CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keywords are used.

Figure 7 shows the conditions of simulation for the derailment while driving at a speed of 13 (km/h).
Table 3 shows the simulation time for the analyses. The computing time of the real model is about 1545 (min), and the simplified model is about 741 (min). The simplified model needs only less than half simulation time over the real model. The performance of the computer central processing unit (CPU) is shown in Table 4.

**Table 3. The comparison of simulation time.**

| Model               | Real Model | Simplified Model |
|---------------------|------------|------------------|
| Computing Time(Min) | 1545       | 741              |

**Table 4. The specifications of computer CPU.**

| Company   | Model          | Clock         |
|-----------|----------------|---------------|
| Intel     | Xeon(R) E5-2687W v2 | 3.4 GHz       |

The simulation results for X-displacement (longitudinal) and Y-displacement (lateral) over time are shown in Figure 8. The largest difference in X-displacement is 186 (mm) at 5000 (ms) and the largest difference in Y-displacement is 103 (mm) at about 916 (ms). The differences in the simulation results are very slight. Consequently, it was confirmed that the simplified frame model could replace the refined real frame model.

**Figure 7.** The condition of the derailment simulation.

**Figure 8.** The comparison of results between the real and simplified models in simulation.
4. Model Validation

4.1. Derailment Test Field

Derailment field tests were carried out in a closed station area. The purpose of the field tests is to develop a DCP facility on a concrete track. Therefore, the concrete track was constructed by referring to the Rheda 2000 structure after removing ballasts on the track [24].

Two side barriers were constructed to block the excessive lateral movement of bogies during tests. The length (100 m) of concrete tracks was designed considering the maximum test speed of 60 (km/h). Figure 9 shows the view of the testing ground.

![Derailment testing ground](image)

Figure 9. The derailment testing ground.

4.2. Derailment Tests with One Bogie

Derailment tests were performed with only one bogie at first [25]. The speed measured by the speed sensor right before derailment was 27 (km/h). The behavior and accelerations were measured by a high-speed camera and the acceleration sensors. Figure 10 shows the derailment behaviors. They showed that the field test and simulations have a similar derailment behavior. After the bogie was derailed by the derailment device (approx. 420 ms), the front wheel collided with the third sleeper. The rear wheel collided with the fourth sleeper at about 680 (ms) as shown in Figure 10a.

![Derailment behaviors](image)

Figure 10. Derailment behaviors. (a) Derailment behavior (Side view); (b) Derailment behavior (Front view).
Figure 10b shows the behavior of the bogie after derailment and finally. Although collision between wheel and rail does not occur in the field test while the bogie was running on the sleeper, the wheel collided with the rail in the simulation.

This difference in the wheel–rail impact behaviors occurred because the track components were simplified in the simulation, while real track components like tension clamps and screw spikes hindered the wheel-set from moving to the rail in the field test.

Figure 11 shows the comparison of damaged sleepers between the field test and the simulation. Although there was a slight difference in damage degree, the damage of sleepers occurred at similar locations.

![Figure 11. The broken sleepers.](image)

X-displacement and velocity (Longitudinal direction) of the bogie were obtained through the sensors attached to the bogie. Figure 12 shows similar the X-velocity and displacements between the field test and simulations.

![Figure 12. The comparison of results between the field test and the simulation.](image)

The Y-displacement (lateral direction) of the bogie was obtained using the trace of wheels. Figure 13a shows the Y-displacement results of the field test and simulations over time. The reason the Y-displacement of the simulation is larger than that of the field test is that the tension clamps and the screw spikes in field tests obstructed the lateral motion of the wheel as mentioned above. As shown in Figure 13b, the distance between the rail and the tension clamp is 155 (mm), which is similar to the lateral difference of 147 (mm).
The impact accelerations of the bogie were measured by acceleration sensors installed on the bolster. Since the measured acceleration data include unnecessary frequency components such as noise, the data should be filtered by an appropriate filter to analyze the dynamic trend. There are various techniques for data filtering, and there are acceleration-filtering criteria for each field. In case of the vehicle collision test, there is a test standard for handling the vehicle collision data in each country and Butterworth low-pass filtering is generally used. There is no clear standard of impact acceleration filtering for derailment tests of railway vehicles. In Europe, a 40 Hz low-pass filter is usually used to evaluate high-speed train body acceleration [26–28]. Numerical model validation for car bodies was evaluated using a 40 Hz low-pass filter. But it could lower the peaks of impact accelerations in collision, so a 180 Hz low-pass filter was used according to EN15227 B.2.1, as well.

Figures 14 and 15 show the comparison of the measured acceleration data in the field test with the simulation results for each acceleration component using different low-pass filters (40 Hz, 180 Hz). The maximum acceleration occurred at about 420 (ms) after collision with a wheelset and a sleeper. The 180 Hz filtering is shown to vibrate acceleration as it contains high frequency when compared to 40 Hz filtering. The maximum acceleration values are shown in Table 5. Maximum acceleration of 180 Hz filtering is about twice as high as 40 Hz filtering, and further research is needed to determine what kind of filtering methods should be used to estimate the DCP impact load. Despite the use of different low-pass filtering, the tendency of the acceleration is similar and the deviations of the experiment and simulation are small.
Figure 14. The comparison of accelerations between the field test and the simulation (40 Hz low pass filter). (a) X-acceleration; (b) Y-acceleration; (c) Z-acceleration.

Figure 15. The comparison of acceleration between the field test and the simulation (180 Hz low-pass filter). (a) X-acceleration; (b) Y-acceleration; (c) Z-acceleration.

Table 5. The comparison of maximum acceleration.

| Direction   | Field Test (40 Hz) | Simulation (40 Hz) | Field Test (180 Hz) | Simulation (180 Hz) |
|-------------|--------------------|--------------------|--------------------|--------------------|
| Longitudinal (X) | 4.1                | 3.45               | 11.8               | 10.9               |
| Lateral (Y)     | 4.57               | 4.99               | 10                 | 9.5                |
| Vertical (Z)    | 7.14               | 7.59               | 10.7               | 11.7               |
4.3. Concept of the Derailment Containment Provision (DCP)

The DCP is a facility that prevents a large deviation from rails in order to reduce the damage caused by a secondary collision after a train is derailed. It is installed inside or outside the track and guides the wheels or axles of the train to prevent collision with surrounding structures [3,4].

The DCP is classified into three types. Type 1 is a facility that guides the wheels by being installed between the rails. Type 2 is a facility that guides the wheels by being installed outside the rails. Type 3 is a facility that guides the axles from outside the rails [5]. Figure 16 shows the DCP for each type. In this paper, the deviation prevention effects of the DCP Type 1 were studied.

![Figure 16. Types of derailment containment provision (DCP). (a) DCP Type 1, (b) DCP Type 2, (c) DCP Type 3.](image)

4.4. Derailment Test with a Wagon (DCP Is Installed)

The next derailment experiment was conducted with one wagon. The DCP of Type 1 was installed and analyzed to evaluate the derailment prevention effects and vehicle behavior when the DCP is installed. The specifications of the wagon are shown Tables 6–8 [23,29]. Additional specifications of bogie are referred in supplementary materials.

| Parameters      | Values  |
|-----------------|---------|
| Gauge (mm)      | 1435    |
| Wheelbase (mm)  | 1800    |
| Weight (kg)     | 4500    |
| Length (mm)     | 3183    |
| Width (mm)      | 2256    |
| Frame Weight (kg) | 1961  |
| Frame Ixx (Kg·m²) | 1563  |
| Frame Iyy (Kg·m²) | 1114  |
| Frame Izz (Kg·m²) | 2574  |

Table 6. The specification of welded bogie frame.

| Parameters      | Values  |
|-----------------|---------|
| Weight (ton)    | 5.0     |
| Ixx (Kg·m²)     | 4166    |
| Iyy (Kg·m²)     | 58,835  |
| Izz (Kg·m²)     | 62,610  |

Table 7. The specification of wagon body frame.

| Parameters      | Values  |
|-----------------|---------|
| Outer Spring constant | 42.35 kg/mm |
| Solid height     | 155 mm   |
| Free length      | 270 mm   |

Table 8. The specification of bogie coil spring.
The primary suspension spring of the welded bogie consists of an inner coil spring and an outer coil spring. The outer spring operates at low loads and the inner spring operates when the load is increased and compressed to a certain displacement. Figure 17 shows the wagon frame. The left is a real shape frame model composed of finite elements and the right is a simplified frame model. The wagon used in derailment tests is shown Figure 18.

![Figure 17. Different models of the wagon frame.](image1)

![Figure 18. View of the test wagon.](image2)

The wagon model consists of two main parts, bogie and body frame. To connect the bogie and frame, three beam elements were used. One beam element was for the center pivot and two elements for side bearer.

To verify that the simplified frame model and the real frame model have same behaviors, two models were evaluated under the same testing conditions in simulation.

![Figure 19. Comparison between the real frame model and the simplified frame model. (a) Longitudinal displacement (b) Lateral displacement (c) Vertical displacement.](image3)
Figure 19 shows a comparison of displacement between the real frame model and the simplified frame model. Displacement was measured at the center of the frame, and X, Y, and Z displacements show similar curves. Since comparison of the two models showed the similar behavior, the reliability of the vehicle models was verified by comparing with the field test and the simplified model given in this study.

The speed measured by the speed sensor right before the derailment was 52 (km/h). The first collision after derailment occurred at about 350 ms. The front wheel collided with the seventh sleeper. Figure 20 shows that the collision occurred at the seventh sleeper. After the first collision, the vehicle proceeds and collides with the installed DCP. The lateral displacement is limited by the DCP so that the wheel does not depart from the rail within a certain distance. The configuration at the moment of collision with the DCP is shown in Figure 21, and it is checked that collisions with the DCP occur at the similar location.

Comparing damage of the track, Figure 22 shows that there is a difference in the degree of damage between experiment and simulation, but the collision locations of the experiment and simulation were reproduced well because the failure occurred at similar locations.
In the field test, only the seventh and eighth sleepers were damaged. In the simulation, damage occurred at the edge of the ninth and tenth sleepers as well as the seventh and eighth sleepers. However, the initial collision occurred at the same location. Figure 23 shows broken sleepers.

The lateral displacements of the simulation and field tests are shown in Figure 24. The simulation and derailment experiments showed a maximum difference of 7.97% and 8.07% at the front and center points, respectively, and showed the same trend. Figure 24 also indicates that if the DCP is installed, it guides the wheel of the derailed bogie in the distance shown Figure 25. From the result of the simulation and experiment, it was confirmed that if the DCP is installed, it could prevent a large deviation of the derailed vehicle.

Figure 22. Comparison of location of broken DCP.

Figure 23. Comparison of location of broken sleepers.

Figure 24. The comparison of Y displacement (lateral) between the field test and the simulation.
The lateral acceleration for the initial 1 s was compared for a period of colliding with the sleepers and DCP, because the DCP is designed based on lateral motion. As a result of the comparison, the two acceleration curves were similar, as shown Figure 26.

Acceleration of the first collision was measured as 0.79 g when the front wheel collided with the DCP at 0.5 s and acceleration of the simulation was 0.85 g. Acceleration of second collision was measured as 1.15 g and acceleration of the simulation was 1.42 g.

The overall trend of collision acceleration was found to be similar. This shows that the experiment and the simulation have similar behaviors derailing and colliding at the same time.

5. Conclusions

Protective facilities such as barrier walls are installed in a dangerous zone in order to reduce damage after the derailment of a train, but research on protective facilities with derailment behaviors of railway vehicles is insufficient. Dynamic simulation is the most efficient way to check the derailment behavior in order to design a protective facility. However, if we use a model including a car and bogie frame consisting of finite elements, computing time of simulation could take considerable time. Therefore, a simplified frame-modeling technique which can be used in the design phase of the derailment protective facility was proposed. After the modeling of a simplified frame model, a full-scale derailment test was conducted to verify the model.

From the comparison results of simulation and derailment tests, we can derive the following conclusions:

(1) Since the analysis of post-derailment behaviors of trains takes an excessive period of time, the simplified frame model using NODEL RIGID BODY INERTIA in Ls-Dyna was proposed.
(2) In order to verify the reliability of the simplified model, actual derailment tests were conducted. The post-derailment behaviors were captured with a high-speed camera and lateral acceleration was measured. As a result, the simplified frame model reproduced the derailment behaviors well.

(3) The impact accelerations were measured by acceleration sensors. When the data of the field test and the simulation results were compared during every stage of derailment, the acceleration curves and the maximum impact accelerations were similar.

(4) The deviation prevention effects of DCP after derailment were verified through an experiment and simulation. DCP prevents large lateral deviation of wheels and a simplified frame model reproduced the derailment behaviors well when the DCP is installed.

In this study, a freight wagon was used to validate the simplified frame model but the protective facility will be constructed in a high-speed train line. Therefore, a further study is necessary to evaluate design loads and locations of the facility using a high-speed train model with the same modeling technique.

Supplementary Materials: The data of the bogie used to support the findings of this study have been deposited in the National Digital Science Library in Republic of Korean repository. http://www.ndsl.kr/ndsl/search/detail/report/reportSearchResultDetail.do?cn=TRKO201000018779, http://www.ndsl.kr/ndsl/search/detail/report/reportSearchResultDetail.do?cn=TRKO201300032730, and http://www.ndsl.kr/ndsl/search/detail/report/reportSearchResultDetail.do?cn=TRKO200300002651.

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