

A Study on Crashworthiness Assessment and Improvement of Tilting Train made of Sandwich Composites

Hyung-Jin Jang, Kwang-Bok Shin, Sung-Ho Han

Abstract—This paper describes the crashworthiness assessment and improvement of tilting train made of sandwich composites. The crashworthiness assessment of tilting train was conducted according to four collision scenarios of the Korean railway safety law. Collision analysis was carried out using explicit finite element analysis code LS-DYNA 3D. The finite element model consists of 3-D finite element model and 1-D equivalent model to save the finite element modeling and calculation time. It found that the crashworthiness analysis results were satisfied with the performance requirements except the crash scenario-2. In order to meet the crashworthiness requirements for crash scenario-2, the stiffness reinforcement for the laminate composite cover and metal frames of cabmask structure were proposed. Consequentially, it has satisfied the requirement for crash scenario-2.

Keywords—Crashworthiness, Collision scenario, Korean railway safety law, Sandwich composite, Tilting train

I. INTRODUCTION

RECENTLY, the Korean railway industry has progressed active research of environmental pollution reduction, transportation cost reduction, and maximization of energy efficiency through the mass reduction of railway vehicle. Since the opening of Korea Train eXpress (KTX) in 2004, the nation has enjoyed reduced travel times between areas. However, in areas not affected by high-speed railway (HSR), a reduction in balanced regional development and the dissatisfaction of local residents have arisen. Accordingly, tilting train has been proposed to improve the quality of life of those areas currently without HSR services. The tilting train has an advantage to reduce the risk of overturning in curves at high-speed and passenger discomfort from high centrifugal forces. To reduce the weight of tilting train, sandwich composites have been applied to the primarily members of carbody. The sandwich composite has had the effect of reducing the weight, improving the durability, and increasing the corrosion resistance of the components. In addition, production cost reductions and simplification of the manufacturing process are possible through co-curing technique of carbody structures[1,2].

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Also, the importance of the structures design has increased against train collision accidents according to improvement of railway vehicle speed capabilities. In Europe, the crashworthiness regulation of railway vehicle was legislated in 2000. The related study is in progress[3]. In Korea, in order to ensure the safety of the driver and passengers from the train crash, the Korean railway safety law began to strengthen the evaluation criteria of crashworthiness for newly developed trains in 2007. Crashworthiness assessments are classified into crash tests for real vehicles and simulations through finite element analysis. Crash tests for real vehicle can bring in results that best correspond to real situations. However, they require considerable investments in cost and time. Therefore, the analytical evaluations, which can yield economical and effective results, have been conducted more often[4].

The objective of this study is to conduct the crashworthiness assessment of tilting train made of composites according to the crashworthiness regulations of Korean railway vehicle law. Collision analysis of tilting train is carried out using the explicit finite element method (FEM) analysis code LS-DYNA3D. In order to reduce finite element modeling and calculation time, 1-D equivalent model with collision characteristics identical to those of 3-D models was developed. Hybrid finite element modeling technique, combined with 1-D equivalent and 3-D model, was applied to the collision analysis of tilting train, to improve efficiency of collision analysis. The collision improvement model of tilting train is presented through two proposed reinforcement methods.

II. FINITE ELEMENT MODEL FOR TILTING TRAIN

A. Description of Tilting Train

In order to reduce the mass of tilting train, sandwich composites and laminate composites were applied, as shown in Fig. 1. The sandwich construction is considered for application to primary carbody structures while laminated composites are applied only for components with a relatively high curvature and complex geometry, which are more troublesome to manufacture using the sandwich panels. Also, to improve the bending stiffness, stainless steel was applied, as reinforcement inside the sandwich composites of carbody. For the underframe, aluminum extrusions was applied, which reduced the mass and improved the stiffness of the railway vehicle. Tilting trains are organized into units of six cars consisting of two Mcp-car, two M-car, and two T-car.

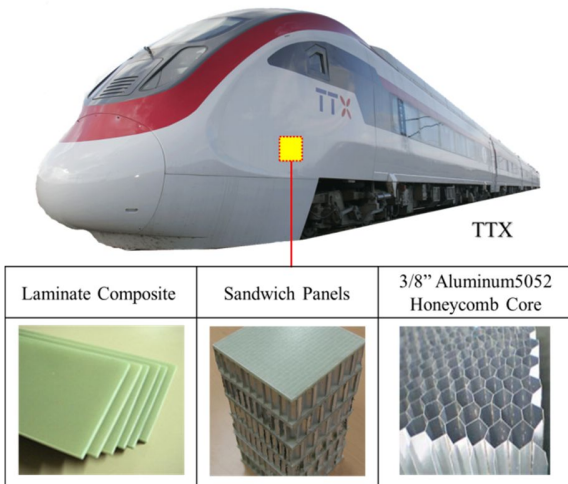


Fig. 1 Tilting train made of sandwich composites

B. Selection of Element Type for Structural Parts

In order to build the finite element model of laminate composites carbody structures, laminate composite model #54-55 (*MAT_ENHANCED_COMPOSITE_DAMAGE) of the LS-DYNA material model library were used for shell element.

For the honeycomb core, LS-DYNA material model #126(*MAT_MODIFIED_HONEYCOMB) was used in combination with the one point co-rotational solid element type. In this orthotropic material model, nonlinear elastoplastic constitutive behavior based on experimentally determined stress-strain curve can be defined for z-direction. The underframe and the reinforced metal frame are modeled using the material model #24 (*MAT_PIECEWISE_LINEAR_PLAS-TICTIY) of the LS-DYNA material model library. These materials were defined in stress-strain curve as tensile test[5].

The real shapes of vehicle couplers are too complicated to be applied to a collision analysis, thus the simplified 1-D equivalent model was applied. The 1-D equivalent model #121(*MAT_GENERAL_NONLINEAR_1DOF_DISCRTE_BEAM) can reduce the calculation time and effectively the dynamic characteristics were appeared. A shear-off was made to occur automatically when the couplers' allowable load (1,025 kN) was exceeded[6].

Fig. 2 shows the Mcp-car and the M-car for the finite element modeling of a tilting train. The total number of elements was 503,756 and 402,654 for the MCP-car and the M-car, respectively.

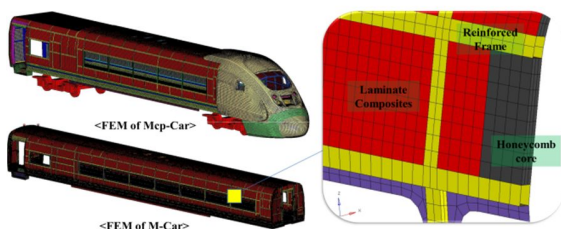


Fig. 2 Finite element models of tilting train

C. Finite Element Model

In order to make the hybrid finite element model of full

railway vehicle, 1-D equivalent modeling is applied to vehicle in the rear, on which the effect of a collision is relatively minimal. This excludes 2 to 3 vehicle in the front (which typically absorbed for over 90% of the total collision energy). The 1-D equivalent model uses LS-DYNA material model #121, which has the advantage of enabling a quick evaluation of the collision behavior of railway vehicle[7,8].

To develop a 1-D equivalent model, collision analysis of carbody structures must be conducted per section so that the crush characteristics are identical to those of the 3-D shapes. Therefore, in consideration of the two vehicles in the front, crush characteristics was derived by designating a cross-section option (cross-section plane of LS-DYNA) on the vehicle. Fig. 3 shows the division of the sections in tilting trains.

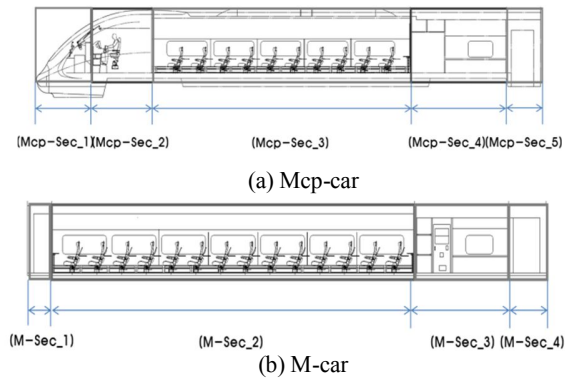


Fig. 3 Definition of cross section plane for tilting train

For Mcp-car, it was divided into a total of five sections consisting of the collision energy absorbed section, the driver section, the passenger section, the lavatory section, and the entrance section. The M-car was divided into a total of four sections consisting of the carbody end section, passenger section, lavatory section, and entrance section.

Fig. 4 is the hybrid finite element model of full railway vehicle to which the 3-D finite element model was applied to the three vehicles in the front, while a 1-D equivalent model was applied to the three vehicles in the rear.

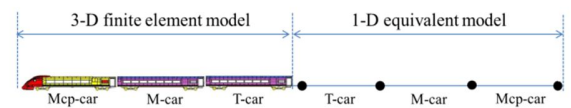


Fig. 4 The concept of hybrid finite element model for tilting train

D. Material Properties

Table I shows the material properties of the laminate composites and honeycomb core applied to the tilting train carbody structures. The material properties of each laminate composite and aluminum honeycomb core were obtained through tests. Material properties of the stainless steel and aluminum extrusion are shown in Table II.

TABLE I
MATERIAL PROPERTIES OF LAMINATE COMPOSITES AND ALUMINUM HONEYCOMB

Properties	HG 1581	CF 1263	CU 125	Aluminum honeycomb
Density (kg/m ³)	2000	1520	1600	59
Elastic Modulus (GPa)	E _x	24.60	58.36	0.693×10 ⁻³
	E _y	24.60	48.42	0.693×10 ⁻³
	E _z	10.66	10.66	0.105
Shear Modulus (GPa)	G _{xy}	5.84	5.84	0.618×10 ⁻³
	G _{yz}	3.65	3.65	0.032
	G _{zx}	3.65	3.65	0.032
Poisson's ratio	γ _{xy}	0.12	0.12	0.33
	γ _{yz}	0.45	0.45	0.0001
	γ _{xz}	0.45	0.45	0.0001

TABLE II
MATERIAL PROPERTIES OF ALUMINUM 6063 T6 AND STS304

Properties	Aluminum 6063 T6	STS304
Density (kg/m ³)	2,700	7,850
Elastic Modulus(GPa)	68.9	200
Shear Modulus (GPa)	0.33	0.30
Poisson's ratio	215	375

TABLE III
THE FOUR SCENARIOS OF CRASHWORTHINESS

Collision Scenario	Collusion Condition	Velocity & Load	Requirements
Scenario-1	Frontal	36 km/h	1. Anti-climbing 2. Survival space 3. Absorbed energy 4. Collision deceleration
Scenario-2	Heavy obstacle	110 km/h	
Scenario-3	Small obstacle	a-type : 300 kN b-type : 250 kN	Non-plastic deformation of carbody and coupler
Scenario-4	Coupler	10 km/h	

III. COLLISION ANALYSIS

A. Collision Scenario Conditions

The collision analysis was performed in accordance with the crashworthiness regulations of Korean railway safety law. Because tilting train is classified as general railways and class 1 vehicles operated on high-speed lines with boarded passengers, a total of four scenarios were taken into consideration in collision analysis. Table 3 shows the simulation conditions and evaluation standards for each collision scenario[9].

B. Collision Scenario-1

The collision scenario-1 is a head-on collision condition between two railway vehicles at the relative velocity of 36 km/h. The collision analysis was performed under the condition of collision into a rigid wall at a velocity of 18 km/h to save the calculation time. In order to evaluate climbing of vehicle-to-vehicle, the impact force and shear-off of the middle couplers was confirmed. The results of the analysis, the couplers between the first vehicle (Mcp-car) and the second vehicle (M-car) occurred a maximum load of 1,007 kN smaller than 1,025 kN, which is the allowable load. The climbing of vehicle-to-vehicle did not occur.

For the survival space presented in the crashworthiness regulations, in the case of the driver section, it must be maintained at 80% or above the original length or height after head-on collision. And, the passenger section must occur deformation that is less than 1% of the total length. The deformed shapes in the frontal section with crash event time are shown in Fig. 5. While the deformation of approximately 240 mm was occurred at the expected energy absorbed region, the driver section was no deformation. The maximum deformation of passenger section was 0.08mm, which satisfied of less than 1% of the original length(12,680mm).

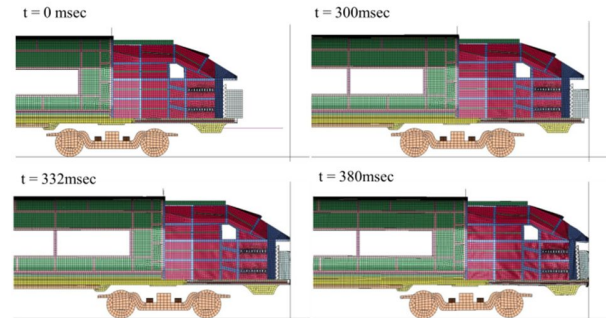


Fig. 5 The deformed shapes of frontal section for the scenario-1

Fig. 6 shows a graph of the force history curves for the collision. After first event of the impact force in the front coupler, second event was occurred at collision energy absorbed devices. Impact force was imposed on the underframe and the upper frames, thus leading to a gradual increase in the impact force. Consequently, collision energy absorption scenarios for frontal crashworthiness of tilting train were occurred according to the design intent.

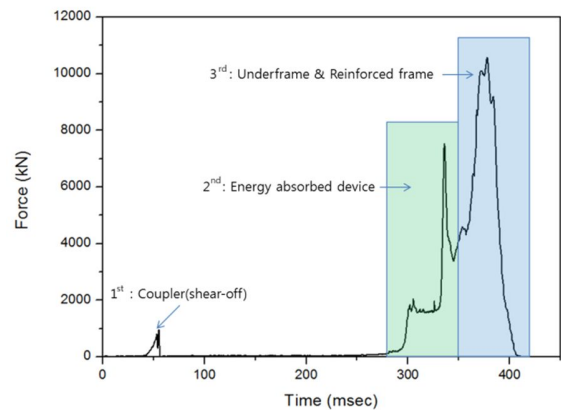


Fig. 6 The impact force-time curves for the scenario-1

Collision deceleration is a design factor related to injury, where passengers collide with internal structures. The average collision deceleration of the passenger section for the crashworthiness is 5 g or below, and its maximum deceleration is 7.5 g or below. In order to evaluate the collision deceleration of tilting trains, the Fourier 40 Hz low-pass filtering method of the European Union (EU) was used. The maximum and average collision decelerations of Mcp-car were respectively, thus confirming that crashworthiness standards were satisfied.

C. Collision Scenario-2

Collision scenario-2 consists of a heavy obstacle collision, the collision of railway vehicle and large cars of the types that can occur at railway crossings. The heavy obstacle collisions lead to serious damages to the front sections and derailment accidents due to the high crash velocity(110km/h).

The results of the collision analysis, impact force occurred in the middle couplers between the first and second vehicle was 859 kN, which was lower than the allowable load (1,025 kN). Therefore, climbing of vehicle-to-vehicle did not occur.

Fig. 7 shows the deformed shapes in the frontal section in accordance with crash event time. Because the deformation of about 748mm was occurred at cabmask section including driver survival space, crashworthiness requirement of collision scenario-2 did not satisfy.

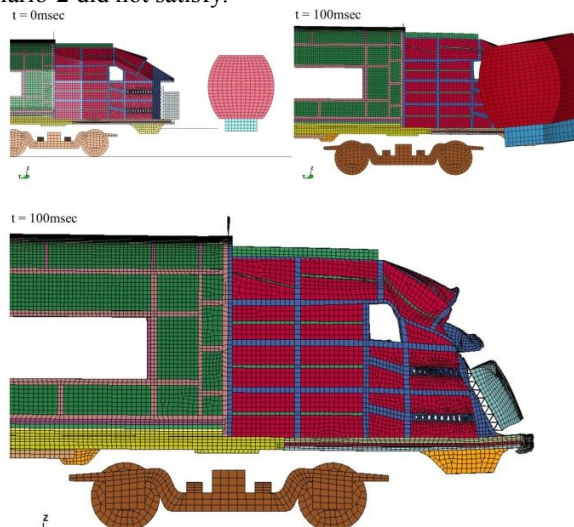


Fig. 7 The deformed shapes of frontal section for the scenario-2

The collision energy absorption standard of collision scenario-2 was satisfied that leading to a gradual increase in the impact force, as in scenario-1.

Collision deceleration of the railway vehicle continued to proceed after the collision, unlike a scenario-1. It means that the effect of collision deceleration was minimal on railway vehicle relatively in the back, with the exception of the Mcp-car in the front. Collision deceleration on of Mcp-car passenger section was confirmed to occur at 7.88 g, which exceeds 7.5 g of the maximum deceleration standard.

In scenario-2, which involved a high-speed collision, collision energy absorption was insufficient, due to the characteristics of heavy obstacles; the effect is greater on the upper frames than on the underframe. Consequently, the upper frames in the front section and impact absorbed devices must be reinforced.

D. Collision Scenario-3

Collision scenario-3 consisted of with a small obstacle collision. The static load was applied on the obstacle removers to determine the occurrence of plastic deformation in the carbody and the connection devices. The static load analysis was performed using ANSYS V13.0. The load condition of scenario-3 can be classified as either a-type (300 kN) or b-type (250 kN). The analysis was performed in consideration only of

the frontal section of the Mcp-car to conduct numerical analysis efficiency. In the analysis results of a-type load condition, the maximum deformation and Von-Mises stress of the support frames for the obstacle removers were respectively 3.51 mm and 182 MPa. In the analysis results of b-type load condition, the maximum deformation and Von-Mises stress were respectively 4.50 mm 194 MPa. Both the a-type and the b-type load condition occurred stress that was lower than the yield strength (215 MPa) of aluminum, thus crashworthiness regulation of collision scenario-3 were satisfied.

E. Collision Scenario-4

Collision scenario-4 consists of the couplers connecting vehicle-to-vehicle. This is a condition in which two trains with the same organization collide at a relative velocity of 10 km/h. The collision analysis was performed on a collision into a rigid wall at a velocity of 5 km/h to save calculation time. The result of the maximum impact force of the front couplers was 829 kN, which did not exceed the allowable load (1,025 kN). Fig. 8 shows that the maximum Von-Mises stress on the center sill was 117MP, which occurred less than the yield strength of aluminum (215 MPa). Consequently, the crashworthiness regulations of collision scenario-4 were satisfied.

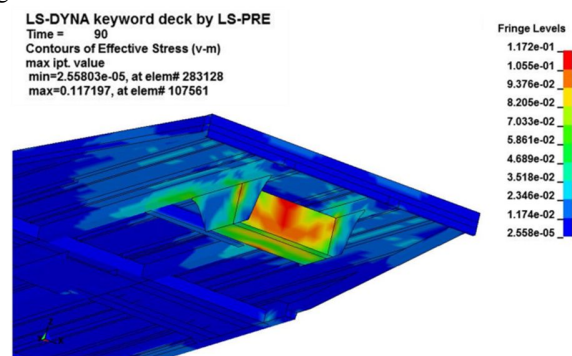


Fig. 8 Von-Mises stress of coupler part for the scenario-4

IV. THE PRESENTATION FOR THE CRASHWORTHINESS IMPROVEMENT OF TILTING TRAIN

A. The reinforcement of the upper frames

The results of collision scenario-2 did not satisfy the maintenance of the driver survival space and the collision deceleration standards. Therefore, to satisfy the crashworthiness requirement of collision scenario-2, the reinforcement method of the upper frames was proposed. The thickness of the steel frames was changed from the existing 3 mm to 5 mm.

In the results of the analysis, Fig.9 shows that the maximum deformation of energy absorbed region was 244mm and the driver section was no deformation. The maximum and average decelerations of the passenger section were 7.33 g and 3.98 g respectively, confirming that the crashworthiness regulations were satisfied. However, the weight of the vehicle was increased by approximately 283 kg due to the change in the thickness of the steel frames.

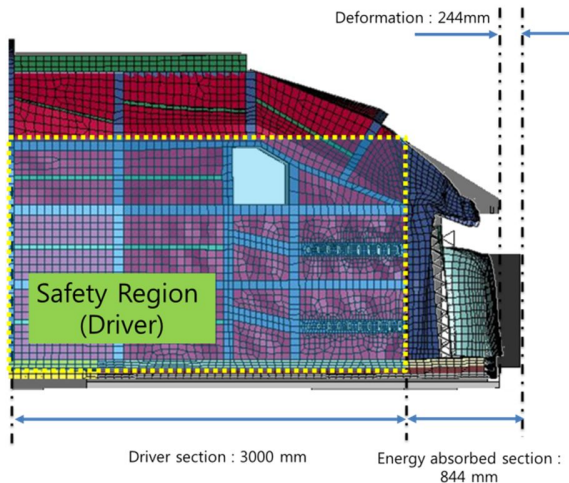


Fig. 9 The deformation of frontal section for the scenario-2

B. The reinforcement of the laminate composite covers

The second method to improve collision characteristics was to strengthen the stiffness by increasing the thickness of the laminate composites cover applied to the cabmask structures. Thickness increase from the existing 5 mm to 7 mm was presented, and an analysis of scenario-2 was performed. In the results of the analysis, maximum deformation of the driver section was maintained at 77%, which did not satisfy the condition of maintaining 80% or above. The weight increased by approximately 139 kg. Consequently, it was confirmed that, despite some increase in the weight, reinforcement of upper frames was more effective than one to increase the thickness of the laminate composites cover.

V. CONCLUSION

In this study, a crashworthiness assessment of tilting train made of sandwich composites was conducted.

The conclusions of this paper are as follows:

- 1) For the crashworthiness assessment of tilting trains made of sandwich composites, a hybrid finite element model for full railway vehicles was developed, and a crashworthiness assessment was performed by applying the four collision scenario of the railway safety law. The 1-D equivalent model displaying collision characteristics identical to those of 3-D models were developed to save calculation time and the analysis was performed efficiently.
- 2) The analysis results of collision scenario-1 satisfied the evaluation standards, which included anti-climbing, maintenance of the driver's and passengers' survival spaces, energy dispersion and absorption, and collision deceleration. For collision scenarios-3 and 4, no plastic deformation occurred in the bodies, thus satisfying the evaluation standards.
- 3) In the analysis results of collision scenario-2, the anti-climbing and energy dispersion and absorption findings satisfied the evaluation standards. However, the driver's survival space and collision deceleration results did not satisfy the evaluation standards. To improve the collision performance, a suggestion for changing the thickness of the upper frames of cabmask structures was

presented. Reinforced model that satisfies the crashworthiness regulations was presented. However, there were disadvantages to an increase of the carbody weight due to an increase in the thickness of reinforcement frames of cabmask structures. Therefore, in the further study, it will be necessary to conduct size optimization analysis for thickness of the reinforcement frame applied to improve the stiffness of cabmask structures in order to reduce the carbody weight of tilting train.

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