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This paper describes the numerical results on crashworthiness assessment and improvement scheme of tilting train made of composite materials. The bodyshell of tilting train was composed of aluminum honeycomb sandwich panels and carbon-fabric/epoxy laminate composites. The input parameters for numerical analysis were obtained from material tests. Crashworthiness analysis of the tilting train was conducted using the explicit finite element analysis code LS-DYNA3D and according to four collision scenarios of the Korean railway safety rule. The hybrid finite element modeling technique, which is made up of 2D shell and 3D solid elements for three cars in the front and 1D equivalent element for the rest cars in the rear, was introduced to ensure fast and accurate design verification for crashworthiness of railway vehicle. The numerical results showed that hybrid modeling technique was an economical approach for the analyzed results, finite element modeling, and calculating time in comparison with conventional modeling method using 2D shell and 3D solid elements for railway vehicles.

Keywords: collision analysis; crashworthiness; hybrid finite element model; tilting train

1. Introduction

Recently, railway industry has pursued active research on the environmental pollution reduction, transportation cost reduction, and the maximization of energy efficiency through the weight reduction of railway vehicles. Several countries have developed advanced composite materials and manufacturing technologies to save the weight of railway carriage structures [1]. In particular, sandwich composite structures are recommended as the best way to reduce the weight of railway vehicles because such structures offer high specific stiffness and strength, and provide an efficient solution to increase bending stiffness without significant increase in structural weight. In addition, the sandwich composite has had the effect of reducing weight, as well as improving durability and increasing the corrosion resistance of the

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components. Also, production cost reductions and simplification of the manufacturing process are easily attainable by co-curing production method for car-body structures [2].

In Korea, tilting train has developed to increase the speed of conventional lines with high percentage of curves and provide convenience for citizens in areas without high-speed railway (HSR) services. The tilting train has the advantage of reduced risk of overturning on curves at high speed, as well as reduced passenger discomfort from high centrifugal forces thanks to a mechanism that tilts the vehicle body of the train when negotiating curves. Therefore, the weight saving of tilting train is a significant problem to operate the tilting mechanism without failure and to minimize wear and tear on wheel and rail. Also, the safety of the driver and passengers according to train crash accident has become an important issue in relation to improvement in railway vehicle speed capabilities and material alterations for carbody structures.

In Europe, crashworthiness regulations for railway vehicles were legislated in 2000, and the related study is in progress [3]. In Korea, railway safety law was altered on the basis of crashworthiness regulation of Europe in 2007 to ensure the safety of the driver and passengers and to strengthen the evaluation criteria of the crashworthiness of newly developed trains. In this regulation, crashworthiness assessment is classified into crash test for real vehicles and numerical simulation through finite element analysis. Crash test for real vehicles can bring in results that best correspond to real situation for crash accident. However, this method requires considerable investments in cost and time. Therefore, the numerical analysis based on finite element method (FEM) is being spotlighted as economical and effective way to verify and evaluate the crashworthiness of railway vehicles [4].

The finite element analysis for crashworthiness evaluation of railway vehicles would usually be performed using a 2D shell element and a 3D solid element for all trains to obtain good numerical results [5–7]. However, the use of 2D shell and 3D solid elements for all trains is not an economical approach because it requires much time for numerical analysis and finite element modeling, especially if the formation of a train is composed of over four cars. Therefore, a new finite element modeling technique is needed to ensure fast and accurate design verification for crashworthiness of railway vehicle [8]. In this study, a hybrid finite element modeling technique is introduced to evaluate and verify crashworthiness of tilting train with the formation of six cars. Three cars in the front, which are typically absorbed for over 90% of the total crash energy, are modeled using conventional 2D shell and 3D solid elements. 1D equivalent element modeling is applied to the rest cars in the rear, on which the effect of a crash will be relatively minimal.

Kirkpartrick et al. [9] have compared the various experimental, analytical, and computational approaches used to evaluate crashworthiness of railway vehicle. This study showed that the finite element model applied crash test data of the railway vehicle components was very useful to evaluate and improve the complex railway collision response. Kim et al. [10] studied a conceptual design for high-speed electric multiple unit (EMU) train to satisfy the crashworthiness requirement according to Korean railway safety law. The derived conceptual design was evaluated and improved using one-dimensional dynamic simulation for the bar-spring-damper-mass finite element model. Kumar et al. [11] presented the detailed finite element (FE) models of these two types of vehicle designs and carrying out crash simulation analysis of various types including the lumped mass model. They showed that the function of the primary and secondary energy absorbers was predicted accurately with the presented model. The model also predicted the headstock deformation similar to those seen in the test. Koo et al. [12] studied a crashworthiness of Korean high speed train (KHST) by one dimensional dynamic model composed of nonlinear spring, damper and bars. The numerical results show that one-dimensional model can easily evaluate the absorbed impact energy and acceleration in a heavy collision. Ko et al. [13] conducted the finite element analysis for the structural integrity and crashworthiness of an automatic guideway transit made of a sandwich composite. They conducted the material tests to determine the input parameters of the composite laminate facesheet model and the effective equivalent damage model for the orthotropic honeycomb core material. They showed that the effective equivalent damage model for honeycomb core could reduce the time of calculation and modeling work without the error between the real and the effective models.

The objective of this paper is to describe the numerical analysis results on crashworthiness assessment and improvement scheme of tilting train made of sandwich composites according to the Korean railway vehicle law. Crashworthiness analysis of tilting trains was carried out using the explicit FEM analysis code LS-DYNA3D, confirming the deformation of the passenger and driver section and the failure modes of composite carbody structures. In order to improve the efficiency of crashworthiness analysis of tilting trains, a hybrid finite element modeling technique was introduced in this study. In hybrid model, 2D shell and 3D solid elements were used to generate the finite element model of three cars in the front, and 1D equivalent element was applied to create the simplified equivalent model of the rest cars in the rear. Crashworthiness improvement scheme for tilting trains is presented through two reinforcement methods in the cabmask structures.

2. Finite element model of tilting train

2.1. Description of tilting train

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

2.2. Generation of finite element model for three cars in the front

Generally, the finite element model of carbody structures for crashworthiness assessment of railway vehicles is generated using 2D shell element and 3D solid element to ensure and obtain a good numerical result. However, the use of 2D shell and 3D solid elements for all trains is not very efficient modeling method because over 90% of total crash energy is designed to be absorbed by two or three cars in the front [14]. Therefore, it is desirable that 2D shell and 3D solid elements are applied only for the generation of finite element model of three cars in the front.

In order to generate finite element models for carbody structures of three cars in the front of tilting trains, LS-DYNA3D material model #54-55(*MAT_ENHANCED_COMPOSITE_DAMAGE) is used as shell element to laminated composite parts and carbon fabric/epoxy composite facesheet of sandwich panels. This constitutive model is based on the theory of continuum damage mechanics. It is assumed that the deformation of the materials introduces microcracks and cavities, which reduce the material stiffness. This is expressed through the internal damage parameters that describe the evolution of the damage state under

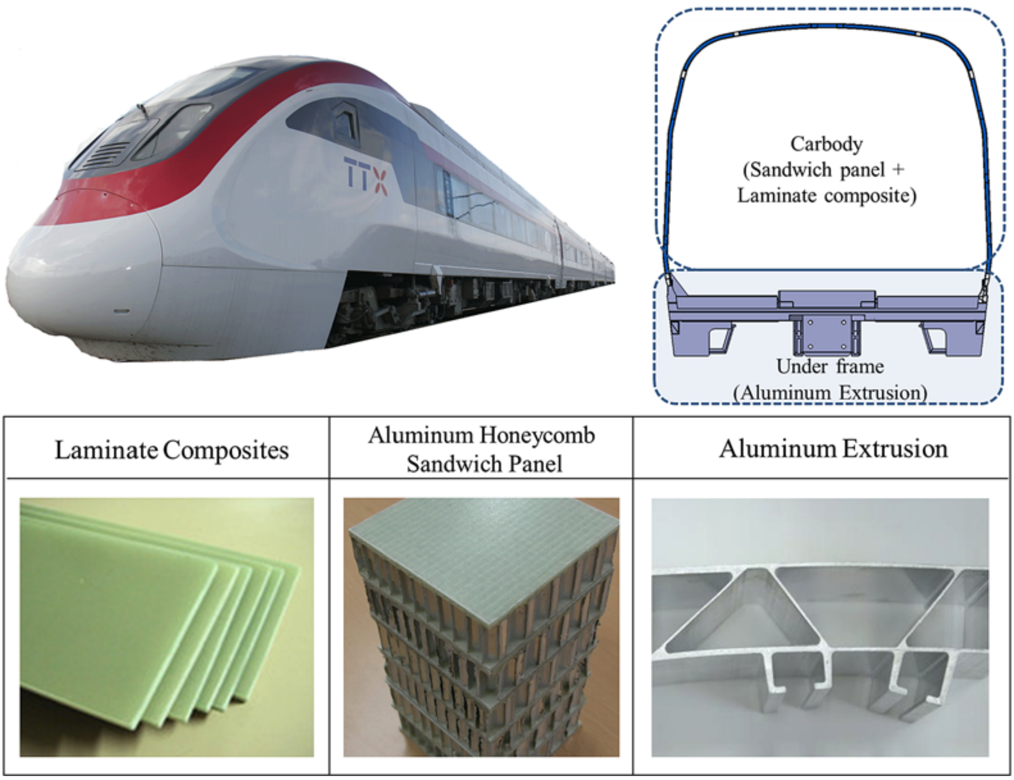

Figure 1. Tilting train made of sandwich composites.

Table 1. Design weights of tilting train.

Items		Weight (kg)
Standard curb weight	Mcp-car	54,348
	M-car	47,245
	T-car	43,595
Passenger weight	Mcp-car	2175
	M-car, T-car	4200
Bogie weight	Mcp-car	9400
	M-car	9000
	T-car	7100
Empty weight	Mcp-car	11,383
	M-car, T-car	9674

loading and hence the stiffness degradation [15]. The basis of the model is the modification made by Matzenmiller et al. [16] to the well-known Chang and Chang composite damage model [17]. The Chang and Chang failure criterion is utilized by the model to predict matrix cracking, compressive failure, and fiber breakage of the laminate. The modified Chang and Chang failure criterion is shown in Table 2. Table 3 shows the mechanical properties of laminate composite materials used to carbody structures.

Table 2. The modified Chang–Chang failure criterion in LS-DYNA 3D.

Mode	Following conditions
Fiber breakage	• Tensile, $\sigma_x > 0$ $$e_{\mathrm{ft}}^2 = \left(\frac{\sigma_x}{X_t}\right)^2 + \left(\frac{\tau_{xy}}{S}\right) - 1$$ where, $e_{\mathrm{ft}}^2 \geq 0$: failed & $e_{\mathrm{ft}}^2 < 0$: elastic • Compressive, $\sigma_x < 0$ $$e_{fc}^2 = \left(\frac{\sigma_x}{X_c}\right)^2 - 1$$ where, $e_{\mathrm{fc}}^2 \geq 0$: failed & $e_{\mathrm{fc}}^2 < 0$: elastic
Matrix cracking	• Tensile, $\sigma_x < 0$ $$e_{\mathrm{mt}}^2 = \left(\frac{\sigma_y}{Y_t}\right)^2 + \left(\frac{\tau_{xy}}{S}\right)^2 - 1$$ where, $e_{\mathrm{mt}}^2 \geq 0$: failed & $e_{\mathrm{mt}}^2 < 0$: elastic • Compressive, $\sigma_x < 0$ $$e_{\mathrm{mc}}^2 = \left(\frac{\sigma_y}{2S}\right)^2 + \left[\left(\frac{Y_c}{2S}\right)^2 - 1\right]\frac{\sigma_y}{Y_c} + \left(\frac{\tau_{xy}}{S}\right)^2 - 1$$ where, $e_{\mathrm{mc}}^2 \geq 0$: failed & $e_{\mathrm{mc}}^2 < 0$: elastic
Fiber and matrix shearing	• Tensile and compressive $$e_{\mathrm{md}}^2 = \frac{\sigma_y^2}{Y_c Y_t} + \left(\frac{\tau_{xy}}{S}\right)^2 + \frac{(Y_c - Y_t)\sigma_y}{Y_c Y_t} - 1$$ where, $e_{\mathrm{md}}^2 \geq 0$: failed & $e_{\mathrm{md}}^2 < 0$: elastic

σ_x, σ_y, and τ_{xy}: stress of principal material direction; X_t and Y_t: tensile strength of fiber and matrix direction; Y_c and Y_c: compressive strength of fiber and matrix direction; S: in-plane shear strength; e: failure index; ft: fiber tensile; fc: fiber compressive; mt: matrix tensile; mc: matrix compressive; and md: shearing mode of fiber and matrix.

For aluminum honeycomb core of sandwich panels, the LS-DYNA3D material model #126 (*MAT_MODIFIED_HONEYCOMB) is used to simulate the core material as the solid element. In this orthotropic material model, the nonlinear elastoplastic constitutive behavior is used based on the experimentally determined stress–strain curve. For reasons of simplification, the cellular honeycomb core structure was treated as a homogeneous material using its effective orthotropic material properties. This application of the honeycomb core materials properties on the effective equivalent damage model brings about time reduction, which in turn is subjected to analysis. The honeycomb core tests are conducted according to the American Society for Testing and Materials (ASTM) standards. The honeycomb core test is comprised of compression (ASTM C365), tension (ASTM C363), and shear (ASTM C273)

Table 3. Material properties of laminate composite materials.

Properties		HG 1581	CF 1263	CU 125
Density (kg/m^3)		2000	1520	1600
Elastic modulus (GPa)	E_x	24.60	58.36	130.00
	E_y	24.60	48.42	10.00
	E_z	10.66	10.66	10.00
Shear modulus (GPa)	G_{xy}	5.84	5.84	4.85
	G_{yz}	3.65	3.65	4.85
	G_{xz}	3.65	3.65	4.85
Poisson's ratio	v_{xy}	0.12	0.12	0.31
	v_{yz}	0.45	0.45	0.34
	v_{xz}	0.45	0.45	0.31
Tensile strength (MPa)	Fill	410	885	38
	Warp	461	1018	1834
Compressive strength (MPa)	Fill	468	513	42
	Warp	472	542	1165

Table 4. Equivalent mechanical properties of aluminum honeycomb core.

	Elastic modulus (MPa)			Shear modulus (MPa)			Poisson's ratio		
Density (kg/m^3)	E_x	E_y	E_z	G_{xy}	G_{yz}	G_{xz}	v_{xy}	v_{yz}	v_{xz}
59	0.693	0.293	105	0.618	32	32	0.33	0.0001	0.0001

[18–20]. The equivalent material properties of the honeycomb core are listed in Table 4. Figure 2 shows the comparison results of force–time curves and deformed shapes of sandwich panels obtained by low-velocity impact test and finite element analysis using effective equivalent damage model. These comparisons indicate that there were generally good agreements between the experimental and the numerical results in terms of time duration, peak force, and overall profile.

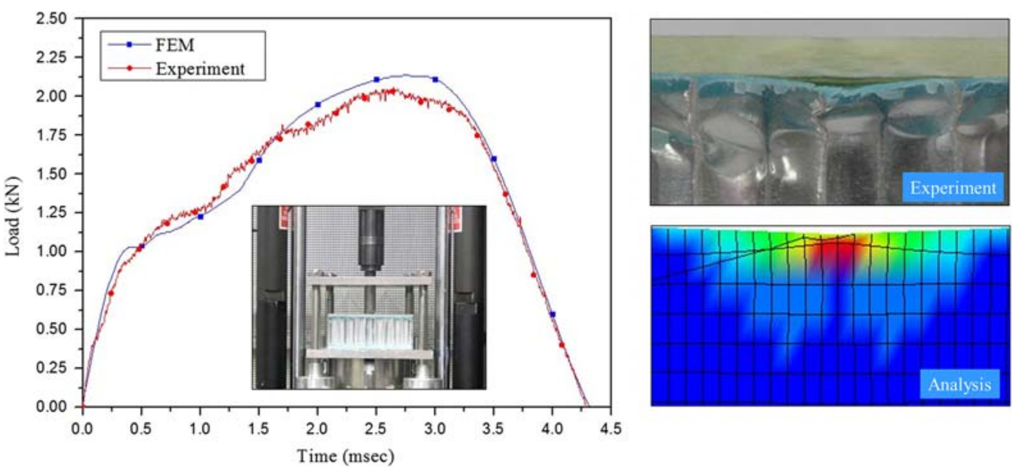

Figure 2. The comparison results of experiment and analysis for sandwich panels with equivalent damage model of honeycomb core under low-velocity impact.

Table 5. Mechanical properties of Aluminum 6063 T6 and STS304.

Properties	Aluminum 6063 T6	STS304
Density (kg/m^3)	2700	7850
Elastic modulus (GPa)	68.9	200
Poisson's ratio	0.33	0.30
Yield strength (MPa)	215	375

The metal structures, such as underframe, and the reinforced frame in sandwich panels were modeled using the material model #24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) from the LS-DYNA3D material library for shell element. These materials are defined in stress–strain curve obtained by tensile test. Table 5 shows the mechanical properties of metal materials used to tilting trains.

Figure 3 shows the finite element models for Mcp-car and the M-car in the front of a tilting train. The total numbers of elements were 503,756 and 402,654 for the MCP-car and M-car, respectively.

2.3. Generation of hybrid finite element models of tilting trains

The hybrid modeling technique using 1D equivalent model and 3D model could reduce the time of calculation and modeling works for collision analysis. In this study, it was found that the calculation time of collision analysis using hybrid modeling technique could be reduced by about 75% in comparison with the collision analysis using full 3D model. It means that the hybrid modeling technique would bring up design and analysis time and cost reduction for the development of railway vehicle. Therefore, we suggested the hybrid modeling technique as an economical approach for the collision analysis of railway vehicle.

In order to create the hybrid finite element model of all of the tilting trains, 1D equivalent element was applied to the rest cars in the rear, on which the effect of a collision would be relatively minimal. The 1D equivalent element was generated by LS-DYNA 3D material model #121(*MAT_GENERAL_NONLINEAR_1DOF_DISC-RTE_BEAM), which has the advantage of enabling a quick evaluation and calculation of the collision behavior of railway vehicles.

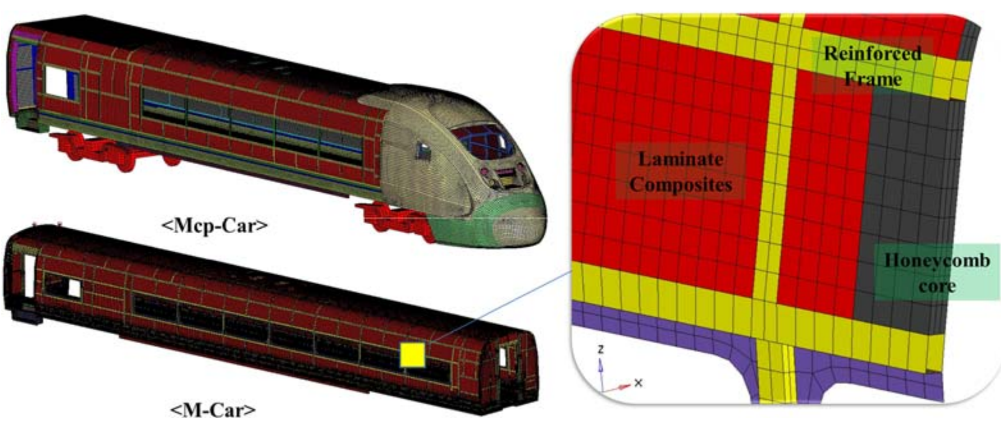

Figure 3. Finite element models for Mcp-car and M-car in the front of tilting train.

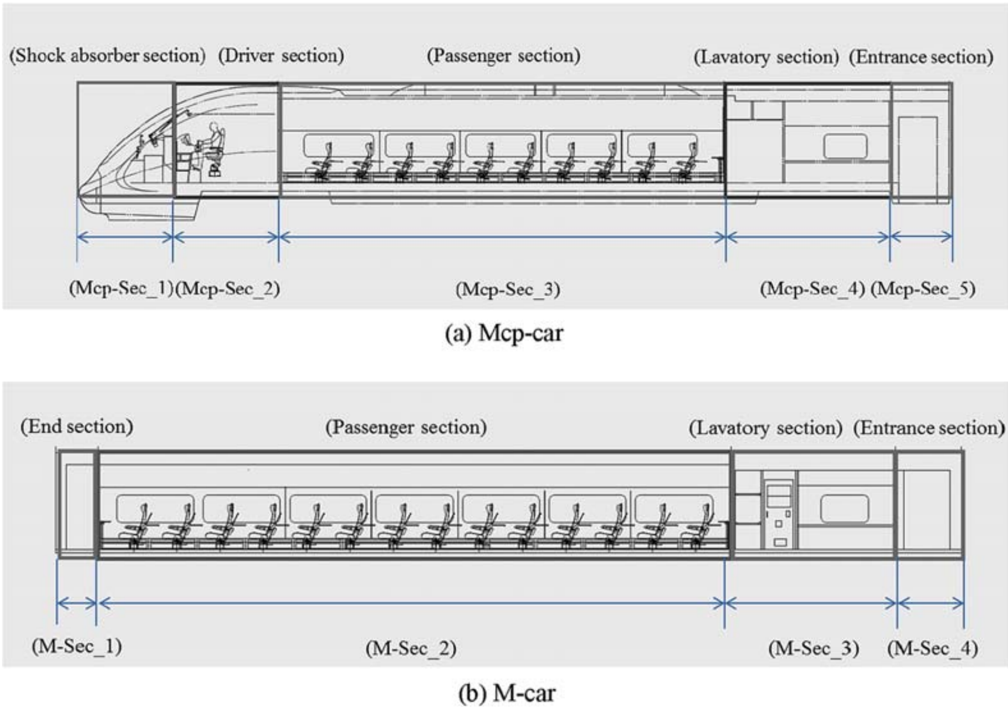

Figure 4. Definition of cross section plane for a subjecting carbody.

In order to apply 1D equivalent model for the rest cars in the rear of tilting train, crush characteristics of 1D equivalent element should be identical to those of carbody structures generated by 2D shell and 3D solid elements. In this study, crush characteristics of 1D equivalent element was derived by designating a cross-section plane option of LS-DYNA3D. This method is that load-deformation diagrams of 1D equivalent element are obtained by collision analysis for the selected cross sections of a subjecting carbody structure as shown in Figure 4. Mcp-car was divided into a total of five sections, consisting of the shock absorber section of cabmask, the driver section, the passenger section, the lavatory section, and the entrance section as shown in Figure 4(a). The M-car was divided into a total of four sections, consisting of the carbody end section, passenger section, lavatory section, and entrance section as shown in Figure 4(b).

Table 6 shows detail information of selected cross sections of a subjecting carbody structure used to 1D equivalent element. Figure 5 shows a comparison on numerical results of

Table 6. Information of selected cross sections in LS-DYNA 3D.

Items	Driver section	Passenger section	Lavatory section	Entrance section	End section
Area (mm^2)	321,542	781,460	781,460	811,460	781,460
Unit mass (kg/m)	515	506	608	647	646
Second moment of area (m^4)	0.622	1.164	1.164	1.345	1.164

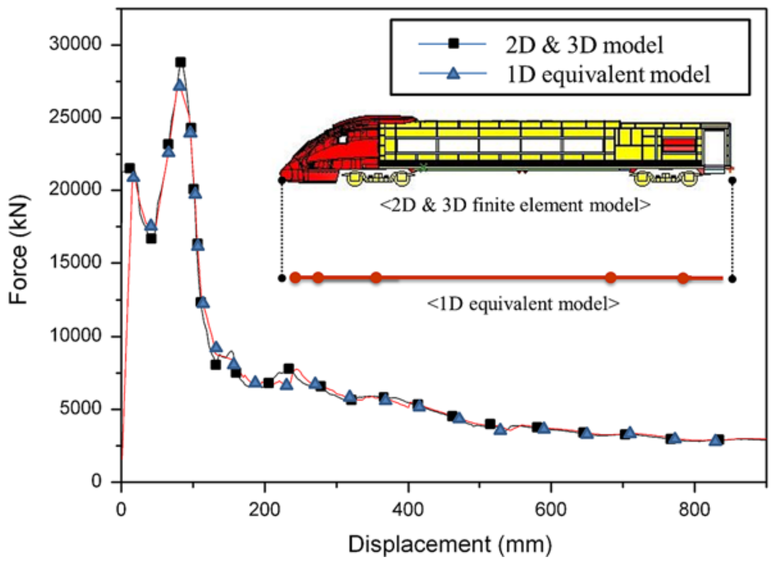

Figure 5. The comparison of collision responses between 2D and 3D models and 1D equivalent model for Mcp-car.

force–displacement curve between 2D shell and 3D solid-based models and 1D equivalent model of Mcp passenger vehicle subjected to collision load. Numerical results of collision response showed a good agreement for 2D shell and 3D solid-based models and 1D equivalent model.

The bogies of the railway vehicle were modeled using solid elements in consideration of the mass effect. 1D spring-damper elements were used to simulate the mechanical properties of the air springs, which connect the railway vehicle and the bogie.

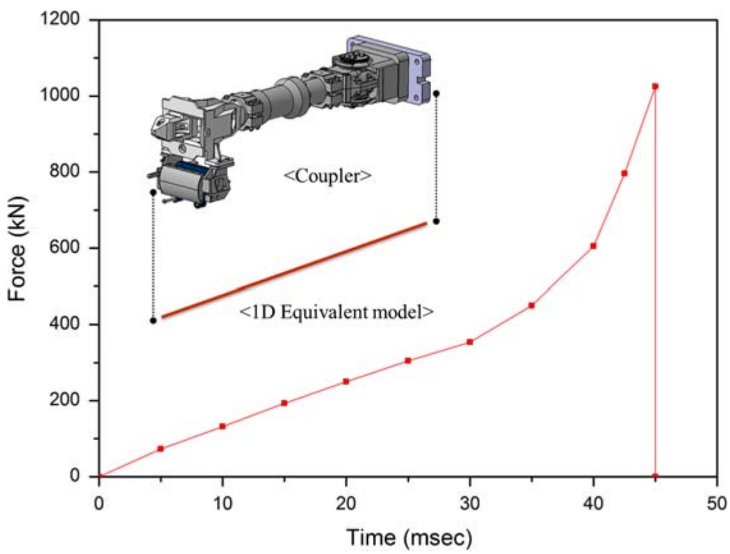

Figure 6. Dynamic characteristics and 1D equivalent model of vehicle couplers.

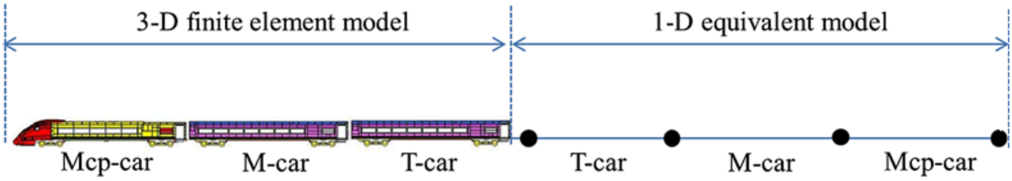

Figure 7. The hybrid finite element model for tilting train.

The real shapes of vehicle couplers are too complicated to be applied to a collision analysis as shown in Figure 6 and, hence, the simplified 1D equivalent model was also applied for vehicle couplers. The 1D equivalent model #121(*MAT_GENERAL_NONLINEAR_1DOF_DISCRTE_BEAM) can reduce the modeling and calculation time, and effectively simulate the dynamic characteristics of vehicle couplers. Figure 6 shows force history curve of 1D equivalent element for vehicle couplers. A shear-off was made to occur automatically when the couplers' allowable load (1025 kN) was exceeded [21].

Figure 7 shows the hybrid finite element model of tilting train consisting of 2D shell and 3D solid elements for three cars in the front and 1D equivalent element for the rest cars in the real.

3. Collision analysis

3.1. Collision scenario conditions

The collision analysis was performed under the crashworthiness regulations of Korean railway safety law. Because tilting trains are classified as general railways and class 1 vehicles operated on high-speed lines with boarded passengers in Korean railway safety law, a total of four scenarios were taken into consideration in the collision analysis. Table 7 shows the four scenarios for crashworthiness evaluation of tilting train defined by Korean railway safety law [22].

3.2. Numerical results

Collision scenario-1 is a head-on collision between two railway vehicles at the relative velocity of 36 km/h. The overriding phenomena of trains due to head-on collision would also be analyzed in collision scenario-1. The key criterion of overriding phenomena is based on shear-off of vehicle couplers caused by impact force during collisions. The collision analysis was performed under the condition of collision into a rigid wall at a velocity of 18 km/h in

Table 7. The four scenarios of crashworthiness.

Collision scenario	Collision condition	Velocity & load	Requirements
Scenario-1	Head-on collision	36 km/h	(1) Anti-climbing (2) Survival space (3) Collision absorbed energy (4) Collision deceleration
Scenario-2	Heavy obstacle collision	110 km/h	
Scenario-3	Small obstacle collision	a-type: 300 kN b-type: 250 kN	Nonplastic deformation of carbody and coupler
Scenario-4	Coupler collision	10 km/h	

consideration of the efficiency improvement and energy equivalence. In the numerical results, the shear-off of coupler between first vehicle (Mcp-car) and second vehicle (M-car) due to head-on collisions had a maximum load of 1007 kN, which is smaller than the allowable load of 1025 kN. It was found that the overriding behavior during a head-on collision between trains did not occur. The deformed shapes in the frontal section during train collision are shown in Figure 8. Although maximum deformation of 240 mm occurred at shock absorption apparatus of cabmask structure, the safety region of driver was secured without deformation. Also, the maximum deformation of the safety region of passenger was 0.08 mm, which satisfied the requirement that in was less than 1% of the original length (12,680 mm). Figure 9 shows the force history curves of tilting train during a head-on collision. The first impact event happened at the coupler between Mcp-car and M-car and then the second impact event occurred in shock absorber of cab-mask structures. After the second impact response, impact force was transferred to the underframe and reinforced metal frame of side wall structures, thus leading to a gradual increase in the impact force. Fortunately, such impact behavior would help to prevent the overriding phenomena due to a head-on collision as the designer intended.

Collision scenario-2 is a heavy obstacle collision condition at the velocity of 110 km/h. A heavy obstacle represents a medium truck of 15 ton and is modeled using a numerical model of standard heavy obstacles in LS-DYNA3D. In numerical results of collision scenario-2, the value of shear-off of coupler between Mcp-car and M-car was 859 kN, which was lower than the allowable load (1025 kN). This result showed that the overriding phenomena of the vehicles did not occur in collision scenario-2. Figure 10 shows the deformed shapes of the cab-mask structures by the lapse of time for collision scenarios-2. Unlike collision scenario-1, the maximum deformation of 748 mm was occurred in the driver section of cab-mask structures as well as the driver survival space at $t = 100$ m sec as shown in Figure 10. This means that collision scenario-2 for tilting trains did not satisfy the crashworthiness requirement. In case of collision scenario-2, the shock absorption apparatus made of aluminum honeycomb sandwich panels could not function normally due to a high-speed collision of 110 km/h. Therefore, in order to ensure the safety of driver for collision scenario-2 of tilting trains, it is necessary to improve impact energy absorption capacity of tilting trains using reinforcing method such as the stiffness improvement of metal frames near driver section and installation of expansion tube.

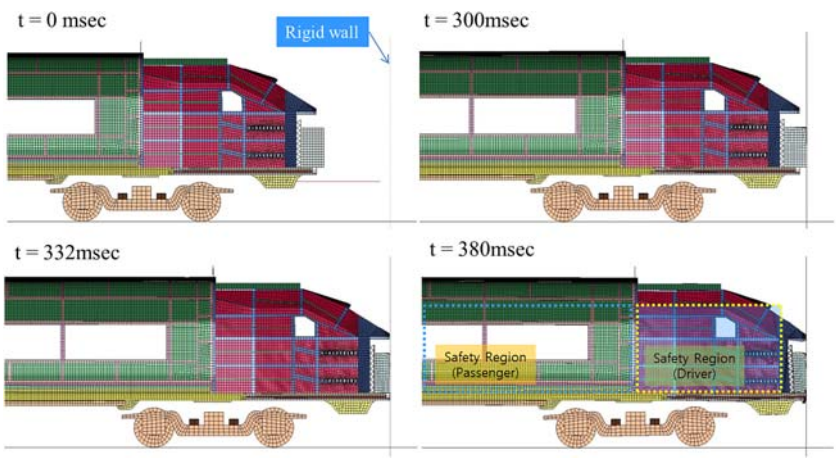

Figure 8. The sequence of deformed shapes of the vehicle for the scenario-1.

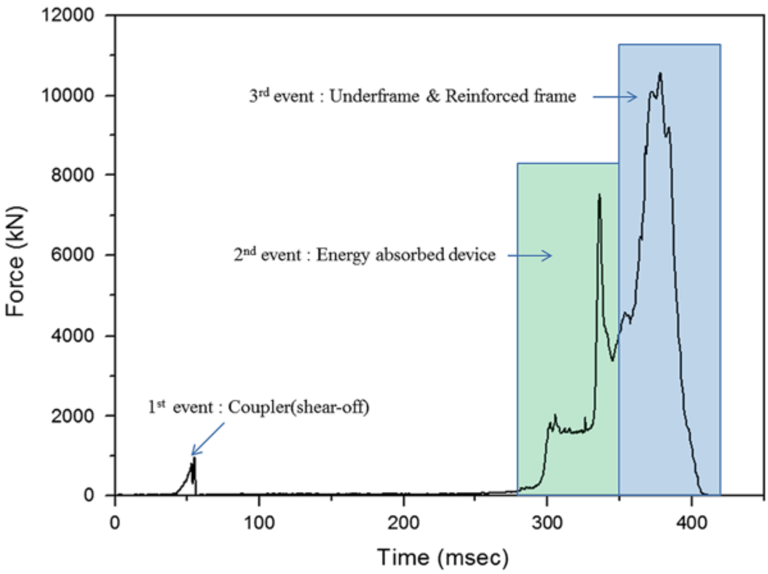

Figure 9. The impact force–time curves for the scenario-1.

Collision scenario-3 is a small obstacle collision condition with compressive load of 300 kN (a-type) and 250 kN (b-type) to evaluate the structural integrity of carbody and coupler due to track clearer of tilting trains. The track clearer structure was used for ensuring structural integrity of vehicle by eliminating obstruction on a track, and it is jointed to underframe of carbody through the connection rod. Figure 11 shows a-type and b-type loading locations for scenario-3. Collision scenario-3 was conducted as static problem using a commercial finite element analysis program (ANSYS v.12). In numerical results of collision scenario-3, the maximum deformation and Von-Mises stress of connection rods of track clearer were 3.51 mm and 182 MPa, respectively, for a-type and 4.50 mm and 194 MPa, respectively, for b-type. Both a-type and b-type loading conditions were not permanent deformation and had a lower stress than yield strength (215 MPa) of aluminum. This means that crashworthiness regulations were satisfied in collision scenario-3.

Collision scenario-4 is a vehicle coupler collision condition 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 similar to collision scenario-1. In numerical results of collision scenario-4, the maximum impact force of couplers between Mcp-car and M-car was 829 kN, which did not exceed the allowable load (1025 kN). Figure 12 shows the contours of Von-Mises stress near center sill of underframe connected to couplers. The center sill is the reinforcement structure for supporting the load in parallel direction with underframe of vehicle. The maximum Von-Mises stress on center sill was 117 MPa, which was less than the yield strength of aluminum (215 MPa). Also, there was no plastic deformation. Consequently, the crashworthiness regulations of collision scenario-4 were satisfied.

4. The crashworthiness improvement scheme of tilting trains for collision scenario-2

For collision scenario-2 with a heavy obstacle collision condition at the velocity of 110 km/h, impact energy absorption capacity of tilting trains was insufficient. As a result, the drive survival space was not secured. The front structure of Mcp-car has shock absorber and coupler of railway vehicles to enhance the crashworthiness of structures, and it is known that these

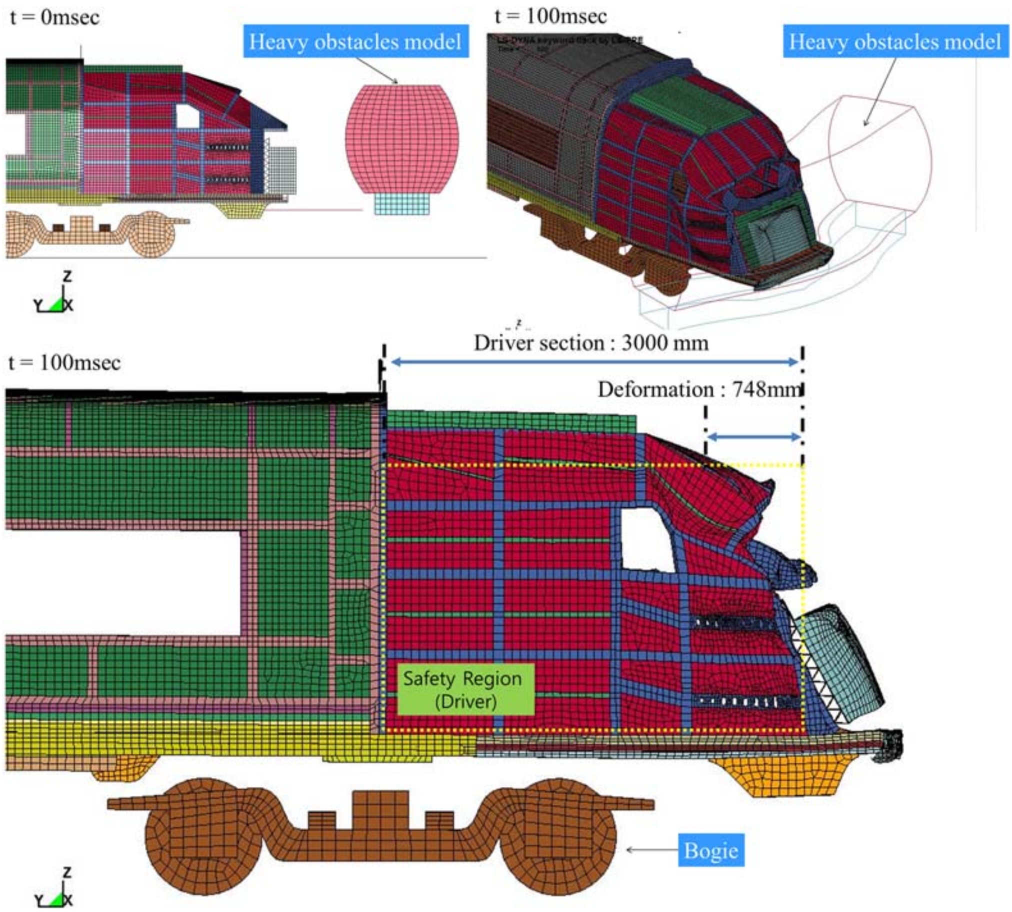

Figure 10. The deformed shapes of cabmask structures for the scenario-2.

structures could absorb more than 3.5 MJ of impact energy. For this reason, the Mcp-car is an important part for collision accident of railway vehicle. Therefore, the reinforcing methods for cabmask structures of Mcp-car have been proposed to improve the crashworthiness of tilting trains in this study.

4.1. The reinforcement of the upper frames of cabmask structures

The first reinforcing method is to improve the structural stiffness through the increasing thickness of metal frames of cabmask structures as shown in Figure 13. The thickness of steel metal frames was changed from 3 to 5 mm.

In numerical results of collision scenario-2 with reinforced metal frames of cabmask structures, the maximum deformation of 244 mm was occurred only in the shock absorber of cabmask structures, and there was no deformation in the driver survival space as shown in Figure 14. Also, the maximum and average decelerations of the passenger section were 7.33 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 changes in the thickness of the steel frames of cabmask structures.

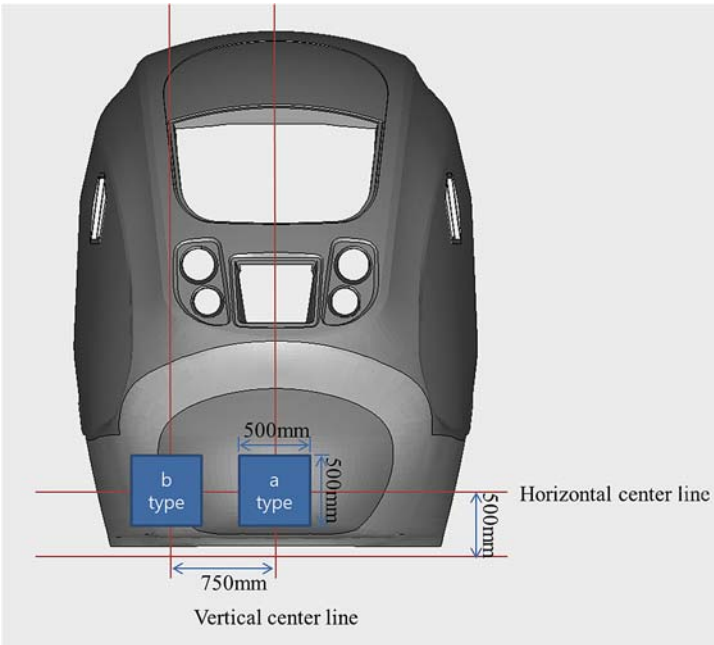

Figure 11. Loading locations of a-type and b-type for the scenario-3.

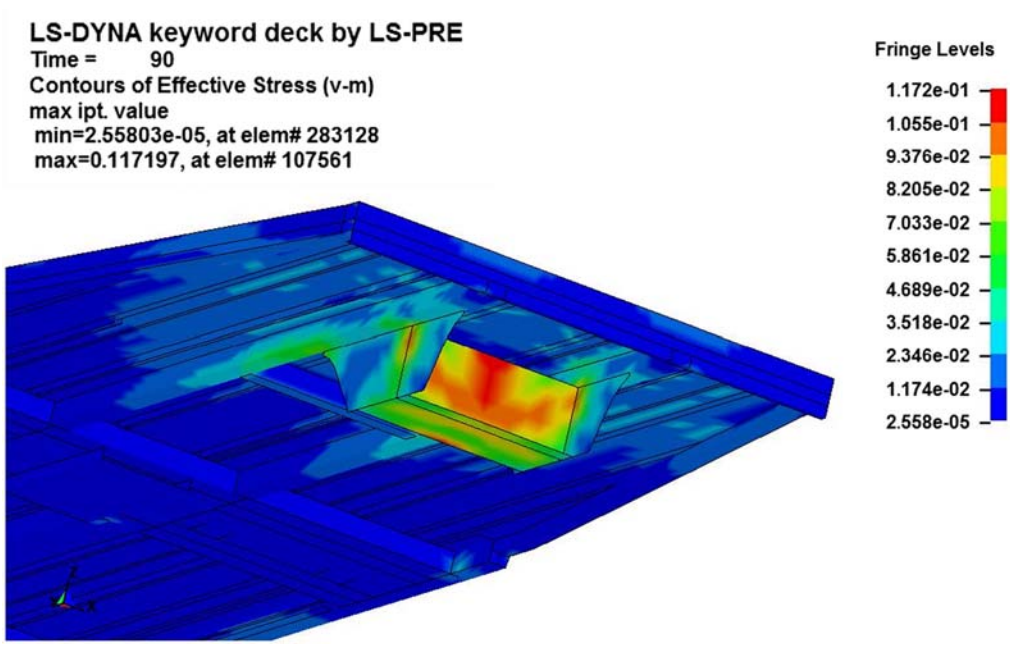

Figure 12. Von-Mises stress of center sill for the scenario-4.

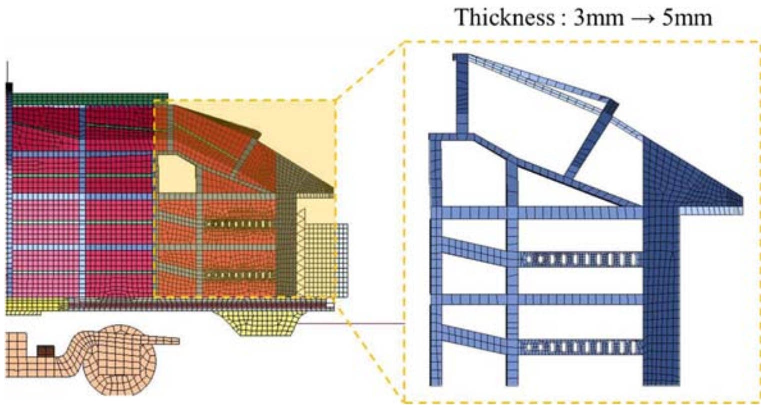

Figure 13. The cabmask structures with reinforced frames.

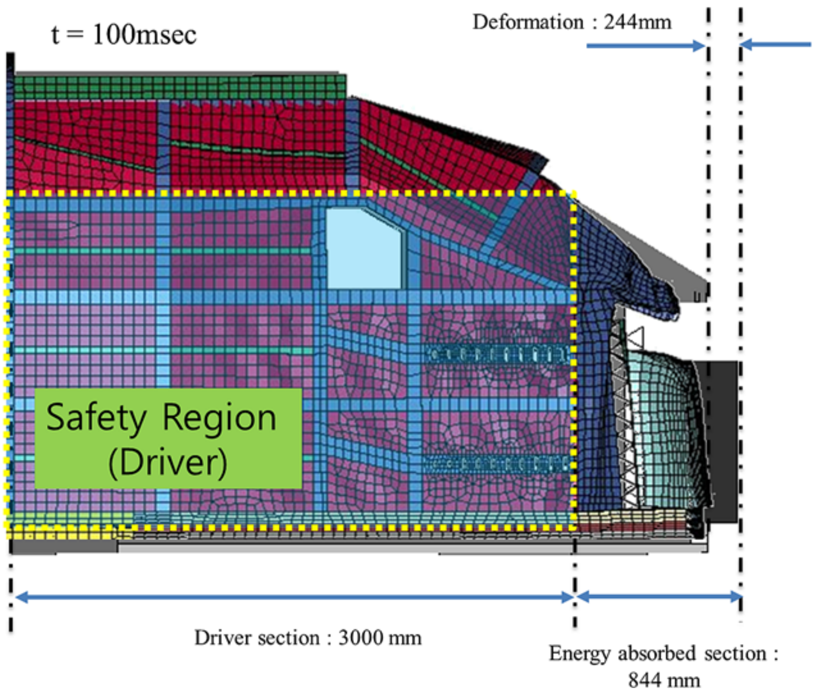

Figure 14. The deformation of cabmask structures for the scenario-2 with reinforced metal frames.

4.2. The reinforcement of the laminate composite covers of the cabmask structures

The second method of improving the collision characteristics of tilting trains is to strengthen the structural stiffness by increasing the thickness of the laminate composite cover applied to the cabmask structures. The thickness of laminate composite cover was increased from 5 to 7 mm. In numerical results of collision scenario-2 with reinforced laminate composite cover of cabmask structures, the maximum deformation of 690 mm was occurred in the driver

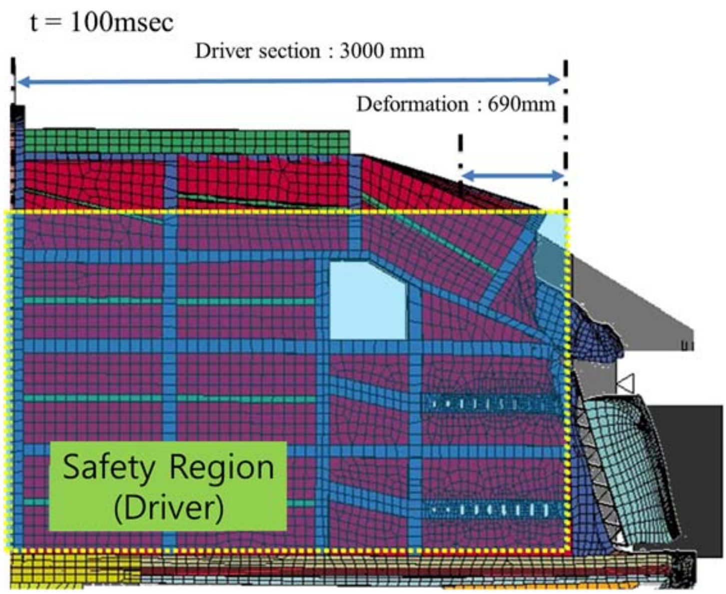

Figure 15. The deformation of cabmask structures for the scenario-2 with reinforced laminate composite cover.

section of cabmask structures as well as the driver survival space as shown in Figure 15. This means that collision scenario-2 for tilting trains did not satisfy the crashworthiness requirement, although the structural stiffness of cabmask structures was improved. Furthermore, the weight of the vehicle was increased by about 139 kg. Consequently, it was confirmed that the reinforcement of thickness of metal frame of cabmask structures was more efficient than one to increase the thickness of its laminate composite cover, even if the weight of the vehicle was slightly increased.

5. Conclusion

Tilting train has developed to increase speed of conventional lines with high percentage of curves and provide convenience for citizens in areas without HSR services in Korea. In order to reduce the weight of tilting train, honeycomb sandwich structures and laminate composites with high stiffness-to-weight and strength-to-weight ratios were considered for the application to primary carbody structures. However, the guarantee of safety of the driver and passengers from train crash accident has become an important issue due to the material alterations for carbody structures and improvement of railway vehicle speed.

The present paper describes the numerical analysis results on crashworthiness assessment and improvement scheme of tilting train made of sandwich composites subjected to various train collision conditions. The collision conditions of tilting train was a head-on collision, a heavy obstacle collision, a small obstacle collision, and a vehicle coupler collision by Korean railway safety law. To obtain input parameters for collision analysis of tilting train, the mechanical property test of the applied materials was done. The conclusions of this paper are as follows:

(1) For hexagon aluminum honeycomb core, the effective equivalent damage model was applied to reduce a long modeling time and a convergence time for analysis. The effective material properties for honeycomb core were obtained from mechanical tests. The validity of the effective equivalent damage model for honeycomb core was verified up through the comparison results of experiment and analysis for the force–time curves and deformed shapes of sandwich panels subjected to low-velocity impact.
(2) In order to improve the efficiency of collision analysis of tilting train, a hybrid finite element modeling technique, which composed of 2D shell and 3D solid elements for three cars in the front and 1D equivalent element for the rest cars in the rear of tilting train, was introduced in this study. The crush characteristics of the proposed 1D equivalent element was confirmed by a comparative study on force–displacement response of 2D shell and 3D solid-based models and 1D equivalent model of Mcp passenger car subjected to collision load. The results showed that the hybrid finite element model could reduce the modeling and the calculating time in comparison with 2D shell and 3D solid finite element models for all cars of railway vehicles.
(3) The collision analysis of tilting train made of sandwich composites showed that the safety region of driver and passenger was secured, except collision scenario-2 of a heavy obstacle collision condition. In the case of collision scenario-2, the shock absorber made of aluminum honeycomb sandwich panels could not function normally due to a high-speed obstacle collision. As a result, the deformation induced by collision was occurred in the driver section of cabmask structures as well as the driver survival space and hence the crashworthiness requirement was not satisfied.
(4) In order to meet crashworthiness requirement for collision scenario-2 of tilting train, the reinforcement of the upper metal frames and laminate composite covers of cabmask structures have proposed in this study. In case of the reinforcing method for thickness of steel metal frames of cabmask structures, the deformation after a heavy obstacle collision was occurred only in the shock absorber, and there was no deformation in the driver survival space. Consequently, it found that the reinforcement of thickness of metal frames of cabmask structures was more efficient than one to increase the thickness of its laminate composite covers, although the weight of tilting train was slightly increased.

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