Journal of Mechanical Science and Technology 25 (5) (2011) 1185~1192
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-011-0228-z

The suggestion of the standardized finite element model through the experimental verifications of various railway vehicle structures made of sandwich composites †

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(Manuscript Received August 27, 2010; Revised January 19, 2011; Accepted February 8, 2011)

Abstract

In this study, a standardized finite element model for the carbody structures of various railway vehicles made of sandwich composites was suggested. The standardized finite element model for composite carbody structures was introduced and proposed by comparing the results of real structural tests under vertical, compressive, twisting load and natural frequency tests of various railway vehicles. The results showed that the quadratic shell element was suitable to model the reinforced metal frame used to improve the flexural stiffness of sandwich panels compared to beam elements, and layered shells and solid elements were recommended to model the skin and honeycomb core of sandwich panels compared to sandwich shell elements. Also, the proposed standard finite element model has the merit of being applied to crashworthiness analysis just by minor modifications, such as contact conditions and constraint equations.

Keywords: Railway vehicle; Structural test; Standard finite element model; Sandwich composite

1. Introduction

With the increasing demand for the development of eco-friendly transportation vehicles that involve less energy and low or no pollution, the railway vehicle technology is developing and its market is widening. In Korea, many studies are being conducted on the development of eco-friendly railway systems to improve the country's competitive power [1]. The light weight of vehicles is one of the important factors for saving energy and improving performance. Accordingly, sandwich composites are increasingly being applied to the primary members, which comprise many parts of the carbody, to improve energy efficiency [2, 3]. The sandwich composite, which has a higher bending stiffness and strength than single-member materials or laminate composites, is being applied to many sectors, including the aerospace and ground transportation industries, because it contributes to the reduction of the vehicle weight and ensures sufficient space [4, 5]. Therefore, it was applied to the Korean tilting train, the Korean low-floor bus, the automated people mover (APM), and the bimodal tram, and the developed products are in the test run stage. The structural integrity of the carbody structure that is made of sandwich composites must be verified before the manufacturing process, and the structural integrity is generally evaluated by using an analytical method based on finite element analysis and an experimental method based on a structural test [6]. The structural test can obtain the engineering data for the design check of the carbody, by testing the structural integrity, durability, and dynamic stability under the similar conditions to real operating environments such as loading condition, temperature, and vibration. Also, it is advantageous in that it can be used to directly check the structural integrity of the parts that are difficult to theoretically analyze due to the complex shapes. However, the experimental method has spent much time and cost to manufacture the test carbody, and quick structural application for design modification is not possible. On the other hand, an analytical method based on finite element analysis enables quick structural design modification without much time and cost through comparing between the results of structural test and numerical analysis [7, 8]. Many studies on the finite element analysis modeling technology for the honeycomb structure have been conducted in the aerospace industry, and are being used for analytical evaluation [9-11]. In the railway vehicle sector, however, few studies have been conducted on the modeling technique.

Therefore, in this study, an optimal and standardized finite element modeling technique was developed and introduced by comparing the experimental results obtained by the real struc-

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† This paper was recommended for publication in revised form by Associate Editor Chang-Wan Kim

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Table 1. The materials used to various railway carbody structures.

Part	Carbody Structure	Under Frame	Reinforced Frame
Bimodal Tram	1)Sandwich Panel + 2)Laminate composite	Aluminum Extrusion profile (Al6063 T6)	Aluminum Extrusion profile (Al6063 T6)
APM	1)Sandwich Panel + 2)Laminate composite	Stainless Steel Extrusion profile (SMA490B)	Stainless Steel Extrusion profile (SS400)
TTX	3)Sandwich Panel + 4)Laminate composite	Stainless Steel Extrusion profile (SMA490B)	Stainless Steel Extrusion profile (SS400)

1) Glass/Epoxy laminate + Honeycomb core(Al6005-3/8″)
2) Glass/Epoxy laminate
3) Glass/epoxy & Carbon/Epoxy laminate + Honeycomb core(Al6005-3/8″)
4) Glass/epoxy & Carbon/Epoxy laminate

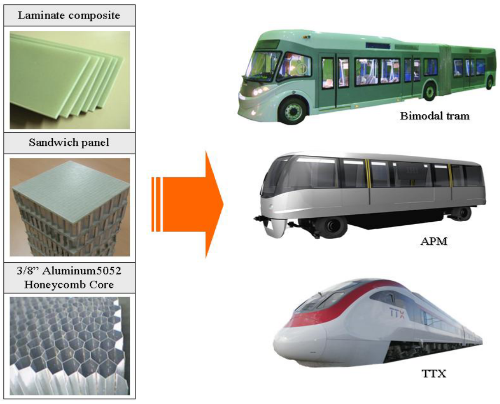


Fig. 1. Various railway vehicles made of sandwich composites.

tural test and the numerical analysis results derived by various finite element modeling methods for railway vehicles made of lightweight sandwich composites.

2. Finite element models for carbodies made of sandwich composites

2.1 Composition of the materials applied to the various sandwich composite carbody structures

To present a standardized finite element model for railway vehicles made of sandwich composites, the proposed finite element models were verified by comparing the results of the structural test and the finite element analysis for the bimodal tram, the automated people mover (APM), and the tilting train (TTX), which have been developed and are in the test run stage. Table 1 shows the materials applied to the carbody structures of the bimodal tram, the automated people mover, and the tilting train. The sandwich construction is considered for application to primary structures such as the body shell, roof, and floor, 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.

Table 2. The proposed modeling methods for composite carbody structures.

Part	Element Type	
	1st Method	2nd Method
Sandwich Panels	Layered shell*	Layered shell(Skin) + Solid(core)
Laminate Composite	Layered shell	Layered shell
Reinforced Frame	Timoshenko 3D beam	Elastic shell

**with sandwich options*

The bimodal tram had sandwich panels in the carbody and the under frame, and reinforced extruding aluminum frames to improve the structural stiffness of the vehicle. For the automated people mover and the tilting train, the sandwich panels were applied to the carbody structures only, and a stainless steel material was used for the under frame and reinforcements. Fig. 1 shows the bimodal tram, the automated people mover and the tilting train, made of sandwich composite materials.

2.2 The introduction of standardized finite element models

As shown in Table 2, two proposed finite element modeling methods were considered for each part of the carbody to present the standardized finite element model for the railway vehicle made of sandwich composite through literature survey [12, 13]. The commercial finite element software, Ansys v11.0, was used in this study.

In the first method, layered shell elements were applied to the sandwich panels and laminate composites to easily and quickly conduct the finite element modeling and analysis. The metal frame, as reinforcement, was simulated using the 3D Timoshenko beam element.

In the second method, layered shell elements were used for the laminate composites and the face sheets of the sandwich panels, and solid elements were used for the honeycomb core. The reinforced metal frame was simulated using the elastic shell elements to consider the inplane elastic behavior. The second method is based on 3D finite element modeling, which, in addition, can apply without the major modifications of modeling for crashworthiness analysis.

The description of detailed finite element modeling for each parts of composite carbody structures is as follows. The sandwich panel applied to the carbody structure was modeled as shown in Fig. 2. As mentioned, the first method is based on layered shell element, which can simulate the orthotropic materials with different properties in the thickness direction, and can reduce the modeling time. It is disadvantageous, however; the layered shell element cannot simulate the real behavior of the honeycomb core because it continues to be plain after the deformation of the honeycomb core, which is perpendicular to the neutral plane [14]. In the second method, the face sheets of sandwich panel were modeled using layered shell elements, and the honeycomb cores of sandwich panel were simulated

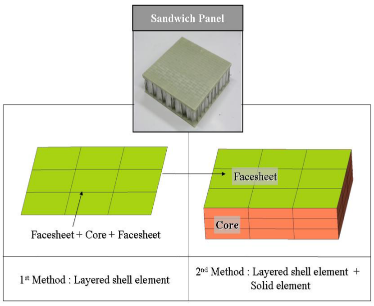


Fig. 2. The methods of finite element modeling for sandwich panels.

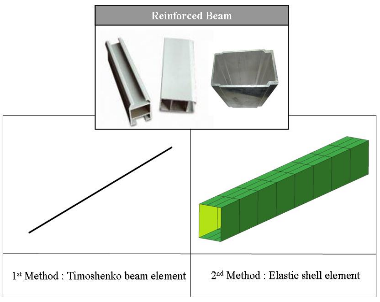


Fig. 3. The methods of finite element modeling for reinforced metal frame.

using the solid elements. For the hexagon honeycomb core, 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 [15]. This modeling method can simulate the actual behavior of the sandwich composites but requires more modeling time than the first method.

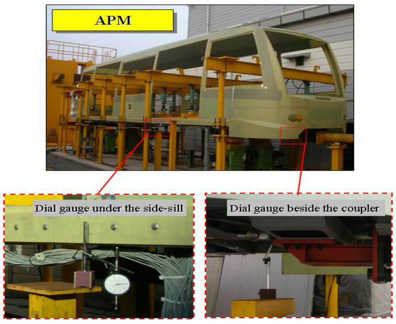
The reinforced metal frames for improving the bending stiffness of the composite carbody structure were modeled as shown in Fig. 3. The 3D Timoshenko beam element was used in the first method. The Timoshenko beam element can be generally used for FE analysis because of a reduction in modeling time and convergence time for analysis. However, this method cannot simulate the plane stress and plane strain like shell elements [16]. In the second method, the reinforced metal frames are modeled using the elastic shell elements. This method can identify the local strain of reinforcements. However, it requires a long modeling time, because the actual section of the reinforcement should be considered.

3. Verification of the proposed finite element models

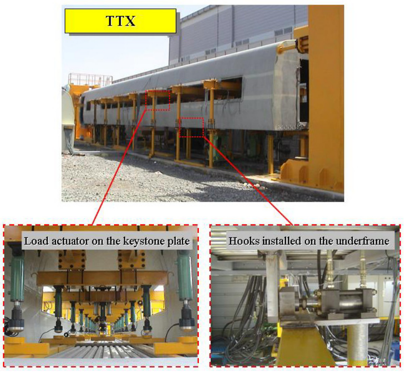
3.1 Structural test for the various railway vehicles

The tests were performed according to the railway vehicle test standard, JIS E 7105 [17], on the bimodal tram, the automated people mover, and the tilting train carbodies that were made of sandwich composites. The JIS E 7105 is composed of five tests: a vertical load test, an end compressive load test, a torsional test, a 3-point support test and a natural frequency-measuring test. The vertical load test was performed to investigate the structural behavior of the composite carbody under full weight. For the compressive load test, first, a vertical load was imposed on the keystone plate of the carbody. Then, a compressive load was applied to the coupler connection support. The torsional load test was performed to investigate the structural behavior of the composite carbody under twisting load due to the bad track condition. For the 3-point support test, first, the vertical load was imposed on the keystone plate of the carbody. Then, one of the four vertical supports was moved down to accomplish the 3-point support condition. The deflection, strain and natural frequency were measured during tests. A dial gauge was installed on the carbody bottom to measure the deflection, and strain gauges were attached to the corners of windows and doors, on which strain was concentrated, to measure the strain. Fig. 4 shows the structural test

(a) Bimodal tram

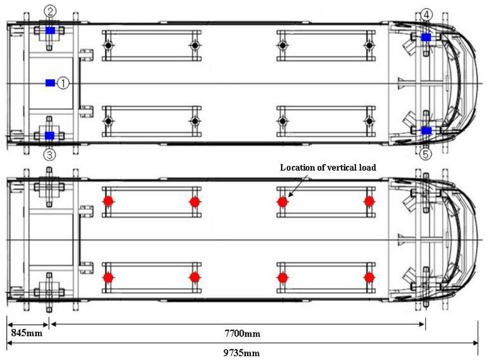


(b) APM

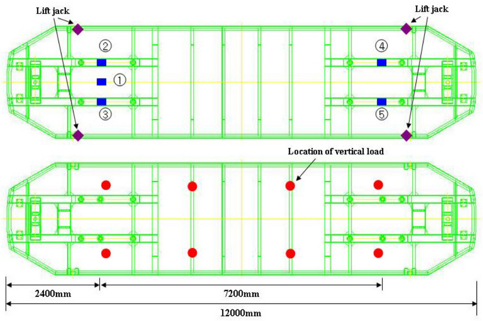


(c) Tilting train

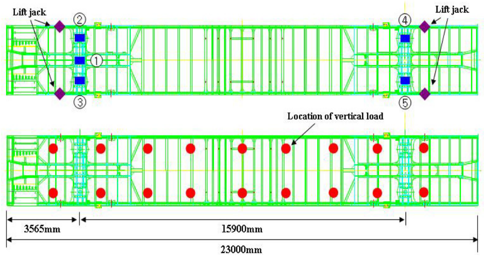
Fig. 4. Structural test equipments of various railway vehicle structures.



(a) Bimodal tram



(b) APM



(c) Tilting train

Fig. 5. The location of the vertical supports and hydraulic actuators.

equipment and location of strain gage and dial gages for the bimodal tram, the automated people mover, and the tilting train. Fig. 5 shows the location of the vertical supports and hydraulic actuators.

3.2 Comparison of the results of the structural test and finite element analysis

To develop an optimal finite element model for composite carbodies using the two proposed finite element model methods, the bimodal tram carriages (carriages 1 and 3), an automated people mover (APM), and a tilting train (TTX) were modeled as shown in Fig. 6. To simulate the boundary conditions for the structural analysis models, the degree of freedom(DOF) for the nodal displacement and rotation were constrained at supporting points using the rigid link element. The loading conditions were subjected as distributed load on the part to which the load was applied in the test. The finite element model was usually modeled in a 40~50mm element size, and the parts where stress was concentrated were more densely modeled. The element size was obtained from the prior studies, as the optimal sizes for minimizing the error and analysis time. Table 3 shows the numbers and types of the used elements according to the proposed finite element modeling method. The number of elements was greater in the second method than in the first method because of the use of solid element for honeycomb core and shell elements for reinforced metal frames. The maximum deflection, strain, and natural frequency that were measured under each load case were compared with the results of the finite element analyses. The finite element analysis was conducted using Ansys classic v12.0.

Table 3. The numbers and types of finite element according to the proposed FE modeling methods.

Vehicles		1st Method			2nd Method		
		1)1D	2)2D	Total	3)2D	4)3D	Total
Bimodal Tram	Carriage 1	10,258	112,875	123,133	127,282	38,212	165,494
	Carriage 3	7,988	67,539	75,527	75,863	23,724	99,587
APM		6,311	178,994	185,305	215,572	56,100	271,672
TTX					231,404	146,679	378,083

1) Timoshenko beam element (for reinforced frame)
2) Layered shell element (for sandwich panel)
3) Shell element (for reinforced frame)
4) Layered shell element + Solid element (for sandwich panel)

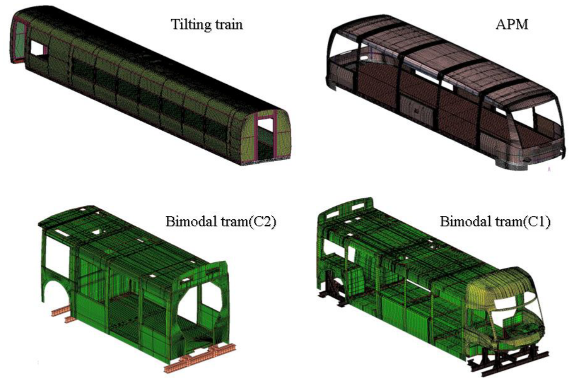
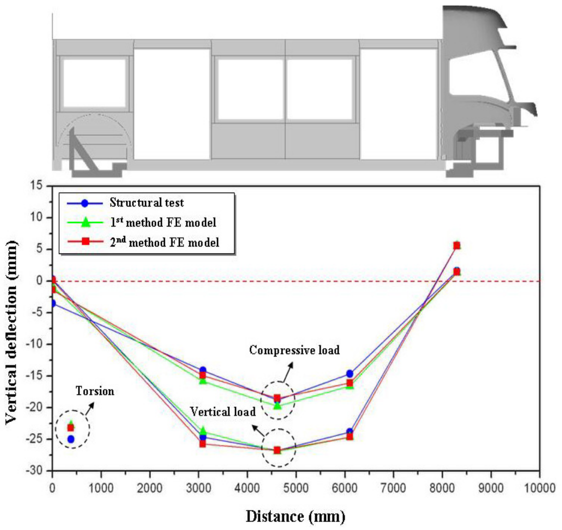


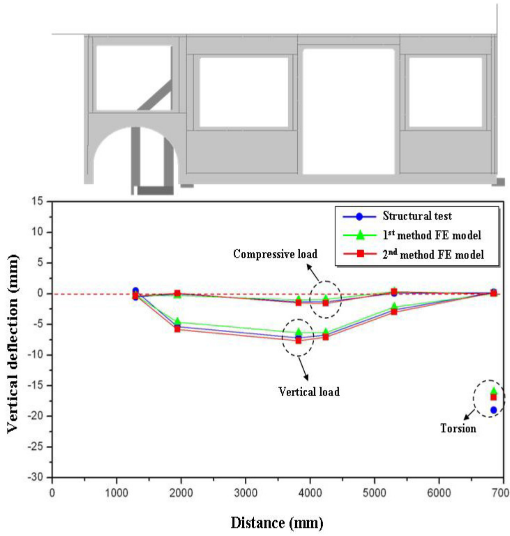
Fig. 6. The finite element model of various railway vehicles.

3.2.1 Bimodal tram case

Fig. 7 shows the results of vertical deflection between structural test and FE analysis for bimodal tram under the vertical, compressive and torsional load. In the first method, the difference between the test and analysis results was in an error range of 9.0%, except for the compressive load and torsion load of carriage 3. In the second method, the difference between the test and analysis results was in an error range of 7.2%, except for the compressive load and torsion load of carriage 3. The error was generally smaller in the second modeling method. The large error for maximum deflection



(a) Carriage 1



(b) Carriage 3

Fig. 7. The deflection graph under the vertical load of bimodal tram.

between experimental and numerical results in the compressive load for carriage 3 seems attributable to the value of small deflection measured in the structural test. For the case of the torsion load for carriage 3, in order to establish the cause of large error for the results of maximum deflection, an additional structural test was attempted, but it could not be performed because of the structural problems of the test vehicle.

Table 4 shows the comparisons of results of the maximum strain measured to the corners of the windows and doors against the vertical load, the compressive load, and the torsion. The difference of strain values between the test and FE analysis had relatively large errors that ranged from 12.0% to 43.1% in the first method, but smaller errors that ranged from 1.0% to 9.7% in the second method. The deviations of values of maximum strain according to modeling methods were because of the difference in the elements used to simulate the reinforced metal frame at the corners of the windows and doors. The Timoshenko beam element used to first modeling method could not simulate the behavior of plane direction of reinforced metal frame such as plane stress and plane strain.

Table 4. Comparisons of the value of maximum strain between structural test and finite element analysis.

	Load Type	Max. Strain (με)				
		Test	FE Analysis			
			1st Method	Error (%)	2nd Method	Error (%)
1)C1	Vertical load	-1082	-784	27.5	-1131	4.5
	Compressive load	593	406	31.5	638	7.6
	Torsion	921	524	43.1	977	6.1
2)C3	Vertical load	1087	1217	12.0	1076	1.0
	Compressive load	-651	-391	40.0	-640	1.7
	Torsion	308	430	39.6	338	9.7

1) Carriage 1, 2) Carriage 3

Table 5. Comparisons of natural frequencies between structural test and finite element analysis.

	Load Type	Natural Frequency (Hz)				
		Test	FE Analysis			
			1st Method	Error (%)	2nd Method	Error (%)
1)C1	1st Bending	10.67	11.64	9.1	11.56	8.3
	1st Twisting	3.47	4.20	21.0	4.14	19.3
2)C3	1st Bending	17.29	17.81	3.0	17.49	1.2
	1st Twisting	4.79	4.49	6.3	4.83	0.8

1) Carriage 1, 2) Carriage 3

Table 5 shows the comparisons of the test and analysis results for the first bending and first twisting natural frequencies. In the first method, the error between the test and analysis results was 9.1% or less, except for the first twisting natural frequency of carriage 1. In the second method, it was 8.3% or less, except for the twisting natural frequency of carriage 1. The large error for the first twisting natural frequency of carriage 1 between experimental and numerical results seems attributable to the value of small natural frequency measured in the structural test. However, the comparison of the test and analysis results showed that the error was smaller in the second model than in the first model.

3.2.2 Automated people mover (APM) case

Fig. 8 shows the results of deflection between structural test and FE analysis of the carbody structure of the automated people mover under the vertical, compressive and 3-point support. In the first method, the difference between the test and FE analysis results had an error of 5.7% or less, except for the compressive load. In the second method, the difference

Table 6. Comparisons of the value of maximum strain between structural test and finite element analysis.

	Load Type	Max. Strain (με)				
		Test	FE Analysis			
			1st Method	Error (%)	2nd Method	Error (%)
APM	Vertical load	-281	-232	18.5	-265	5.7
	Compressive load	-256	-218	14.9	-236	7.8
	3-Point support	1076	1454	35.1	1155	7.3

Table 7. Comparisons of natural frequencies between structural test and finite element analysis.

	Load Type	Natural Frequency (Hz)				
		Test	FE Analysis			
			1st Method	Error (%)	2nd Method	Error (%)
APM	1st Bending	8.70	8.00	8.1	8.78	0.9

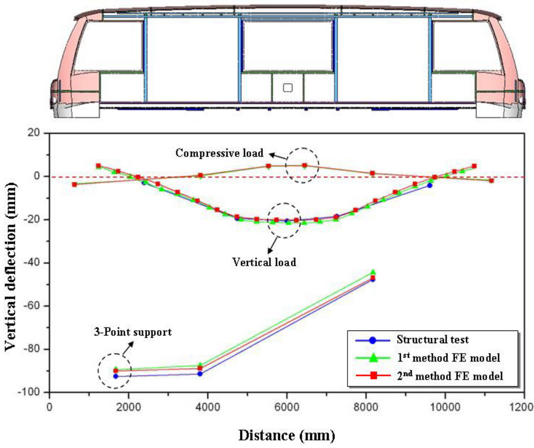


Fig. 8. The deflection graph under the vertical load of APM.

between the test and analysis results had an error of 3.0%, which was better than that in the first method. For the compressive load test, data could not be obtained due to a problem with the deflection sensor. An additional compressive test was not performed due to the plastic deformation and local buckling in the underframe to which the compressive load was applied.

Table 6 shows the comparisons of results of the maximum strain values. In the first method, the difference between the test and FE analysis results was larger from 14.9% to 35.1%. In the second method, however, the error was reduced as a range from 5.7% to 7.8%, and they coincided better than did the results of the first method.

Table 7 shows the comparison of the bending natural frequency results between experiment and numerical analysis. The results had an error of 8.1% in the first method and 0.9% in the second method, which indicates that they coincided well.

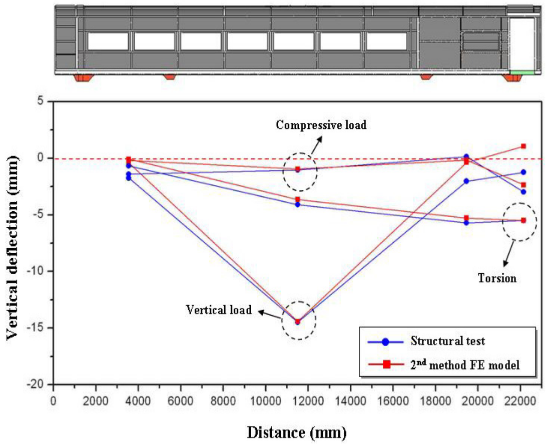


Fig. 9. The deflection graph under the vertical load of tilting train.

The proposed two finite element modeling methods were applied to the composite carbody structures of the bimodal tram and the automated people mover to compare the structural test and FE analysis results. The second modeling method had a smaller error in a comparison of experimental results. The reason is that the first modeling method could simulate the global behavior of the composite carbody structure, such as deflection under vertical loading condition, but the layered shell elements could not simulate the shear characteristics of the sandwich composites, and the Timoshenko beam element could not precisely simulate the structure behavior of plane direction of reinforced metal frame, such as plane stress and plane strain.

Therefore, in the structural analysis of the carbody structures applied to the railway vehicle made of sandwich composites, the results show that the layered shells and solid elements are suitable for the facesheet and honeycomb core of the sandwich panels, and elastic shell elements are suitable for the reinforcements.

3.2.3 Tilting train (TTX) case

The results of the experiment and numerical analysis of the bimodal tram and the automated people mover show that the second modeling method is suitable for the simulation of sandwich composite carbody structure of a railway vehicle. Therefore, for the tilting train, only the second modeling method was applied to compare and evaluate the structural behavior between experiment and numerical analysis.

Fig. 9 shows the results of deflection between structural test and FE analysis of the carbody structure of the tilting train under vertical, compressive and torsion load. The difference of experiment and analysis results was within an error range of 3.6%, except for compressive load. The large error for the compressive load is why the measured deflection value in the structural test was very small, which seems to have a large percentage of error even though the difference in the results of test and FE analysis was small.

Table 8. Comparisons of the value of maximum strain between structural test and finite element analysis.

	Load Type	Max. Strain (με)		
		Test	FE Analysis	
			2nd Method	Error (%)
TTX	Vertical load	881	841	4.6
	Compressive load	-351	-385	9.6
	Torsion	-347	-316	8.7

Table 9. Comparisons of natural frequencies between structural test and finite element analysis.

	Load Type	Natural Frequency (Hz)		
		Test	FE Analysis	
			2nd Method	Error (%)
TTX	1st Bending	10.25	10.03	2.2

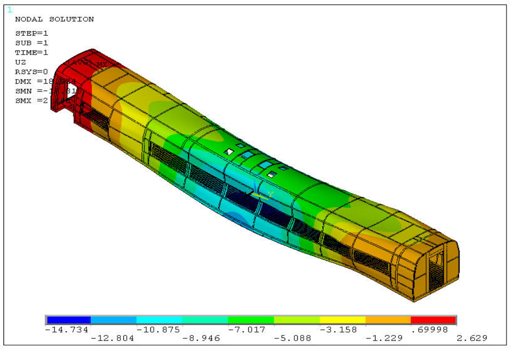


Fig. 10. The contours of deflection for vertical load.

The maximum deflection for each loading condition appeared commonly at the side structure of the carbody, and was smaller than the required maximum allowable deflection (15.97mm). Fig. 10 shows the results of the deflection contours for FE analysis under the vertical load.

Table 8 shows the comparisons of the results of FE analysis for the same location as that with the measured maximum strain in the test. The error was within a range of 10%. Table 9 shows the comparisons of the 1st bending natural frequency. The test and analysis results had an error of 2.2% or less, which indicates that they coincided relatively well and satisfied the natural bending frequency requirement for railway vehicle safety of less than 10 Hz. Through the proposed second modeling method for the composite carbody of the tilting train, it was found that the numerical results of the deflection, strain, and natural frequency coincided with the test results relatively well.

3.3 Introduction of the standardized finite element model

The above results of this study showed that the first modeling method is used for rapid design verification because of the reduction of modeling time and it can check for global behavior. However, this method cannot simulate the behavior of the bending and shear for sandwich structure. Also, it had a large error in the stain results due to the use of Timoshenko beam element. Therefore, the second modeling method, which uses layered shell, solid and elastic shell elements, is proposed for finite element analysis for the vehicle structure of the railway made of sandwich composite. Also, the proposed finite element model can be used for crashworthiness analysis just by minor modifications such as contact condition and constraint equation. The failure mode and deformation results of sandwich composite structure for the crashworthiness simulation can be also confirmed.

4. Conclusions

A standardized finite element model of railway vehicle structure made of sandwich composite was proposed by comparing the results of a structural test and a finite element analysis. The conclusions of this paper are as follows:

(1) Two modeling methods were proposed as the finite element modeling methods for the railway vehicle structure made of sandwich composites. The results of the structural test of the bimodal tram, the automated people mover, and the tilting train carbody structure were compared and evaluated with each analysis result.

(2) The first modeling method with layered shell and Timoshenko beam elements enabled easy and rapid finite element modeling and analysis, but was useful only for evaluating the global behavior due to the characteristics of the elements. The second modeling method with layered shell, solid and elastic shell elements was in a good agreement with those test results, such as deflection, strain and natural frequency, although it takes a long time and costs much for FE modeling.

(3) The quadratic shell element is suitable for modeling the reinforced metal frame used to improve the flexural stiffness of sandwich panels compared to beam elements, and layered shells and solid elements are recommended for modeling the skin and honeycomb core of the sandwich panel compared to sandwich shell element. Therefore, the second modeling method was proposed for the standardized finite element model of the carbody structure made of sandwich composite.

(4) When the carbody structure made of sandwich composite is developed, the proposed standardized finite element model could more accurately predict its structural behaviors and reduce the process of trial and error between experiments and numerical analysis. Also, it can be applied to the crashworthiness analysis just by minor modification, such as contact condition and constraint equation.

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