A study on the crashworthiness and rollover characteristics of low-floor bus made of sandwich composites [†]

Hee-Young Ko[1], Kwang-Bok Shin[2,*], Kwang-Woo Jeon[1] and Seo-Hyun Cho[3]

[1]*Graduate School of Mechanical Engineering, Hanbat National University, Daejeon, 305-719, Korea*
[2]*Division of Mechanical Engineering, Hanbat National University, Daejeon, 305-719, Korea*
[3]*Transit Division, HanKuk Fiber Glass Co., LTD., 627-850, Korea.*

Abstract

This paper describes the results of the numerical evaluation on crashworthiness and rollover characteristics of a low-floor bus vehicle made of sandwich composites. The sandwich composite used for the vehicle structures was composed of aluminum honeycomb core and WR580/NF4000 glass-fabric/epoxy laminate facesheets. Material tests were conducted to determine the input parameters of the composite laminate facesheet model and the effective equivalent damage model for the orthotropic honeycomb core material. Crashworthiness and rollover analysis of the low-floor bus was conducted using the explicit finite element method (FEM) analysis code LS-DYNA3D with the lapse of time. The crash condition of the low-floor bus was a frontal accident with a speed of 60 km/h. Rollover analysis was done according to the safety rules of the European standards (ECE-R66). The angular and translation velocity and its angle with the ground just before impact for rollover were calculated using the dynamic analysis program. The results showed that the survival spaces for the driver and passengers were secured against frontal crashworthiness and rollover of the low-floor bus. In addition, the modified Chang-Chang failure criterion is recommended to predict the failure modes of the composite structures for crashworthiness and rollover analysis.

Keywords: Honeycomb sandwich composite; Crashworthiness analysis; Rollover analysis; Effect equivalent damage model

---

1. Introduction

The current heavy traffic of ground transportation is aggravated due to the increase in the number of private cars. With regard to the environmental impact, the increase in the volume of number of exhaust fumes in accordance with the increasing number of cars severely causes environmental pollution and global warming. To solve these problems, several countries have developed advanced thermoplastic composite materials and manufacturing technologies to reduce the weight of the bus and tram vehicle [1].

Composite sandwich panels are widely used in lightweight structures because of their high specific strength and stiffness [2]. Recently, the use of sandwich composite structures has been developed in Korea for ground transportation applications such as the tilting train, low-floor bus, and tram vehicle [3-4].

The safety of the driver and passengers according to frontal crashworthiness and rollover accident has become an important issue for bus manufactures and customers. Therefore, the structural stability of the vehicle should be evaluated according to the regulation of frontal crashworthiness and rollover before the manufacturing of buses. This regulation has been continued to cover buses made of conventional materials such as stainless steel or aluminum. However, there is no regulation standard for bus structures made

of composites. For some reason, the enforcement proposal for the crashworthiness and rollover test of buses in Europe and Japan has been suggested based on the statistics of bus accidents [5]. The European regulation "ECE-R66" is applied to prevent catastrophic rollover accidents. In this study, these regulations are suggested as standards for the evaluation of securing the survival spaces of the passengers and the driver.

The objective of this study is to evaluate the structural dynamic integrities of a low-floor bus made of composites through the frontal crashworthiness and rollover analysis. Crashworthiness and rollover analysis of a bus is carried out using the explicit finite element method (FEM) analysis code LS-DYNA3D, confirming the deformation of the vehicle structure and the failure modes of the sandwich composite structures. The failure modes of the sandwich composite structures are examined using the modified Chang-Chang failure criterion. The mechanical properties of the laminate composites and aluminum honeycomb core are obtained by coupon tests according to the ASTM standard.

2. Manufacturing concept and finite element model of the low-floor bus

2.1 Description of the low-floor bus

The low-floor bus is developed using a hybrid design concept combined with honeycomb sandwich and laminated composite structures. 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. Fig. 1 shows the manufacturing concept of the low-floor bus made of composites.

Table 1 shows the constructions of the sandwich panel used in the body shell, floor, and roof structures of a low-floor bus. Sandwich panels are composed of a woven glass fabric/epoxy laminate facesheet and aluminum 5052 honeycomb core. The outer facesheet of the sandwich panel has a thickness that is twice thickness of the inner facesheet to save on additional cost and weight. The facesheets of the sandwich panel are laminated with woven glass fabric/epoxy prepreg. This glass fabric has five-hardness satin weaves, with the same tow count in the warp and fill-direction. The

Table 1. The construction of the sandwich panels of a low-floor bus.

Name	Facesheet material	Core material	Thickness $(t_O/t_C/t_I)$
GE/AH	Glass fabric/ Epoxy (WR580/NF4000)	Aluminum 5052 Honeycomb (Cell size : 3/8" / thickness : 0.0025")	3.0/25.4/1.5

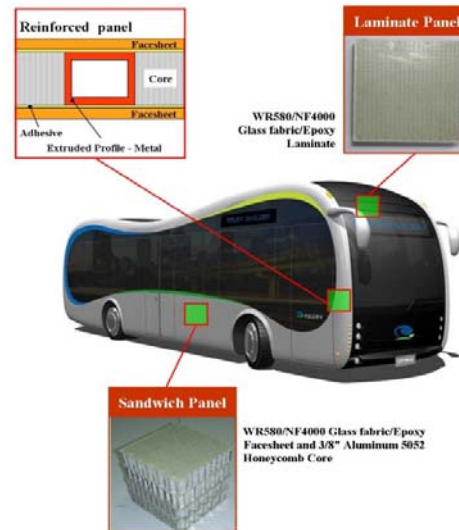t_O: outer facesheet, t_C: core, t_I: inner facesheet

Fig. 1. Design concept of a low-floor bus.

woven glass fabric/epoxy laminates have the dimensions of the sandwich with facesheets of unequal thickness. The core used in the sandwich panels is aluminum honeycomb with a thickness of 25.4 mm.

2.2 Finite element model

The vehicle structure is modeled as a combination of shell, solid, beam, and spring elements. A four-node Belytschko-Tsai shell element is used for modeling the composite facesheet and reinforced beam, while eight-node solid elements are employed to model the effective equivalent honeycomb core. Previous research shows that the effective equivalent damage model of a honeycomb core has confirmed the small error range of experimental and numerical simulations [6].

The finite element model with 149,510 elements has 28 defined property sets and 13 material models. The solid models of the CNG tank, engine, and air conditioner apply weight on each part. All parts are connected using different multi-point constraints and

Table 2. The modified Chang-Chang failure criterion in LS-DYNA3D.

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

$\sigma_x, \sigma_y, \tau_{xy}$: stress of principal material direction,; X_t, Y_t : Tensile strength of fiber and matrix direction; Y_c, 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; md : shearing mode of fiber & matrix

special links to the actual types of structural connections such as bolts and spot welds. Contact represents the interaction between the adjoining parts.

2.3 Definition of the material attributes

The LS-DYNA3D material model #24 (*MAT_ PIECEWISE_LINEAR_PLASTICTIY) is used for the stainless steel material of the shell element, while the LS-DYNA3D material model #54 (*MAT_ ENHANCED_COMPOSITE_DAMAGE) is used for the WR580/NF4000 glass fabric/epoxy facesheet of the shell element. These constitutive models are based on the theory of continuum damage mechanic. It is assumed that the deformation of the materials introduces micro-cracks and cavities, which reduce the material stiffness. This is expressed through the internal damage parameters that describe the evolution of the damage state under loading, hence the stiffness degradation [7].

The basis of the model is the modification made by Matzenmiller [8] to the well-known Chang and Chang composite damage model [9]. The Chang and Chang failure criterion is utilized by the model to

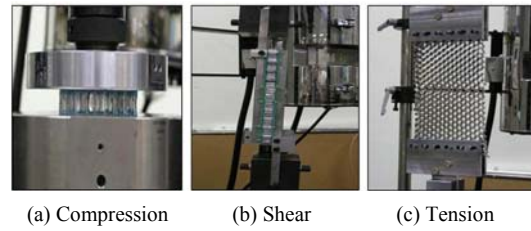(a) Compression   (b) Shear   (c) Tension

Fig. 2. Various types of aluminum honeycomb core test.

predict matrix cracking, compressive failure, and fiber breakage of the laminate. The modified Chang and Chang failure criterion is shown in Table 2.

The LS-DYNA3D material model #126 (*MAT_ MODIFIED_HONEYCOMB) is used for the honeycomb core material of the solid element. In this orthotropic material model, the nonlinear elastoplastic constitutive behavior is used based on the experimentally determined stress-strain curve.

2.4 The effective equivalent damage model of the aluminum honeycomb core

The 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 ASTM standards. The honeycomb core test is comprised of compression (ASTM C365), tension (ASTM C363), and shear (ASTM C273). Fig. 2 shows the various components of the of honeycomb core test [10-12].

The two main components of the honeycomb core test are the compressive and flatwise shear tests [13]. In the compressive test, the core compressive strength and modulus are determined. The compressive test specimen size is 75 mm x 75 mm, and the thickness of the aluminum honeycomb core is 20mm with a laminate composite facesheet of 1 mm. The flatwise shear test is probably the most important honeycomb test. Through this test, the strength and modulus of the honeycomb core shear are determined. The test specimens of the flatwise shear test are bonded to 12.7 mm thick steel plates at the edge of the core material. The tensile test of the honeycomb core is also called the core delamination test. The test specimen consists of putting pins on the top and bottom rows, with a width of 130 mm and lengths of 260 mm, of honeycomb core and then pulling the core apart. In this test, the failure mode manifest from the peeling of the nodes.

Table 3. The effective equivalent mechanical properties of the honeycomb core.

Case	Strength (MPa)	Elastic modulus (MPa)
Compression	1.30	105.50
Shear	1.03	19.40
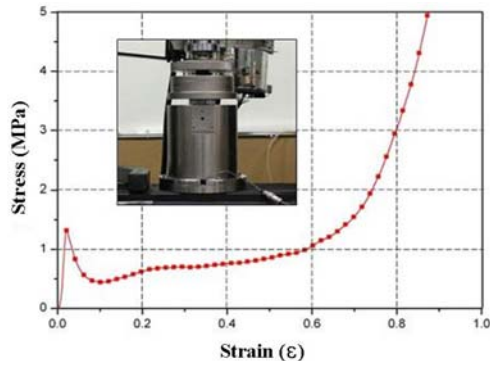
(a) Compressive test
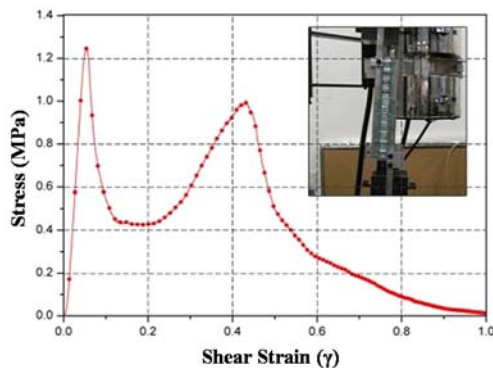
(b) Shear test

Fig. 3. The stress-strain curve for the aluminum honeycomb core.

Fig. 3 shows the stress-strain curves for the aluminum honeycomb core as obtained by the tests. The material properties of the honeycomb core are listed in Table 3.

3. Frontal crashworthiness analysis of the low-floor bus

3.1 Crashworthiness condition

In the frontal crashworthiness analysis, rigid boundaries were used to simulate a stone wall and roads. A set of nodes on the bus model was specified so that it could not penetrate the rigid wall. When contact occurred, the components of the velocity of
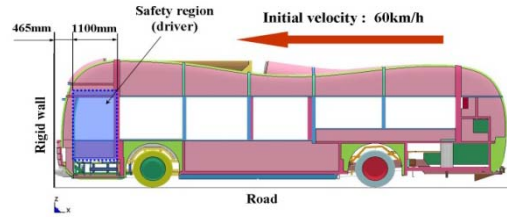

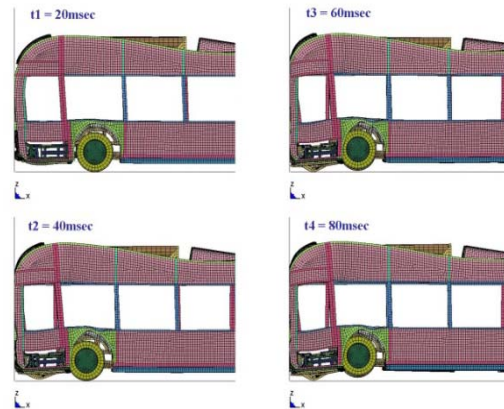Fig. 4. The initial condition of the crashworthiness analysis.

Fig. 5. The sequence of deformation for a frontal crashworthiness event.

the contacting nodes in the normal direction were zero, while it was subject to the friction coefficient in the tangential direction. Each node in the model had the same translational initial velocity of 60 km/h, with zero rotational velocities as shown in Fig. 4. The distance from the rigid wall to the seat of the driver was 465 mm, and the length of the safety region of the driver was 1100 mm. As the regulations on the driver's safety space to the frontal crashworthiness of the bus was not specified, the space of 1100 mm from the location of the driver's seat was selected as the safety space. This confirmed the possibility of penetration due to the car body's deformation.

3.2 Results of the crashworthiness analysis

The deformation of the vehicle and the failure mode of the composite structure were obtained from the frontal crashworthiness analysis. Fig. 5 shows the sequence of deformation of the vehicle in relation to the lapse of time. The maximum deformation of this crashworthiness analysis was 316 mm, which occurred between the stone wall and safety region of the driver. Fig. 6 shows the history curves of the kinetic energy and internal energy, as well as the total energy
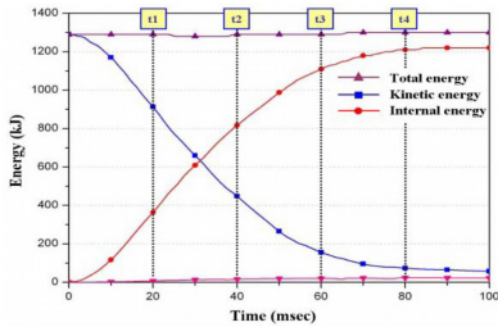
Fig. 6. Energy history curve of the frontal crashworthiness simulation.

(a) The tensile failure mode of matrix (e^2_{mt})

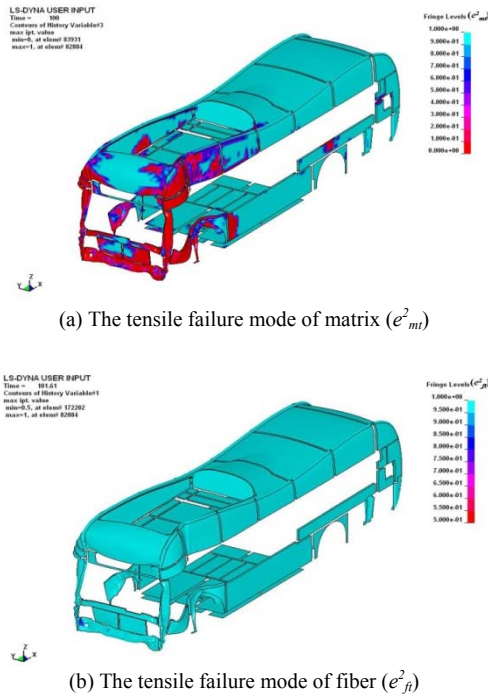(b) The tensile failure mode of fiber (e^2_{ft})

Fig. 7. Failure index contours of composite carbody structure using modified Chang-Chang failure criterion for the crashworthiness event.
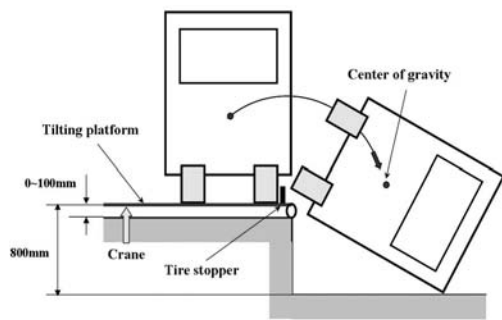

Fig. 8. Specifications of the rollover test.

over time. The kinetic energy of the carbody structure was 1.29 MJ before contact with the rigid wall. In addition, the increase of internal energy and decrease of kinetic energy crossed at 30 msec.

Fig. 7 shows the tensile failure mode of the matrix and fiber for the composite structures of the vehicle. In this process, the failures of composites are considered to result to a damaged state when the damage index turns out to be more than 1 in accordance with the modified Chang-Chang failure criterion. Furthermore, although the damage index turns out to be less than 1, it cannot be considered as a perfectly safe situation because the failures of the composites drastically increase with non-linearity.

4. Rollover analysis of the low-floor bus

4.1 Rollover condition

The rollover analysis of the bus was examined using the European regulation ECE-R66 [14]. According to this regulation, a passenger's survival space is secured against the deformation of the vehicle structure during or after the rollover. This ensures that the bus structure has sufficient strength to avoid the penetration of the deformation into the survival space.

In order to simulate the situation of the rollover of the bus, the bus model was placed on the tilting platform and was tilted slowly from its position. The tire stopper of the tilting platform prevented the sliding motion of the bus tires. The bus platform, according to ECE-R66, was pulled up by a crane rotational speed of one degree per second to let the bus roll over. The height difference between the horizontal lower plane of the ditch and the plane of the tilting platform on which the bus was standing was 800 mm. The axis of its rotation was 100 mm maximum from the verti-
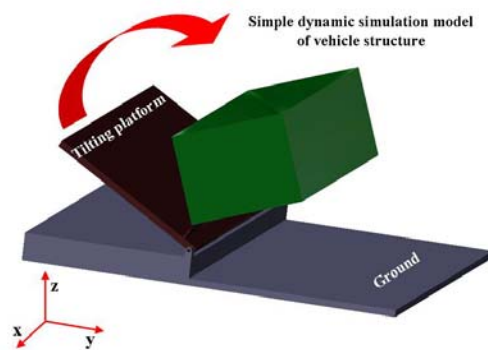

Fig. 9. The dynamic simulation model for the rollover test.

Table 4. Angular and translation velocity during rollover of the bus.

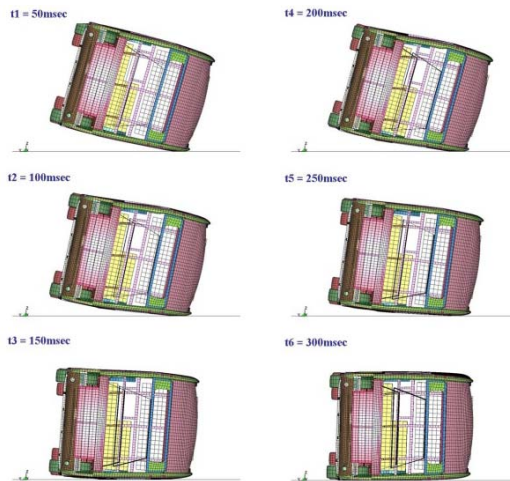| Types	Value
Angular velocity in X-axis	0.398 rad/sec
Angular velocity in Y-axis	0.297×10^{-3} rad/sec
Angular velocity in Z-axis	0.157×10^{-3} rad/sec
Translation velocity in X-axis	2.407 mm/sec
Translation velocity in Y-axis	689.420 mm/sec
Translation velocity in Z-axis	-2081.110 mm/sec

Fig. 10. The sequence of deformation for the rollover test.
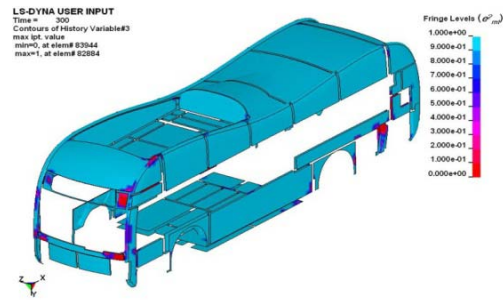

Fig. 11. Failure index contours of the composite carbody structure using the modified Chang-Chang failure criterion for the rollover event.

the rollover analysis.

4.2 Results of the rollover analysis

The deformation of the vehicle and the failure mode of the composite structure were obtained from the rollover analysis. The rollover analysis was conducted until the vehicle and ground touched each other completely. Fig. 10 shows the sequence of the deformation of the vehicle with the lapse of time. In the rollover analysis, the maximum deformation of 100 mm occurred on the side frame. Fig. 11 shows the tensile matrix failure mode of the composites laminate applied to the vehicle structure. The failure of the fiber did not occur in the rollover analysis.

5. Conclusion

The low-floor bus was the first development project subjected to the weight limit regulations for intercity buses in Korea. The low-floor bus was developed using a composite structure with high stiffness towards weight and strength to weight ratios for the reduction of the weight of the vehicle. The sandwich composite used for the vehicle structures was composed of aluminum honeycomb core and WR580/ NF4000 glass-fabric/epoxy laminate facesheets.

This paper discussed the results of the numerical simulation on crashworthiness and rollover characteristics of the low-floor bus. The crash condition of the low-floor bus was a frontal accident with a speed of 60 km/h. Rollover analysis was done according to the ECE-R66. To perform the FEM analysis on the crash and overturn of the low-floor bus where the aluminum honeycomb sandwich panel was applied, as shown in Fig. 3, the basic property test of the specimen was conducted. These experimental data were

cal wall of the ditch and 100 mm maximum below the plane of the horizontal tilting platform. When contact of the vehicle with the ground occurred, the sliding motion was restricted by the friction coefficient. The passengers' weight applied to the vehicle structure was 2,800 kg. The tilting table geometry is shown in Fig. 8.

The initial velocity was applied to the bus for the reduction of analysis time. The initial velocity was calculated using the ADAMS program when the vehicle structure started to hit the ground. Furthermore, the center of gravity of the vehicle was calculated using the CATIA program. Fig. 9 shows the dynamic simulation model applied to the center of gravity of the vehicle using the ADAMS program to calculate the angular velocity and parallel moving velocity of the vehicle.

All angular and translational velocities of the bus block from its first contact point with the ground were noted down, as listed in Table 4. At this time, the y and z direction angular velocity was not considered in

used as an input for the FEM analysis. Likewise, the result of the low velocity crash test on the sandwich panel specimen in conventional research and the result of the FEM analysis using our model were well-corresponded. The frontal crashworthiness and rollover analysis led to the following conclusions:

(1) The frontal crashworthiness analysis of a bus made of honeycomb sandwich composite showed that the safety region of driver was secured. In addition, the rollover analysis of the bus showed that the survival space of passengers was secured. It should be noted that passengers' weight was considered.

(2) In this study, the effective equivalent damage model was used to simulate effectively the orthotropic material properties of the real honeycomb core. The effective equivalent damage model for the honeycomb core was obtained by coupon tests such as tension, compression, and shear. As a result, the use of the effective equivalent damage model for honeycomb core could reduce the time of calculation and modeling work without the error between the real and effective models.

In this process, the properties of the effective equivalent damage model were reduced from 8,904 to 3,080 or 65% in comparison with the real model. Thus, the time of analysis convergence was shortened, and the modeling time was reduced compared with the real honeycomb configuration.

(3) In order to check the failure modes of the matrix and fiber for the composite structure of the bus vehicle, the modified Chang-Chang failure criterion was used in the frontal crashworthiness and rollover analysis. The modified Chang-Chang failure criterion is recommended to predict the failure modes of the composite structures before the crashworthiness and rollover test of a real vehicle.

Acknowledgment

References

[1] Martec Limited Prevost Car, Intercity Bus Weight Reduction Profram Phase, (2000).

[2] C. C. Foo, G. B. Chai and L. K. Seah, A Model to Predict Low-Velocity Impact Response and Damage in Sandwich Composite, *Composites Science and Technology,* Vol. 68 (2008), 1348-1356.

[3] J. S. Kim, S. J. Lee and K. B. Shin, Manufacturing and Structural Safety Evaluation of a Composite Train Carbody, *Composite Structures,* Vol. 20, No. 9 (2007), 465-476.

[4] J. Y. Lee, K. B. Shin and S. J. Lee, A Study on Failure Evaluation if Korean Floor Bus Structure made of Hybrid Sandwich Composite, *Korean Society of Automotive Engineers,* Vol. 15, No. 6 (2007), 50-61.

[5] Pankaj S. Deshmukh, Rollover and Roof Crush Analysis of Low-Floor Mass Transit Bus, *Ambedkar Marathwada University* (2002).

[6] J. Y. Lee, K. B. Shin and J. C. Jeong, Simulation of Low Velocity Impact of Honeycomb Sandwich Composite Panels for the BIMODAL Tram Application, *Korean Society for Composite Materials,* Vol. 20, No. 4 (2007), 42-50.

[7] M. Q. Nguyen, S. S. Jacombs, R. S. Thomson, D Hachenberg and M. L. Scott, Simulation on Impact on Sandwich Structures, *Composite Structures,* 67 (2005), 217-227.

[8] A. Matzenmiller, J. Luvliner and R. L. Taylor, A Constitutive Model for Anisotropic Damage in Fiber-Composites, *Journal of Mechanical of Materials,* 21 (1995), 125-152.

[9] F. K. Chang and K. Y. Chang, A Progressive Damage Model For Laminated Composite containing Stress Concentrations, *Journal of Composite Materials,* 21 (1987), 834-855.

[10] ASTM C 365, Flatwise Compressive Properties of Sandwich Cores.

[11] ASTM C 273, Shear Properties of Sandwich Core Materials.

[12] ASTM C 297, Flatwise Tensile Strength of Sandwich Constructions.

[13] Tom Bitzer, Honeycomb Technology, *Hexcel Corporation,* (1997).

[14] United Nations, Addendum 65: Regulation No. 66, Uniform Provisions Concerning the Approval of Large Passenger Vehicle with Regard to the Strength of their Superstructure (1986).

Kwang-Bok Shin received his Ph.D. degree in Mechanical Engineering from the Korea Advanced Institute of Science and Technology (KAIST), Korea, in 2000. Dr. Shin is a Professor at the Department of Mechanical Engineering at Hanbat National University in Daejeon, Korea. He is a regular member of the Korean Society for Aeronautical and Space Sciences, the Korean Society for Composite Materials, the Korean Society for Mechanical Engineers, the Korean Society for Precision Engineering, the Korean Society for Railway, and the Korean Society for Automotive Engineers.

Hee-Young Ko received his B.S degree in Mechanical Design Engineering from the Hanbat National University, in 2009. Now he is in a graduate school at Mechanical Design Engineering at Hanbat National University. Also, He is working as a research engineer at the LS-CAE lab in Hanbat National University. His research interests are optimization design & CAE.

Kwang-Woo Jeon is in a Mechanical Design Engineering at Hanbat National University. Alos, He is working as a research engineer at the LS-CAE lab in Hanbat National University. His research interests include impact behavior of composite materials and structural analysis.

Seo-Hyun Cho received his B.S degree in Mechanical Design Engineering from the Kyungnam University, in 1991. He then resived his M.S degree form the Hanbat National University, Korea, in 2008. Now he is working as a managing director at the transit division at Hankuk Fiber Glass, in Miryang, Korea.