論 文

# 복합재 튜브를 이용한 고속 열차의 에너지 흡수장치에 대한 실험 및 수치해석 연구

Cao-Son Nguyen*, 장홍규*, 신재환*, 손유나*, 김천곤**+

# Experimental and Numerical Studies on Composite Tubes for the Energy Absorber of High-speed Train

Cao-Son Nguyen*, Hong-Kyu Jang*, Jae-Hwan Shin*, Yu-Na Son*, Chun-Gon Kim**+

## ABSTRACT

This paper presents an experimental and numerical study on composite tubes for the energy absorber of the high-speed train. The purpose of the experimental study is to find out which lay-up is the best lay-up for the energy absorber. Four lay-ups were tested using quasi static method: $[0/45/90/-45]_4$, $[0]_{16}$, $[0/90]_8$, $[0/30/-30]_5$. Two triggering methods were used to create initial damage and guarantee the progressive collapse mode: bevel edge and notch edge. As a result, $[0/45/90/-45]_4$ lay-up was find out the best lay-up among the laminates being tested. In the numerical study, a parametric analysis was done to find out the most proper way to simulate the quasi static test of a composite tube using LS-DYNA program. A single composite tube was modeled to be crashed by a moving wall. Comparison between simulation and experiment was done. Reasonable agreement between experiment and analysis was obtained. Dealing with parameter TFAIL and the mass scaling factor, this parametric study shows the ability and the limitation of LS-DYNA in modeling the quasi static test for the composite tube.

## 초 록

본 논문에서는 복합재료 튜브를 이용한 고속 열차의 에너지 흡수장치에 대한 실험 및 수치 해석에 관한 연구를 수행하였다. 논문의 목적은 에너지 흡수장치에 대한 최적의 적층(lay-up) 형태를 알아내는 것으로, quasi static method를 이용한 네 가지 적층 형태에 대한 실험을 수행 하였다: $[0/45/90/-45]_4$, $[0]_{16}$, $[0/90]_8$, $[0/30/-30]_5$. 실험을 위해 초기 파괴 시작점을 생성하고, 일정 방향으로 진행되는 파괴를 만들기 위해 베벨 엣지(bevel edge)와 노치 엣지(notch edge)의 두 가지 트리거링 방법을 이용하였다. 저속 충돌실험 결과 $[0/45/90/-45]_4$의 적층 형태가 다른 방법과 비교해서 가장 좋은 에너지 흡수 결과를 보여주었다. 수치해석을 위해 LS-DYNA 프로그램의 변수 분석(parametric analysis)을 통해 가장 적합한 복합재료의 quasi static 실험 시뮬레이션 방법 연구를 수행하였다. 움직이는 벽이 복합재 튜브에 저속 충돌하는 모델을 가정하여 해석을 수행하였으며, 실험값과 수치해석 결과의 비교를 통해 비슷한 경향을 보임을 확인 하였다. 특히 TFAIL과 mass scaling factor를 조절하며 수행하는 변수 분석은 LS-DYNA에서 복합재 튜브의 quasi static 실험을 시뮬레이션 하는 능력과 한계를 보여준다.

**Key Words :** 복합재 튜브(Composite tubes), 에너지 흡수(Energy absorption), LS-DYNA(LS-DYNA), 준정적 실험(Quasi static test)

접수: 2010년 1월 19일, 수정: 2010년 12월 17일, 게재승인: 2010년 12월 22일

* KAIST 기계항공시스템학부 항공우주공학전공 대학원
**+ KAIST 기계항공시스템학부 항공우주공학전공, 교신저자(E-mail:cgkim@kaist.ac.kr)

## 1. Introduction

The centrifugal force at the curve is one of the obstructions for the train manufacturers when designing high-speed train. To overcome this kind of difficulty, there are two solutions: one is to tilt the rail, the other is the train has to tilt itself. One disadvantage of the first method is that, tilting tracks can only be dedicated to a specific speed; meanwhile, the tilting train can be operated on any kind of the existent conventional railways. This point makes the method of tilting train more preferred than the method of tilted rail in the development of high-speed train. This paper presents an experimental and numerical study on composite tubes for the energy absorber of the high-speed train. The operating conditions of Korea TTX were used in order to find out the best lay-up for the energy absorber of high-speed train.

The Korean TTX is a tilting train that can tilt itself to a maximum angle of $8^0$ at the corner to maintain high speed during operating time [1]. The information of this train is given in Table 1. Compare to other high-speed trains in the world, the Korean TTX is more light weight and has lower operating speed. During the operating time, the crash worthiness is very important to any vehicle. Based on the crash worthiness standards for the high-speed trains from the United Kingdom and USA [2,3,4,5], a requirement for energy absorption of the driving car of the Korean TTX is suggested as in Table 2.

**Table 1 Information of Korean TTX**

| | | | |
|---|---|---|---|
| Max. design speed (km/h) | 200 | Length (m) | 143 |
| Max. operating speed (km/h) | 180 | $N_o$ of seats | 346 |
| $N_o$ of cars | 6 | $N_o$ of motors | 16 |
| Weight (ton) | 344 | Tilting angle | $8^0$ |

**Table 2 Suggested crash worthiness requirement for the Korean TTX's driving car**

| | |
|---|---|
| Energy absorption | 2MJ |
| Peak load | < 2MN |
| Stroke | 75 cm |
| Deceleration | < 5g |

The main method for energy absorption of vehicles is using tubular structure. In the past metal is often used but nowadays, composite is being used more and more as the material for the energy absorption mechanism of vehicles, thank to its high energy absorption (EA) and specific energy absorption ($E_S$, tens to hundreds kJ/kg). This paper will study the carbon / epoxy composite tubes for the high-speed train's energy absorber experimentally and numerically.

When a collision occurs, the energy absorption and specific energy absorption of the tube can be calculated by the following equations:

$$EA = \int F.dx \qquad E_S = \frac{EA}{\rho A S_b}$$

Where F is the longitudinal force, x is the crush distance, $S_b$ is the final crush distance, A is the cross section of the composite tube, ρ is the density of the material. A composite laminate can be failed in 4 modes: fragmentation crushing, splaying crushing, brittle fracturing crushing and progressive folding crushing [6]. The factors that have effect on the energy absorption of a carbon fiber reinforcement polymer (CFRP) composite laminate are: fiber type, matrix type, fiber direction, specimen geometry, process conditions, fiber volume fraction, and test speed. A study by Farley [7] shows that increase in the fiber strain to failure causes smaller energy absorption. For matrix, the same trend happens in the case of ductile CFRP composite, but in the case of brittle CFRP composite, the contrary occurs. Another study by Farley [8] on the effect of fiber orientation for $[0\pm\Theta]_4$ carbon/epoxy composite showed that ES decreases when increasing Θ up to 45° and remains constant when Θ is above 45°. Thornton and Edwards [9] studied the geometrical effects in energy absorption of composite material and concluded that, for a given fiber lay-up and tube geometry, $E_S$ follows the order: circular > square > rectangle > triangle. Besides, the energy absorption will be a decreasing nonlinear function of the diameter to thickness ratio (D/t). The processing conditions also affect the crashworthiness. During making process, if vacuum is applied, it will reduce the matrix volume fraction and improve consolation, thus provide higher EA and $E_S$ [10]. The effect of fiber volume fraction is more complicated. It is not always true that an increase of the fiber volume fraction will improve $E_S$. At low fiber volume fraction, increase in fiber volume fraction can lead to increase in energy absorption. But at high level of volume fraction (>40%), the contrary will occur [6]. Different test speeds can lead to different collapse modes of the composite laminate, thus different energy absorptions. The two methods for the crash test are impact test and quasi static test. While impact test is a true crash simulation since it applies high test speed which is similar to the real crash and takes into account the strain rate, quasi static test is not a true crash simulation since it applies a very low and constant test speed.

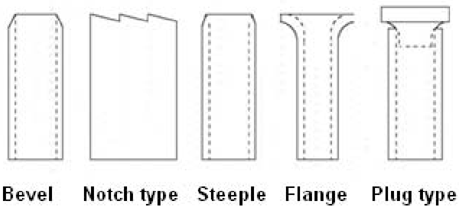



**Fig. 1 Triggering methods.**

**Table 3 Material's properties for CU125NS**

| Properties | Symbol | Value |
|---|---|---|
| Density (kg/m$^3$) | ρ | 1570 |
| Elastic modulus in fiber dir. (GPa) | $E_1$ | 135.4 |
| Elastic modulus in transverse dir. (GPa) | $E_2$, $E_3$ | 9.6 |
| Shear modulus in 1-2 and 1-3 dir. (GPa) | $G_{12}$, $G_{13}$ | 4.8 |
| Shear modulus in 2-3 dir. (GPa) | $G_{23}$ | 3.2 |
| Poisson's ratio | $\upsilon_{12}$, $\upsilon_{13}$ | 0.31 |
| | $\upsilon_{23}$ | 0.52 |
| Tensile strength in fiber dir. (MPa) | $X_T$ | 1933 |
| Compressive strength in fiber dir. (MPa) | $X_C$ | 1051 |
| Tensile strength in transverse dir. (MPa) | $Y_T$ | 51 |
| Compressive strength in transverse dir. (MPa) | $Y_C$ | 141 |
| Shear strength (MPa) | S | 61 |

**Table 4 The specimens' dimensions**

| | Length (mm) | Outer diameter (mm) | Thickness (mm) |
|---|---|---|---|
| $[0/45/90/-45]_4$ | 160 | 100 | 1.8 |
| $[0/90]_8$ | 115 | 100 | 1.8 |
| $[0]_{16}$ | 115 | 100 | 1.8 |
| $[0/30/-30]_5$ | 115 | 100 | 1.7 |

For both test methods, triggers should be used to provide the initial damage and guarantee the progressive collapse mode. The common triggering methods are: bevel, notch, steeple, flange and plug type.

## 2. Experimental study

The specimens were fabricated using the material CU125NS, whose mechanical properties are provided in Table 3. Totally 4 different lay-ups were tested using quasi static method to find out the best lay-up for the energy absorber: $[0/45/90/-45]_4$, $[0/90]_8$, $[0]_{16}$, and $[0/30/-30]_5$. The specimens' dimensions are given in Table 4. Two triggering methods were used to provide the initial damage and ensure the progressive collapse: bevel edge and notch edge. The angle of the bevel is 45°, and the notch edge was cut to create a slope of 5°.

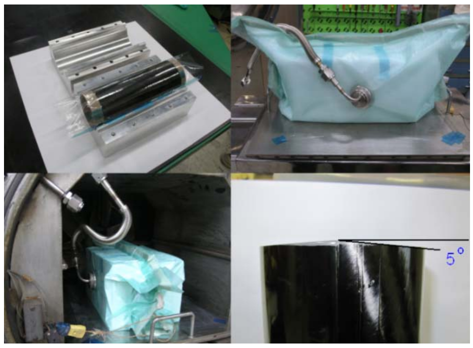



**Fig. 2 The making of the specimens.**

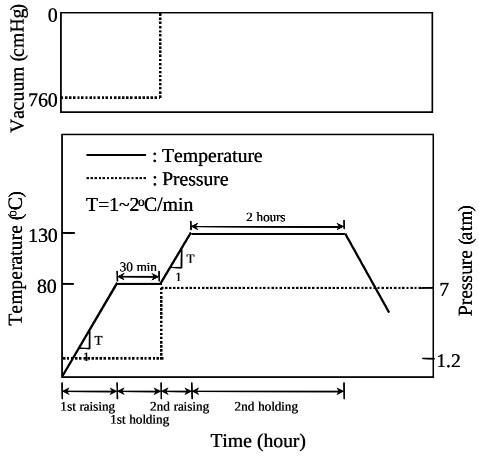



**Fig. 3 Curing cycle of the specimens.**

After a laminate was made using an inner mold of cylindrical shape, this mold is removed and the laminate is placed in a metal mold. Then the vacuum bag is applied and the specimen is cured in the autoclave while pressure is applied from the inner space. Fig. 3 shows the curing cycles for the specimens. After curing, the outer skin of the specimen is perfectly smooth, but its inner side has some corrugation in the horizontal direction. This may due to the compression of the peel plies and bleeders during the curing process. Improvement in skill and stacking method will help to reduce this unexpected phenomenon.

The quasi static tests were carried out using the Universal Tester 4482. The test load is 100kN, the test speed is 2mm/min. The specimen was placed on a flat plate while being crashed from the upper side by a moving plate. No clamping or any other constrains were used. Observation during the tests confirms that there was no slide between the specimen and the lower plate.


**Fig. 4 Quasi static tests set up and results.**

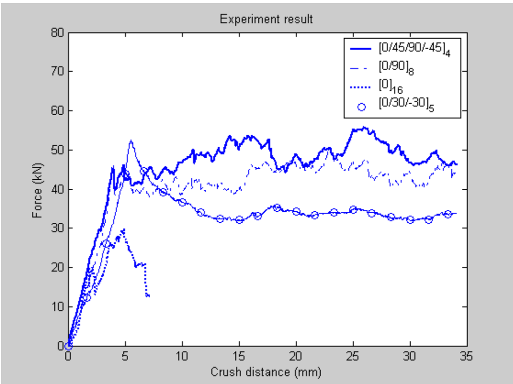



**Fig. 5 Force vs. Crush distance curve for experiment.**

**Table 5 Summary of test result**

| Lay up | $1^{st}$ peak load (kN) | Mean load (kN) | EA (kJ) | Es (kJ/kg) |
|---|---|---|---|---|
| [0/45/90/-45]$_4$ | 45.18 | 45.19 | 1.54 | 51.83 |
| [0/90]$_8$ | 46.49 | 40.31 | 1.37 | 46.23 |
| [0/30/-30]$_5$ | 52.48 | 32.84 | 1.12 | 39.85 |
| [0]$_{16}$ | - | - | - | - |

The energy absorption and mean force are calculated by the following equations, where F is the plate's force, and x is the plate's displacement.

$$EA = \int F.dx \qquad F_{mean} = \frac{EA}{CrushLength}$$

Fig. 5 plots the Force vs. Crush distance curve of the upper plate for all lay-ups of the notch edge case for a crush distance of 34mm. Summary of the crashworthiness parameters are shown in Table 5. The [0]$_{16}$ lay-up fails right after the initial damage. The [0/45/90/-45]$_4$ lay-up has the highest EA and Es.

The comparisons of the two triggering types in the cases of [0/90]$_8$ and [0/30/-30]$_5$ lay-ups are shown in Fig. 6. In the Force - Crush displacement curve, the difference at the beginning in the case of [0/30/-30]$_5$ lay-up may due to the difference in triggering methods. But in both cases, after the initial damage, there is no large difference between the two triggering methods. This can lead to a more general conclusion: in the quasi static test, triggering method only affects the initial damage of the tube. This may not happens in the impact test, where the high test speed can lead to some unstable collapse and the progressive mode cannot be obtained.

From the experiment results, among the different laminates were tested, the [0/45/90/-45]$_4$ lay-up has the highest energy absorption and specific energy absorption (EA=1.54kJ for a crush distance of 34mm, Es=51.83kJ/kg). In order to absorb 2MN of collision energy, if using this lay-up, the Energy Absorber of the high-speed train will consist of totally 64 quasi-isotropic tubes of 70cm length.

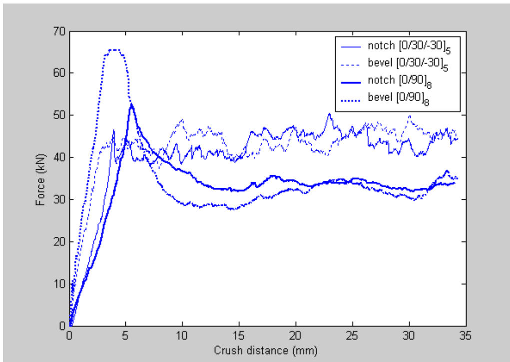



**Fig. 6 Comparison of triggering methods.**

## 3. Numerical study

A parametric study was done in order to find out the most proper method to simulate the quasi static test of composite tubes using LS-DYNA. LS-DYNA is the program which is often used for the simulation of the crash test in the literature [11,12,13]. It is a finite element code which uses the Lagrangian formulation. It obtain a stable solution by integrating the equation of motion every small time step. These small time steps are suitable for the impact and crash simulation. The code also has a large material library for metals and composites and efficient contact algorithms. The simulation was done for the notch edge cases of and compared to the experiment's results. This study was done with a Intel(R) Core(TM) 2Quad core CPU 2.66GHz, 3.25 GB RAM computer. Reasonable agreement between the simulation's result and test's result was obtained. Based on this, a further parametric study can be carried out to determine the optimal design for the Energy Absorber used for the train.

### 3.1 Material for the model

In this study, a crash model was set up using the material model used was ENHANCED_COMPOSITE_DAMAGE MAT55, which was found to be the most proper LS-DYNA's material model for the unidirectional fiber composite [11, 12, 13]. The failure criterion of this material model is the Tsai-Wu criterion. This criterion includes 3 modes that the composite model can fail: tensile fiber mode, compressive fiber mode, and tensile and compressive matrix mode. These modes are given as below [14].

Tensile fiber mode:

$$\sigma_{aa} > 0 \quad \text{then} \quad e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right)^2 + \beta\left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \quad \begin{cases} \geq 0 \rightarrow \textit{failed} \\ < 0 \rightarrow \textit{elastic} \end{cases}$$

$E_a = E_b = G_{ab} = \upsilon_{ba} = \upsilon_{ab} = 0$

Compressive fiber mode

$$\sigma_{aa} < 0 \quad \text{then} \quad e_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1 \quad \begin{cases} \geq 0 \rightarrow \textit{failed} \\ < 0 \rightarrow \textit{elastic} \end{cases}$$

$E_a = \upsilon_{ba} = \upsilon_{ab} = 0$

Tensile and compressive matrix mode

$$e_{md}^2 = \frac{\sigma_{bb}^2}{Y_c Y_t} + \left(\frac{\sigma_{ab}}{S_c}\right)^2 + \frac{(Y_c - Y_t)\sigma_{bb}}{Y_c Y_t} - 1 \quad \begin{cases} \geq 0 \rightarrow \textit{failed} \\ < 0 \rightarrow \textit{elastic} \end{cases}$$

For β=1, the original criteria of Hashin of 1980 is obtained in the tensile fiber direction, while for β=0 we get the Maximum Stress Criterion which is found to compare better to experiments. In this study, β=0 was chosen.

Through the tube's thickness of 1.8mm, there are 16 integration points which are placed equally in each layer (15 points for the case of $[0/30/-30]_5$). The material properties are defined for each layer using by β angle in the local ordinate system of each element. In this local ordinate system, x-direction is the longitudinal direction of the tube, z-direction is the normal direction of the element, and y-direction is defined by the cross product of vector x and z.

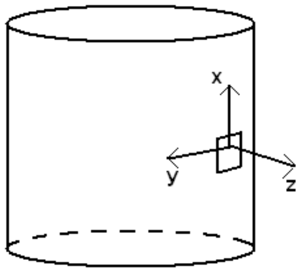



**Fig. 7 Local ordinate system of an element.**

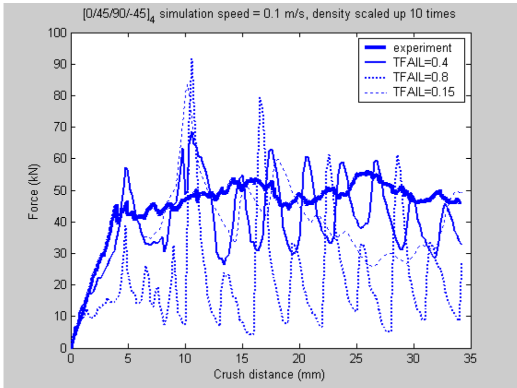



**Fig. 8 Result of preliminary study for TFAIL.**

MAT55 also allows eliminating elements if the strain exceeds a limit value, or when a time step of the analysis decreases to a very small value, this is to prevent the large scale folding and avoid the ductile behavior of the model. This eliminating elements method can be controlled using the time step failure parameter TFAIL. This parameter allows us to keep the brittle behavior of the model, and maintain the level of time step to save the computer time. Varying in the range from 0.1 to 1, low TFAIL provides ductile material, while high TFAIL provides brittle behavior. There is no default value for TFAIL for every material model, so in the simulation the user should test this parameter and choose the most proper value for it which provides the most appropriate behavior compared to real material.

A preliminary study was carried out with several value of TFAIL, and the value of 0.4 was found to be the most proper for this simulation, since it provides the best agreement of the Force-Crush distance curve between analysis and experiment.

### 3.2 Mesh the model

After a preliminary study of convergence, 5700 elements

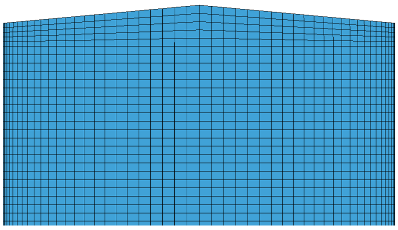


**Fig. 9 The elements at the top of the tube.**

were used for a tube having length of 115mm and outer diameter of 100mm. The size of the element is 3.14 × 2 mm. The element type is Belytschko-Lin-Tsay quadrilateral shell. At the top of the tube, where has the notch edge, refinement in meshing was made to improve the accuracy.

## 3.3 Contact and boundary condition

Since the observation during the experiments confirm no large slide between the tube and the lower plate, in the simulation the tube's bottom was modeled to be fixed. The moving plate was modeled using a RIGIDWALL _GEOMETRY_FLAT_MOTION. The friction coefficient of the wall's surface is 0.4.

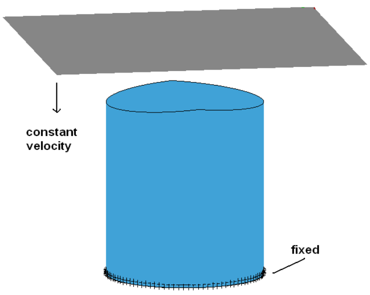



**Fig. 10 Test set up in the numerical study.**

## 3.4 The quasi static condition

To guarantee the quasi static condition, the kinetic energy should be very small during the analysis. Thus low speed should be applied to the moving wall in the simulation. The best case is that the simulation has the same speed with the experiment. But this will require huge amount of computer time. So, higher speed and mass scaling method are needed to save the computer time.

At first a speed of 1m/s was applied to the moving wall in the case of $[0/45/90/-45]_4$ lay-up. This level of speed is also used in the literature papers [11,12,13] for the quasi static test. The simulation shown good agreement compared to the experiment (Fig.11). Computer time is 54 minutes.

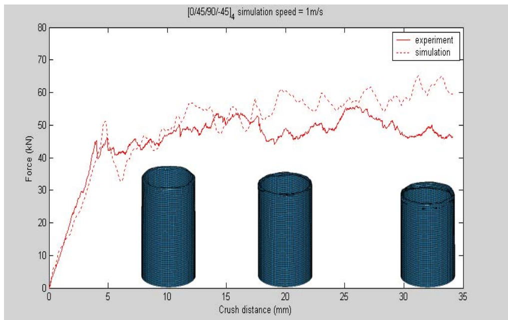



**Fig. 11 Simulation result for [0/45/90/-45]4 lay-up, test speed = 1m/s.**

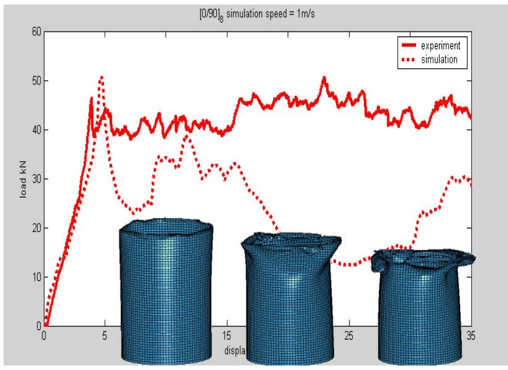



**Fig. 12 Simulation result for [0/90]8 lay-up, test speed = 1m/s.**

**Table 6 Simulation result for $[0/45/90/-45]_4$ lay-up, test speed = 1m/s.**

| | Experiment | Simulation | Difference |
|---|---|---|---|
| Crush distance | 34.14 mm | 34.2 mm | |
| $1^{st}$ peak load (kN) | 45.70 | 51.16 | 12.8% |
| Mean load (kN) | 45.486 | 49.556 | 9.67% |
| EA (kJ) | 1.54 | 1.69 | 9.74% |
| $E_S$ (kJ/kg) | 51.83 | 56.84 | 9.67% |

$$Difference = \frac{|Simulation - Experiment|}{Experiment} \times 100\%$$

Then the same speed was applied to the case of $[0/90]_8$ lay-up. During the simulation, the tube had some remarkable buckling and the Force vs. Crush distance curve showed large difference compared to the experiment (Fig.12). This means lower simulation speed should be used to guarantee the quasi static condition.

Then a speed of 0.1m/s was chosen for this lay-up. At this speed, using the real density of the material costs huge computer time, so mass scaling method is applied to save the

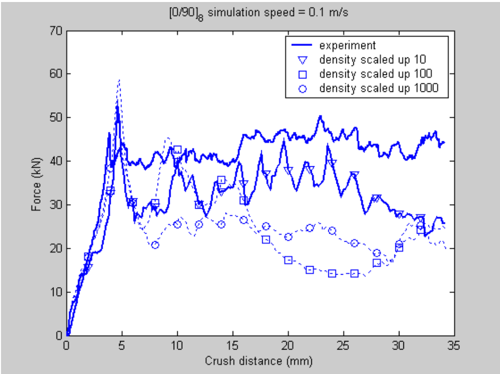


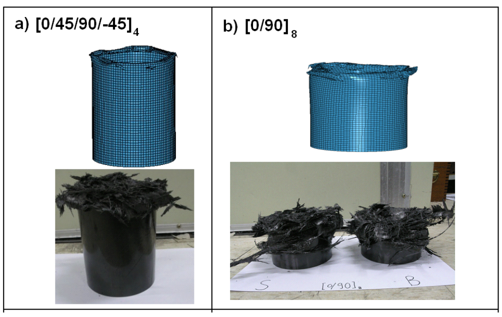

**Fig. 13 Results of different density scale factor.**

computer time. A parametric study was done to test the accuracy and efficiency of mass scaling method. The density of the tube is scaled up 10, 100 and 1000 times, respectively. The more we scale up the material's density, the larger the kinetic energy will be, and so will the error. Fig. 13 shows the result of this parametric study. Scaling up the density 10 times provides the largest computer time but smallest error between simulation and experiment.

Computer time
1000 times: 55 minutes
100 times: 3 hours
10 times: 10 hours

Then the same test speed (0.1m/s) and scale up factor (10 times) were applied for all the other lay-ups. The simulation showed reasonable agreement with the experiment. The simulations' results are shown as follows.

### 3.5 Final simulations' results



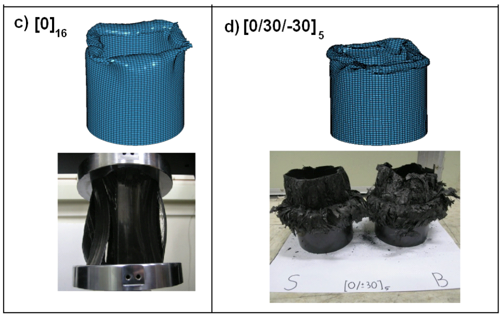




**Fig. 14 Final stage of the specimens (S: notch, B: bevel).**

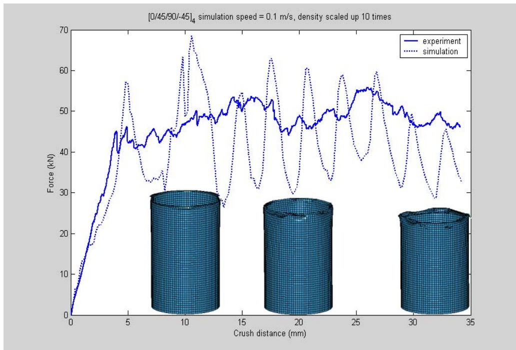



**Fig. 15 Simulation result for [0/45/90/-45]4 lay-up.**

**Table 7 Simulation result for [0/45/90/-45]4 lay-up, test speed = 0.1m/s.**

| | Experiment | Simulation | Difference |
|---|---|---|---|
| Crush distance | 34.14 mm | 34.2 mm | |
| $1^{st}$ peak load (kN) | 45.18 | 57.15 | 26.5% |
| Mean load (kN) | 45.19 | 40.14 | 11.2% |
| EA (kJ) | 1.54 | 1.37 | 11% |
| $E_S$ (kJ/kg) | 51.83 | 46.04 | 11.2% |

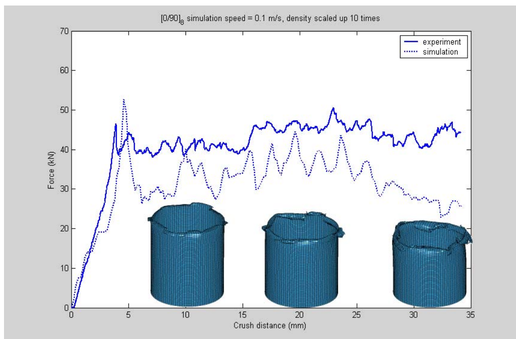



**Fig. 16 Simulation result for [0/90]8 lay-up.**

**Table 8 Simulation result for $[0/90]_8$ lay-up, test speed = 0.1m/s.**

| | Experiment | Simulation | Difference |
|---|---|---|---|
| Crush distance | 34.15 mm | 34.2 mm | |
| $1^{st}$ peak load (kN) | 46.49 | 52.72 | 13.4% |
| Mean load (kN) | 40.31 | 30.93 | 23.27% |

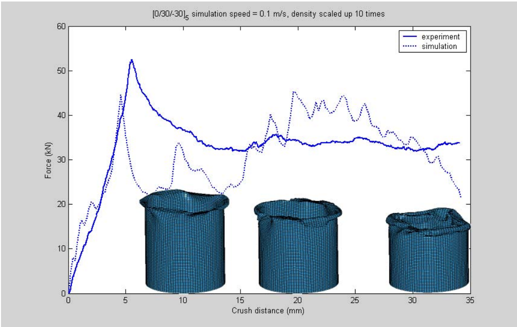



**Fig. 17 Simulation result for $[0/30/-30]_5$ lay-up.**

**Table 7 Simulation result for $[0/30/-30]_5$ lay-up, test speed = 0.1m/s.**

| | Experiment | Simulation | Difference |
|---|---|---|---|
| Crush distance | 34.07 mm | 34.2 mm | |
| $1^{st}$ peak load (kN) | 52.48 | 44.6 | 15% |
| Mean load (kN) | 32.84 | 30.93 | 5.82% |
| EA (kJ) | 11.19 | 10.58 | 5.45% |
| $E_S$ (kJ/kg) | 39.85 | 37.53 | 5.81% |

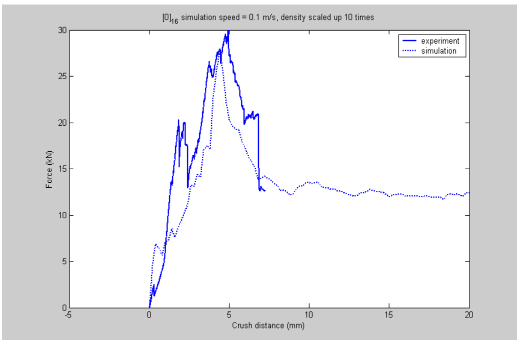



**Fig. 18 Simulation result for $[0]_{16}$ lay-up.**

### 3.6 Discussion

Though a same test set up was used for all the lay-ups, but the analysis shows different error in each case. $[0/45/90/-45]_4$ has the largest error in EA and ES (23%), while $[0/30/-30]_5$ has the smallest error (6%).

Only the $[0/45/90/-45]_4$ lay-up show no buckling in the tube's wall and perfect progressive collapse was obtained. In all the other cases, there was buckling and the collapse mode was not exactly the same as the experiment.

In the experiment, the $[0]_{16}$ lay-up fails right after the initial damage, but the simulation cannot provide the same behavior.

In the experiment, after the initial damage, the Force of the upper plate is quite constant during the progressive collapse for all lay-ups. But in the simulation, different behaviors of the Force are obtained, and this lead to different deviations of the simulation compared to the experiment.

This may due to the capacity of the program LS-DYNA. Further study can be done with different material model, contact algorithm, and meshing method to improve the simulation.

## 4. Conclusion and further study

Experimental and numerical studies were done to test the composite material for the Energy Absorber of the high-speed train. The crashworthiness of the composite tube was tested using quasi static test.

In the experimental study, single composite tubes made of composite material CU125NS were set to be crashed by a moving wall having a constant velocity of 2mm/min. Totally 4 lay-ups were tested to find out the best lay-up for the Energy Absorber: $[0/45/90/-45]_4$, $[0]_{16}$, $[0/90]_8$, $[0/30/-30]_5$. Two triggering methods were used to provide initial damage and guarantee progressive collapse mode: bevel edge and notch edge. Comparison of the triggering methods for the same lay-up shows no large difference after the initial damage. From this result we can make a more conclusion for the quasi static test: triggering method only affects the initial damage of the tube but not the progressive collapse after that. This may not happens in the case of impact test, where some unstable collapse can occur due to high test speed. Comparison of the crashworthiness shows that $[0/45/90/-45]_4$ is the best lay-up among the laminates being tested since it has the highest energy absorption and specific energy absorption ((EA= 1.54kJ for a crush distance of 34mm, $E_S$ = 51.83kJ/kg).

In the numerical study using the LS-DYNA program, a single carbon/epoxy composite tube was modeled using ENHANCED_COMPOSITE_DAMAGE MAT55 and 5700 Belytschko-Lin-Tsay quadrilateral shell elements of 3.14 × 2mm size. This tube is crashed by a moving wall at the speed of 1m/s and 0.1m/s. A study on parameter TFAIL and the mass scaling factor was done to find out the most proper method for the quasi static test. The higher test speed has good agreement between simulation and experiment for one lay-up, but large error for the others; while the lower test speed shows reasonable agreement between simulation and experiment. Still, the simulations have some large buckling, which doesn't occur in the experiment; and the analysis cannot provide the same behavior for the $[0]_{16}$ lay-up, which failed right after the initial damage.

Based on this research, further study can be done to determine the optimal design for the Energy Absorber of the high-speed train. The experimental study can concern with the thickness/diameter ratio, other triggering methods...The numerical study at this stage shows different Force's behaviors for different lay-up after the initial triggering, which should be quite constant for all lay-ups as in the experiment. Further improvement concerning with the material parameters in the model and the layers of the tube should be made to eliminate this limitation.

## Acknowledgement

본 연구는 국토해양부 미래철도기술개발사업 및 과학재단 중견연구자 지원사업(2009-0079968)의 지원으로 수행되었으며, 이에 진심으로 감사드립니다.

## References

1) Kim. J. S, "Fatigue assessment of tilting bogie frame for Korean tilting train: Analysis and static tests," Engineering Failure Analysis, 2005.
2) UK Structural requirement for railway vehicles, GM/RT2100, 2000.
3) US Code of Federal Regulations, 49 CRF-Part 238.
4) Tyrell. D. C, "US Rail Equipment Crashworthiness Standards," What can we realistically expect from crashworthiness? Improving train design to withstand future accidents, London, England, May 2nd, 2001.
5) UK Report RSSB T118T118 "Whole train dynamic behavior in collisions and improving crashworthiness," 2006.
6) Jacob. G. C, Fellers.J.F, "Energy Absorption in Polymer Composites for automotive crashworthiness," *Journal of Composite Material*, Vol. 36, No 07/2002.
7) Farley. G. L, "Effect of fiber and matrix maximum strain on the energy absorption of composite materials," *J. Comp. Mater.*, Vol. 20, 1986, pp. 322–334.
8) Farley. G. L, "Energy absorption of composite material and structures," *Proceedings of the 43rd American Helicopter Society Annual Forum. St. Louis*, USA. pp. 613–627.
9) Thornton. P. H. and Edwards. P. J, "Energy absorption in composite tubes," *Composite Materials*, Vol. 16, pp. 521-545.
10) Melo. J. D. J, Silva. A. L. S, Villena. E. V, "The effect of processing conditions on the energy absorption capability of composite tubes," *Composite structures*, Vol. 82, 2008, pp. 622-628.
11) Bisagni. C, Di Pietro. G, Fraschini. L, Terletti. D, "Progressive crushing of fiber-reinforced composite structural components of a Formula One racing car," *Composite Structures*, Vol. 68, 2005, pp. 491-503.
12) Kakogianis. D, Van Hemelrijck. D, Wastiels. J, "Experimental and numerical study of the energy absorption capacity of pultruded composite tubes," *13th European conference on composite materials*, ECCM, 2008.
13) Mamalis. A. G, Manolakos. D. E, Loannidis. M. B, Papapostolou. D. P, "The static and dynamic axial collapse of CFRP square tubes: Finite element modeling," *Composite Structures*, Vol. 74, 2006, pp. 213-225.
14) LS-DYNA keyword manual, version 971.