OPTIMUM DESIGN OF COMPOSITE ROLL BAR FOR IMPROVEMENT OF BUS ROLLOVER CRASHWORTHINESS

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1. Introduction

There are a large number of bus crashes throughout the world. In Europe 150,000 people are injured and 150 people are killed annually [1]. In the United States in 2004, the National Highway Traffic Safety Administration reports estimated 16,000 injured and fatal occupants in bus crashes; of these more than half of the fatalities are categorized as non-collisions [2]. Therefore, the bus passenger safety is the important issue in the bus market, and this concern is gradually growing every year like the case in the car market. According to the literature survey [3] on the pattern in bus and coach incident related injuries and facilities, the rollovers occurred in almost all cases of severe bus crashes. In the rollover case, passengers run the risk for being exposed to ejection, partial ejection or intrusion. In other words, they are exposed to a high-fatality risk. The difference in bus or coach passenger, in biomechanics and space perspectives, ~~as~~ compared to those of lighter vehicle obviously more stand out in a rollover crash. In the bus or coach rollover accident, the occupant will be in further distance from the center of rotation ~~as~~ compared to the occupant in car accident. For this reason, the Economic Commission for Europe enforced Regulation No. 66 for the Bus Strength of Superstructure in 1987 (ECE R66) in order to provide protection to bus and coach occupants during rollover accidents through the provision of a survival space [4,5]. Nowadays, ECE R66 is almost a gold standard for all motor coaches. It allows for bus manufacturers to assess crashworthiness in rollover events in real tests or by computer simulation [5]. Thus, the design requirement must strictly satisfy ECE R66 while the vehicle's structural design has to carry the required load with minimum component weight without failure. Therefore, the rollover of a bus is simulated using the finite element analysis (FEA) program and the researchers [6-8] have showed good agreements between the tests and the analysis technique. Thus the recommendations have been made for many years to prevent the ejection of occupants from buses by maintaining structural integrity, providing seat belts, and using glazing systems that do not allow ejection of the occupants from the vehicle. Nowadays, many researches on bus structures built with composites are being carried out, because of their outstanding advantages in the transportation industry such as the weight saving obtained by means of the substitution of heavy parts by light pieces made of composite materials. Low fuel consumption and higher velocities are significant benefits that can be achieved as the consequence of the weight reduction. However, there have been only a limited number of demonstrations of the use of carbon fiber composite in automotive bodies, and none have been designed using finite element analysis, much less tested for structural performance [9, 10]. Aiming for such goals, the present paper shows a new concept of carbon-epoxy composite roll bar to be equipped in a bus structure. The bus structure is attempted to meet the stiffness and strength requirements with maintaining the initial traditional metallic structural parts reinforced by the composite roll bar. The rollover of the bus is studied by means of the development of analytical calculation technique and the implementation of adequate material models for the accurate treatment of the special characteristics of composites. The benefits of this new material included the mass reduction, lower center of gravity and the reduction in roll moment of inertia of the vehicle. The performance of the bus structures regarding ECE R66 was compared between the initial bus model and the composite roll bar bus. The FEA modeling is done by the specialized pre-processing software Hypermesh 10.0 (Altair Engineering, Inc., Troy, MI); and the FEA analysis is made by means of a nonlinear, explicit, 3-D, dynamic FE computer code

ABAQUS 6.10 (Abaqus, Inc., Providence, RI).

2. Materials and Methods

2.1 Design of Composite Roll Bar

Fig. 1 shows the shape and mounting configuration of the composite roll bar. The uni-directional carbon fiber epoxy prepreg (USN 125, SK Chemicals, Suwon, Korea) was used for the materials of composite roll bar. The tensile, compressive and shear properties of these materials were measured by ASTM D 3039, ASTM 3210 and ASTM D 3518, respectively, using a static universal testing machine (MTS 810). Table 1 shows the mechanical properties of the composites roll bar. For the development of composite roll bar with high bending strength and the ease for mass production, design parameters such as the stacking sequence, cross sectional shape and thickness of the beam should be determined. Since a square cross-sectional shape has better bending strength than a circular one, the composite roll bar was designed with the rectangular cross section whose outer dimensions are limited by the size of other parts such as mounting components and the bus superstructure.

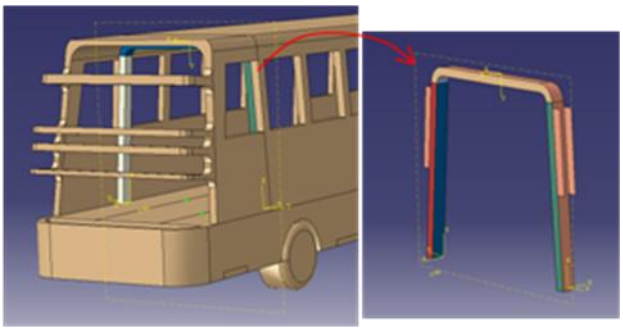


Fig. 1. Shape and mounting configuration of the composite roll bar

Table.1. Mechanical properties of the carbon epoxy composites

Property	Symbol	Experimental
Elastic modulus in fiber-direction	E_1	**141GPa**
Elastic modulus in transverse-direction	E_2	**8.7GPa**
Shear modulus in 1-2 plane	G_{12}	**5.6GPa**
Poisson's ratio	V_{12}	**0.30**
Longitudinal tensile strength	X_T	**1925MPa**
Transverse tensile strength	Y_T	**76MPa**
Longitudinal compressive strength	X_C	**1725MPa**
Transverse compressive strength	Y_C	**228MPa**
Shear strength in 1-2 plane	S_{12}	**72MPa**

2.2 Three Point Bending Test of Composite Roll bar

Prior to practicing the ECE R66 simulation and certification process, a verification of analysis procedure set forth by the regulation ECE R66 was performed. Two separate specimens ($[0]_{30}$, $[0/90/0/90/0/90/0/90/0/90/0]_S$) were prepared for experimental investigations. These parts were displayed on the rigid surface and were subjected to quasi-static perpendicular loads applied in the middle region of the part, as in the three-point bending test, at laboratory testing facility.

Fig. 2 shows the jig for the three point bending test of the composite roll bar. As shown in Fig. 2, the jig span was 700 mm and two cylinders were used to support the composite roll bar.

The force deflection curve was measured. The goal of the experiment is to generate the bending moment which is comparable to the load case during rollover (see Figs 3 and 4). The same test scenarios were simulated by using ABAQUS (see Figs 5 and 6) for verification and tuning up the mesh size was required for the composite roll bar.

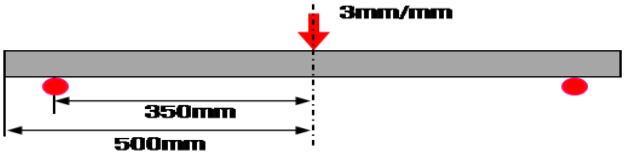


Fig. 2. Jig for the three-point static bending test.

Fig. 3. Test applied on the composite roll bar

Fig. 4. Test on the special roof profile

Force-deflection curves in both the experiment and simulation were compared and it was seen that there is a good correlation between the experiment and simulation results in Fig.7.

From the experiments, it was found that the maximum bending load-carrying capacity of the composite roll bar was 11 kN. Although the composite roll bar with the stacking sequence of $[0]_{30}$ had the highest axial stiffness, it could not effectively resist the external bending load because of its low hoop strength. The composite beams with stacking sequences of $[0/90/0/90/0/90/0/90/0/90/0]_S$ have higher bending strength but these type of composite roll bar are not easy to be mass-produced due to the hoop winding. Therefore, the composite roll bar with stacking sequence of $[0_2/90_2/0_2/+45_2/-45_2/0_2/90_2/0_2]$s were simulate and found that they had the highest bending strength.

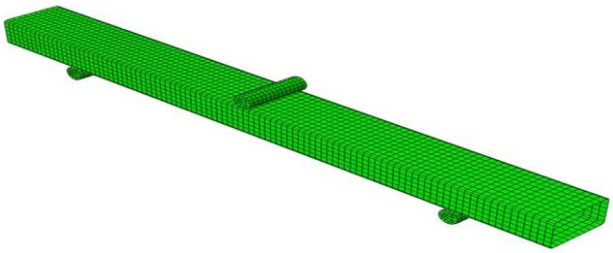


Fig. 5. ABAQUS simulation ont the composite roll bar

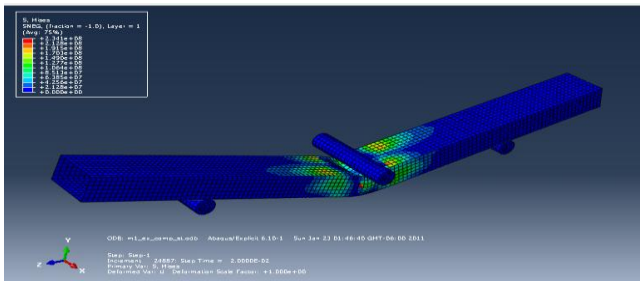


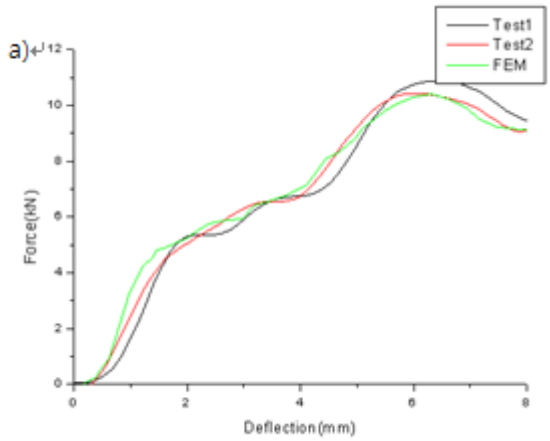
Fig.6. ABAQUS simulation on the speical roof profile

2.3 Simulation of the Bus Rollover Test on a Complete Bus Built on Composite Roll Bar

ECE Regulation 66 requires the coach to provide adequate survival space for un-belted passengers during the rollover test shown in Fig. 8.

The finite element model of a 14,014kg bus was modeled (Fig. 9). The portion of the bus structure above the floor was modeled with finite elements, and the remaining inertia of the bus was modeled as four lumped masses.

The center of gravity of the vehicle was located vertically at 40 % of the height of the bus, which coincided with the level of the floor. The lumped masses were spaced laterally by the distance equal to about 70% of the bus width to approximate the roll inertia of the bus. The finite element model was used to simulate various lateral rollover impacts using ABAQUS Explicit, and it was observed that the weak point deformed extensively under fairly mild rollover impacts. The mechanical properties (stiffness and strength) used were for a composite material with 65% fiber by weight, and a reinforcement architecture where 80% of the fiber is oriented in the axial direction of the tubes and 20%in the transverse direction. A composite roll bar provides an inexpensive solution to improve the crashworthiness in terms of high specific stiffness and strength, and excellent corrosion resistance.



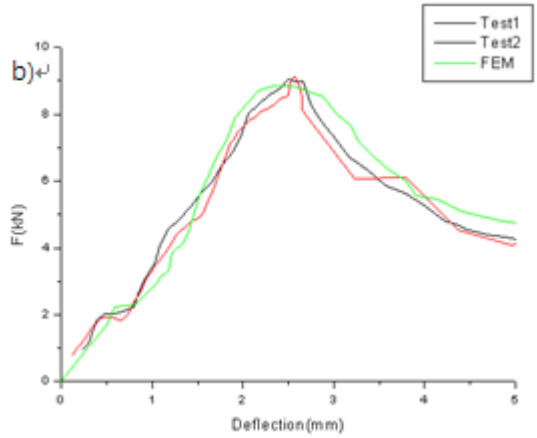


Fig.7. Comparison of the test and ABAQUS simulation on the 3point bending a) $[0]_{30}$ b) $[0/90/0/90/0/90/0/90/0/90/0]_S$

The center of gravity of the vehicle was located vertically at 40 % of the height of the bus, which coincided with the level of the floor. The lumped masses were spaced laterally by the distance equal to about 70% of the bus width to approximate the roll inertia of the bus. The finite element model was used to simulate various lateral rollover impacts using ABAQUS Explicit, and it was observed that the weak point deformed extensively under fairly mild rollover impacts. The mechanical properties (stiffness and strength) used were for a composite material with 65% fiber by weight, and a reinforcement architecture where 80% of the fiber is oriented in the axial direction of the tubes and 20%in the transverse direction. A composite roll bar provides an inexpensive solution to improve the crashworthiness in terms of high specific stiffness and strength, and excellent corrosion resistance.

In order to optimize composite roll bar, the bus structure demonstrated significantly higher rollover strength while the mass added by the roll bar to the initial bus model was only 13.15kg. If the composite roll bar were substituted for the roof structure of the initial model, a stronger composite roll bar would result in more weight savings. In the rollover impacts simulated, the increased strength of the composite roll bar arrested the rollover so that the bus did not provide the survival zone.

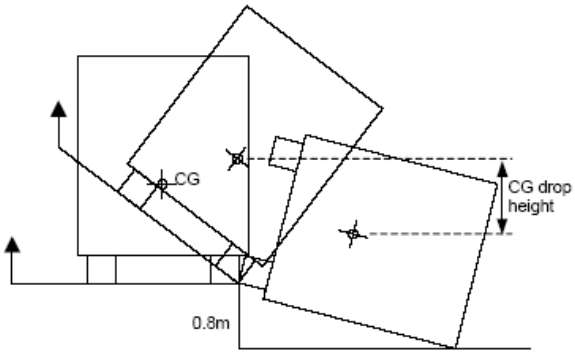


Fig. 8. Position of bus CG during R66 rollover

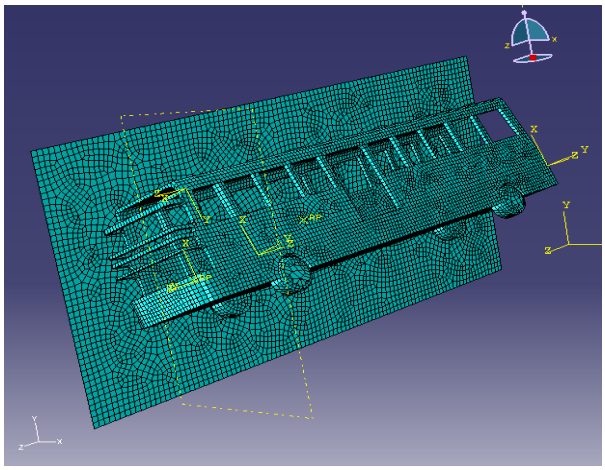
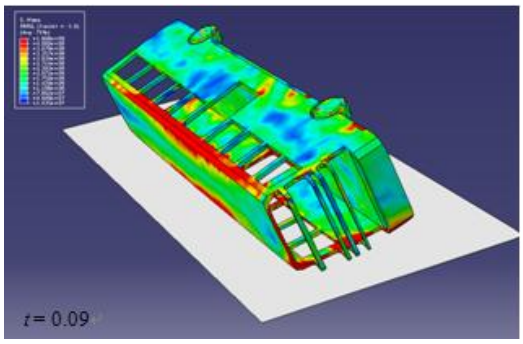


Fig. 9. Finite element model

3. Results

As shown in the Fig. 10 and Fig. 11, the significantly lower stress distribution was shown in the composite roll bar bus structure compared to that initial bus structure. In addition, the lower deformation was shown in the front part of composite roll bar bus whereas the initial bus structure was deformed expressively. The deformation of front part of the bust compared to the rear side is due to the massive engine location in ahead.



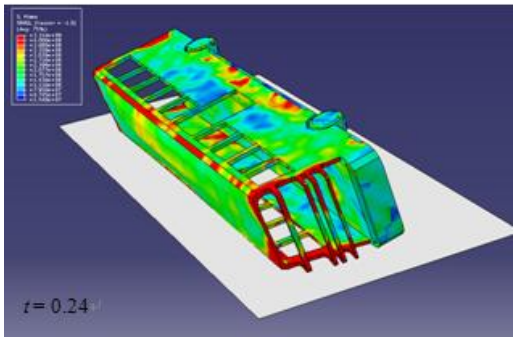


Fig. 10. Initial bus roll over

A stronger structure, like the design with composite roll bar in this study, resists lateral rollover in the same impact (Fig. 12). The reduction structure crush in combination with the roll bar geometry prevents the bus from rolling onto its roof because the roll energy is insufficient to raise the center of gravity to its maximum height in a rollover, which is the distance from the bus center of gravity to the top outside extremity of the roof.

Fig. 13 shows the comparison in internal strain energy. There was not much difference in energy shown in early time of crash, but, as time goes by, the difference became reasonably bigger, up to 40%. In other words, the composite roll bar resists the deformation of the bus structure absorbing internal strain energy as the crash progressed.

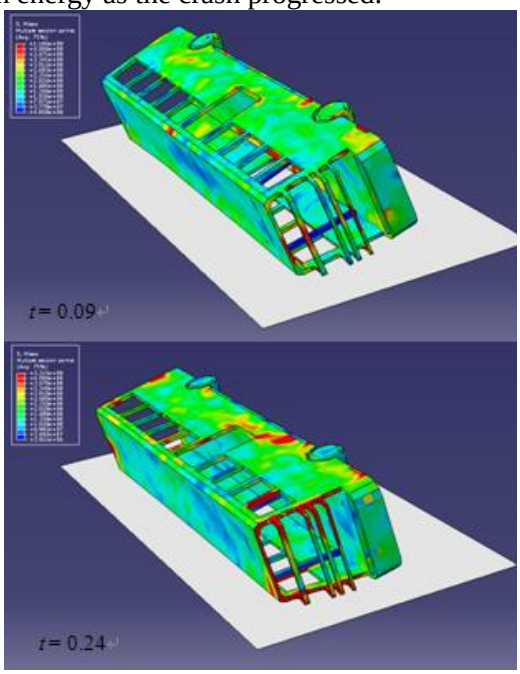


Fig. 11. Composite roll bar bus roll over

In order to obtain the deformed displacement related to the regulation requirement, a series of measurements at the most meaningful points in the bus structure (points U and L, shown on fig. 14.) have been made, which are upper and lower distances to the survival zone (Fig.3). The attained results in the superstructure are shown in Table. 2. As shown in Table.2, the bus structure reinforced by the composite roll bar is able to secure a substantial margin of the survival zone as well as to meet the requirement specified by ECE R66.

Table.2. Comparison of displacement Initial bus and Composite roll bar bus

Measurement Position	Initial Bus	Composite roll bar bus
L	42.55mm	367mm
U	38.34mm	228mm

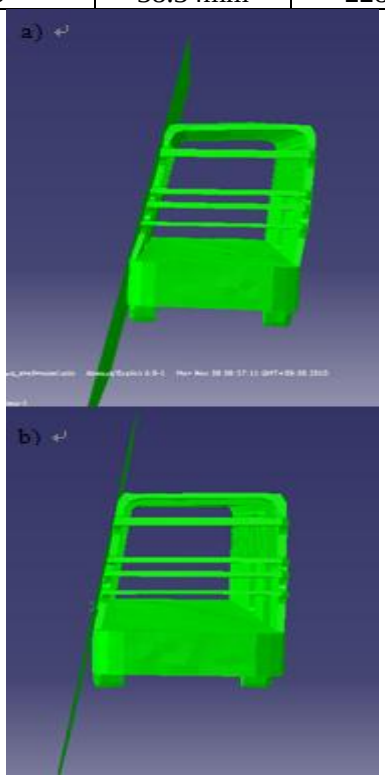


Fig. 12. Eternal deformation of rollover simulation
a) Initial bus model b) Composite roll bar bus model

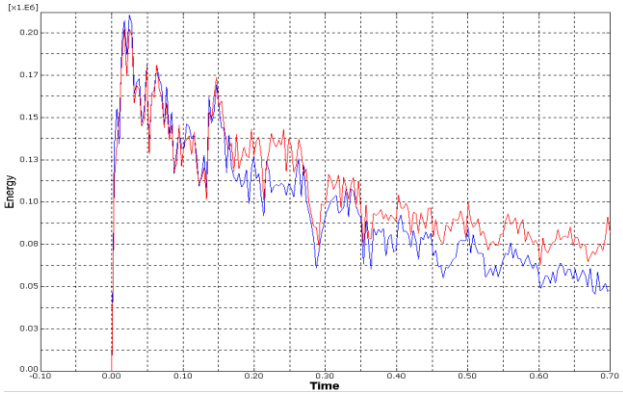


Fig. 13. Comparison of strain energy distribution (Red: Initial bus, Blue: Composite roll bar bus)

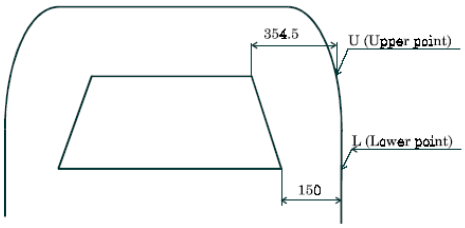


Fig. 14. Distance (in mm) between U and L points of the bus transversal frame and the survival zone.

4. Conclusions

Due to the high ratio of injured and casualties per accident existing in those accidents involving roll over phenomenon, it needs to create an operative regulation to provide the bus structures with a minimum resistance against roll over arose. This is the Regulation number 66 of Geneva. In this paper, the technique developed to simulate the roll over test of buses is shown, which is in accordance with the requirements expressed in the Regulation. This technique allows both initial and composites roll bar modes to be analyzed.

This study has demonstrated that inexpensive composite roof structure can provide significant improvements in rollover strength over initial bus structure for the same weight in transit buses. The composite roll bar bus structure can significantly reduce the severity of bus rollovers by limiting the rollover to a quarter roll. Thus the combination with the reduction in lateral deformation and effective containment design reduce the likelihood of occupant ejection in a rollover. The excellent corrosion resistance of composite material over the conventional steel is the additional benefit and it would prevent the degradation of bus superstructure and extend the operational lifetime. The component demonstration developed for the composite roll bar is generic to rail cars, trucks, marine and aerospace structures.

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