Modelling of composite energy absorbing structures for automotive load-bearing systems

G A Harutyunyan and A B Kartashov
1 Bauman Moscow State Technical University, 2-nd Baumanskaya, 5, b.1, 105005, Moscow, Russia
E-mail: georgy.arut@bmstu.ru, kartashov@bmstu.ru

Abstract. Due to the increasing demands for environmental friendliness and fuel economy of cars, the task of reducing their weight is becoming topical. One of the promising ways to solve this problem is the use of composite materials for the manufacture of automotive body. The body of the car is subjected not only to static and slowly changing dynamic loads, but also can be subjected to impact loading. Therefore, it is necessary to assess the effectiveness of the use of composite materials for the manufacture of elements responsible for energy absorption. The paper analyzes the features of energy absorption during the destruction of composite structures, describes the ongoing processes and gives recommendations on the design of composite front rails. To assess the effectiveness of the composite front rail, a simulation of process of its crushing is carried out. To confirm the performance of the design, a crash test of a car with a composite energy absorbing structure is simulated. The applicability and high efficiency of composite energy absorber are confirmed.

1. Introduction
Currently, more and more of the world's largest automotive manufacturers are moving towards the use of polymeric fiber composite materials in the vehicle's load-bearing system. One of the applications of composite materials is the fabrication of energy-absorbing structures in the front and rear parts of passenger cars, designed to absorb energy and reduce accelerations in the event of a collision [1]. These structures are used in such cars as Mercedes-Benz SLR McLaren, Lexus LFA, Dallara Stradale Aston Martin Vanquish, and Lotus Elise. Carbon fiber structures find the widest application. From the point of view of ensuring passive safety, the use of composite materials has significant differences from metals [2, 3]. Energy absorption in composite structures does not occur by deforming with the formation of plastic folds, but due to gradual stable destruction with the formation of a large number of fragments.

2. Mathematical model
This paper proposes a technique for modeling composite energy-absorbing structures for load-bearing systems of automobiles, and also substantiates the basic structural solutions for composite energy-absorbing elements.
A carbon-fiber energy-absorbing structure is being modeled for the vehicle's load-bearing system, as shown in Figure 1.

This work is licensed under the Creative Commons Attribution 3.0 Unported License. To view a copy of this license, visit http://creativecommons.org/licenses/by/3.0/ or send a letter to Creative Commons, PO Box 1866, Mountain View, CA 94042, USA
The energy absorbing structure comprises two longitudinal composite frame rails and a cross member connecting them. Frame rails have a corrugated cross section, which contributes to increasing the rigidity of the walls and the uniform formation of fragments.

First, the frame rail is considered separately from the rest of the structure, and then the crash test of the frame rail as part of the vehicle is simulated.

Currently, shock loading is simulated using the finite element method. Since the task at hand includes the destruction of materials, complex contact loads, as well as high dynamic loads, a Radioss solver is used, which is included in Altair Hyperworks finite element analysis software package, and implements integration by an explicit method [4, 5, 6].

For the mathematical description of the work of composite materials, phenomenological failure criteria are widely used, which are formulated on the basis of processing a large amount of experimental data. Tsai-Wu failure criterion related to quadratic failure criteria is of wide use. The function of the failure criterion reads:

$$F(\sigma) = F_1 \sigma_1 - F_2 \sigma_2 + F_{11} \sigma_1^2 + F_{12} \sigma_1 \sigma_2 + F_{22} \sigma_2^2$$

where $\sigma_i$ – stresses in different directions,

$F_i$ – stress-dependent failure criterion coefficients. The Tsai-Wu criterion enables to determine the current state of the material:

- $F(\sigma)<1$ – zone of elastic strains;
- $F(\sigma)=1$ – beginning of the plastic zone;
- $F(\sigma)>1$ – zone of plastic strain.

When calculating structures that react mainly static and slowly varying loads, performance is considered when the failure criterion is less than 1. A feature of the calculation of structures exposed to impact failure is the need to simulate the work of a composite material with values of the failure criterion in excess of 1 and in the presence of significant failures. For this, a modified form of failure criterion is used. In the software package for the description of composite materials, a model of material No. 25 “Orthotropic shell and solid material” was chosen, based on the material model “CRASURV” [7] and taking into account a large number of features of composite materials. The dependence of the failure criterion coefficients on the magnitude of the energy of plastic strain is taken into account, and the dependence of the yield strength on the energy of plastic strain is introduced.

The model takes into account the accumulation of failures and softening in composite materials, being considered separately for tension and compression. Load curves are shown in Figure 2.
When in tension, the softening begins when the relative elongation reaches $\varepsilon 1 ti$ and lasts until the relative elongation $\varepsilon 2 ti$, upon reaching which the stresses become equal to $\sigma rsti$. Accumulation of failures begins with a relative elongation of $\varepsilon 1 i$.

A similar process occurs during compression upon the achievement of relative deformations $\varepsilon 1 ci$ and $\varepsilon 2 ci$.

The model provides two conditions for the failure of finite elements.

First, destructive failure in the process of stretching occurs when the relative strain exceeds $\varepsilon m$. The value of the maximum relative strain is set separately for different directions of loading, and its value can be set so that the failure in this direction occurs earlier than softening or accumulation of failures. The second criterion responsible for the failure and removal of the final element is the value of the energy of plastic strain. When the value of $Wp$ is reached, the element fails. This is the only failure mechanism when subjected to compressive stresses. When subjected to tensile stresses, failure can occur due both to the achievement of maximum relative strain and to the achievement of the maximum energy of plastic strain.

The model of the material allows one set of parameters to take into account different forms of the loading curve, which are characteristic of composite materials when loaded in different directions. It can be described both as a brittle failure in the elastic zone, which is characteristic of stretching a unidirectional composite material along or across the fibers, or a plastic failure when sheared or compressed across the fibers, wherein the effects of hardening and softening appear. This feature allows to calculate the structures, the elements of which are in a complex stress state.

In the selected Radioss solver for four-node elements with reduced integration, QEPH (Quadrilateral ElastoPlastic Physical Hourglass Control) formulation is used [8].

To model a multilayer composite material, a special formulation for shell elements is used. In the Altair Hyperworks software package “Type 11” element is used for this purpose.

3. Results

The frame rail is considered separately to evaluate the efficiency of energy absorption and eliminate the influence of other structural elements. The design model and a fragment of the finite element model are shown in Figure 3.
The frame rail is fixed at the base, the impact is produced by an absolutely rigid wall weighing 500 kg at a speed of 56 km/h. The splitting into finite elements is irregular, which increases the stability of the results in modeling. As an initiator of the failure, one of the ends of the frame rail includes an area with a reduced number of layers of composite material. The wall thickness of the frame rail is 3 mm, with the frame rail modeled as 10 successively alternating annular and longitudinal layers.

The intermediate stages of failure resulting from the simulation are shown in Figure 4.

To evaluate the structure, the criterion of specific energy absorption is used, which is calculated as the ratio of the absorbed energy to the mass of the destroyed or deformed part. The specific energy absorption was 42.3 kJ/kg, that is more than two times higher than the values characteristic for metallic energy absorbing structures. Figure 5 shows a comparison of reactions on a rigid wall that occur in the process of energy absorption of the carbon fiber-reinforced plastic frame rail under consideration and a similar steel structure.
Both structures in the process of the failure create a reaction with a fairly constant average value, but the range of change in the magnitude of the reaction is much larger when the steel structure is deformed. This is due to the discreteness of the formation of plastic folds. Due to the uniform failure and the fact that the material entirely participates in the energy absorption, the carbon fiber-reinforced plastic frame rail creates a reaction of almost constant magnitude. With the failure of the composite frame rail, a smooth increase in the reaction occurs without a pronounced peak at the beginning, which indicates the effectiveness of the applied initiator of the failure. The crash test is modeled on a vehicle with a composite energy absorbing structure to evaluate its performance and estimate the accelerations, allowing to draw conclusions about the safety of the vehicle. The design model is depicted in Figure 6.
The boundary conditions correspond to the crash test under the UNECE rule No. 94 [9]. The impact is simulated with 40% overlap into a deformable barrier at a speed of 56 km/h. Vehicle weight is 1200 kg. A deformable obstacle is modeled by volume finite elements. For this purpose, the Altair Hyperworks software package uses material model No. 28 "Honeycomb orthotropic".

To assess the performance of passive safety, the CE model of the Hybrid III dummy is used. Seat belts are modeled to connect the dummy to the load-bearing system. The stages of the collision process resulting from the simulation are shown in Figure 7.

![Image of crash test stages](image)

**Figure 7.** Crash Test Stages.

The frame rail fails uniformly from the side of the obstacle. No undermining and cracking are observed where the EP passes to the main load-bearing system. The wheel did not have a significant influence on the process of energy absorption and the nature of the failure of the composite EP.

Based on the acceleration of the dummy's head, HIC (Head Injury Criterion) is evaluated, which is calculated by the formula:

\[
HIC = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2.5} \cdot (t_2 - t_1),
\]

where \( a \) is the acceleration of the dummy's head, \( t_2 \) and \( t_1 \) are the limits of the time interval, which are chosen so that the value of the criterion is the greatest. Figure 8 shows the acceleration of the dummy's head and the calculation of the HIC criterion.
The highest short-term acceleration value is 65g. The HIC criterion is 248.5 units within the 15 ms interval, which is significantly less than the permissible value of 1000 units. Figure 9 shows the frame rail in the process of failure.

4. Conclusion
The failure is observed by fragmentation with the separation of fragments. Due to the deformation of the barrier, the surface that contacts the frame rail is not perpendicular to the axis of the frame rail. Despite the presence of a force acting on the frame rail in the lateral direction, no catastrophic failure is observed. The front of the failure is where the frame rail contacts with an obstacle and oriented non-perpendicularly to the axis of the frame rail.

Thus, this paper defines approaches to modeling energy absorption in the process of the failure of composite structures. Significantly greater energy absorption efficiency of composite structures compared to that of the metal ones was demonstrated. The crash test was simulated on a vehicle fitted with a composite energy absorbing structure. The latter’s performance and ability to ensure safety requirements were confirmed.

References
[1] Mikhailov M S, Yuryevich V, Aleksandro维奇 D 2017 Exploring fracture dynamics and passive safety of a superstructure made of composite materials. *International Journal of Applied Engineering Research* **10**, vol 12 2447-2456.
[2] Chermoshentseva A S, Pokrovskiy A M and Bokhoeva L A The behavior of delaminations in composite materials - Experimental results. *IOP Conference Series: Materials Science and Engineering*. 0161 vol 116
[3] Lurie S and Belov P 2014 Gradient effects in fracture mechanics for nano-structured materials. *Engineering Fracture Mechanics* Vol 130 3-11.

[4] 2015 Practical aspects of finite element simulation. 3rd edition. Altair Engineering. 503 p.

[5] Buyanov I A, Rostovtsev M Y and Shelofast V V 2016 Validation of software for computer-aided engineering of composite constructions in relation to calculating the natural frequencies of asymmetrical laminated plates *Russian Aeronautics* 4 Vol 59 606-612.

[6] Dimitrienko Yu I, Sborshchikov S V and Sokolov A P 2013 Numerical simulation of microdestruction and strength characteristics of spatially reinforced composites. *Composites: Mechanics, Computations, Applications*. 4 Vol 4 345-364.

[7] Wang L H, Atluri S N 1994 An analysis of an explicit algorithm and the radial return algorithm, and a proposed modification, in finite plasticity. *Computational Mechanics*. Vol 13 5 380-389.

[8] UNECE Regulation No. 94 (document E/ECE/324/Rev.1/Add.93/Rev.1, E/ECE/TRANS/505). Uniform prescriptions concerning vehicle approval for driver and passenger protection in the event of a frontal collision. UN 2007 p86