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Development of composite energy absorber

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Abstract

This paper presents experimental investigation and numerical prediction of the deformation behaviour of several types of composite deformation elements, whose potential use is in public passenger transport. Experiments were conducted on two types of samples. First, on filament wound composite tubes with thermoset polymer matrix and on moulded thermoplastic corrugated plates. Tests have shown that the absorbed deformation energy of elements made from filament wound composite tubes depends on the laminate layup. Deformation elements made from moulded thermoplastic carbon sheets are also promising for parts of composite absorbers. The full-scale crash-test simulations (in the PamCrash software) showed that applied deformation boxes in the front bumper of the city bus can effectively absorb large percentage of the impact energy in the initial stage of the crash.

Keywords: composite, energy absorber, crash tests,

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1. Introduction

Composite materials are nowadays coming to the forefront in many areas. No exception is their use for passive safety of vehicles, where these materials are applied, because of their very favourable properties. Compared with traditional conventional metal deformation parts, which are based on plastic deformation, the composite deformation elements can achieve not only a lower weight, but also significantly higher specific absorbed energy. This is due to entirely different mechanisms of gradual breaches of composite materials.

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Resulting properties of the absorber determine the stacking of the laminate, the type of fiber and matrix, the orientation and number of individual layers. It is possible, by a suitable design, to achieve conversion of kinetic energy into deformation through dissipation. It starts with delamination mechanism followed by breaches of matrix and fibers.

Suitable materials and construction of the deformation element (for example, using high strength carbon fiber or using thermoplastic matrix) can be achieved by energetically favourable spreading of damage over a substantial part of the absorber, and without loss of stability of the element due to the compression load.

Nowadays, composite deformation elements are used, for example, in aerospace (aircraft undercarriage, helicopter body), in the automotive industry in racing and custom made sports-cars. In mass production, these materials have not made a significant impact, but we can observe an increase in individual applications. This paper presents a comparison of the deformation behaviour of several types of composite deformation elements, whose potential use is in public passenger transport.

2. Experimental investigation

2.1. Design of deformation elements

The primary objective of this study was to clarify the influence of design parameters on the deformation response of the deformation elements. The structural parameters were:

- type of fiber and matrix
- laminate layer orientation
- technology of production
- shape of elements

Experiments were conducted on two types of samples. In view of geometry, type of the matrix and technology, the experimental samples can be divided in the two groups:

- filament wound composite tubes with thermoset polymer matrix
- semi-moulded composite plate with thermo-plastic matrix.

2.2. Deformation elements made from filament wound composite tubes

Individual tubes or bundles of four or seven tubes were investigated, see Fig. 1a. All test specimens consisted of 150 mm long tubes with an inner diameter of 26 mm. Wall thickness (depended on a composite stacking) was around 1 mm. The test tubes were wound from high-strength carbon fibers (T34-700) and epoxy resin LG120. Seven variants of laminate layups were made, as outlined in the Tab. 1.

Table 1. Layup of wound composite tubes.

Specimen Nr.	Laminate layup [degree]
#1	87/0
#2	0/87
#3	0/+23/-23
#4	0/+23/-23/87
#5	0/+15/-15
#6	0/+15/-15/87
#7	0/+7/-7/87

2.3. Deformation elements made from moulded thermoplastic corrugated plates

Deformation elements moulded from thermoplastics fabric, included thermoplastic matrix, had the form of corrugated sheets. These sheets were glued together, or spot welded into compact blocks (see Fig. 1b). Four basic corrugated plates were connected together to create an analogy box to the tubular bundles of tubes. Height of the blocks was 120 mm, the transverse dimensions of the block were 84 mm and 150 mm. The wall thickness was also approximately 1 mm. Three types of materials were tested, see Tab. 2.

Table 2. Material specification of thermoplastic corrugated plates.

Specimen	VS	VP	VC
Material	TEPEX® dynalite 101-FG290(4)/45%	PURE Polypropylene	TEPEX® dynalite 208-C200(4)/45%
Layup	$[(0/90)/\pm45)]_s$	$[(0/90)2]_s$	$[(0/90)2]_s$
Fibers	Glass	Polypropylene	Carbon
Matrix	Polyamide 6.6	Polypropylene	Polyurethane
Tensile Strength [MPa]	472	200	710
Young Modulus [GPa]	23	5.5	48

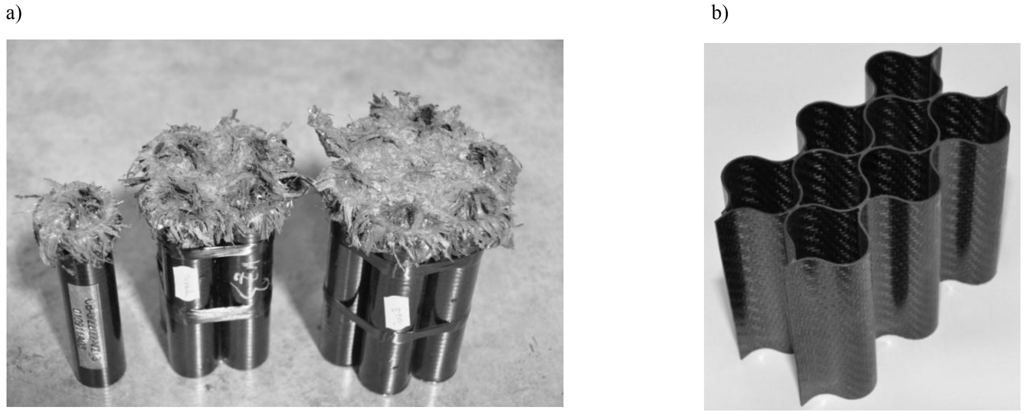
a)
b)

Fig. 1. (a) Individual tubes and bundles of 4 and 7 tubes (after the impact test); (b) Deformation element box made from four connected corrugated sheets (before impact test).

2.4. Experiments

The quasi-static compression loading tests as well as dynamic impact tests were performed on both types of samples. The quasi-static testing was carried out on a single-acting universal testing machine Heckert EU-100. Dynamic tests were performed on the device IMATEC IM10T-30HV with an integrated high frequency camera. The impact energy was in the range of 250 – 2000 J. Load and deformation of the tested elements, as well as loading velocity, deceleration and deformation energy were measured.

3. Numerical simulations

FE models of absorber based on a single composite tube were modelled as first. Two types of numerical models were tested. The starting models were prepared with a case of progressive damage in carbon/epoxy composite during loading in ABAQUS software. This model was found as unsuitable for impact calculation, mostly because it led to buckling modes, not steady crushing. Therefore, second model was created. It was based on user subroutine VUMAT that implements Hashing or Chang-Chang failure criterion into the model for element removal. Parallel to this, the tube absorber box model with Chang-Chang failure criterion and LS-DYNA model were compared.

Both deformation element boxes made from four connected corrugated sheets as well as from carbon tube bundles were built into the bus bumper. Equivalent stiffness properties determined from experiments were assigned to these elements. Crash simulations of the whole bus structure with the bumper deformation box were simulated in the PamCrash software.

4. Results and analysis

4.1. Results and analysis for deformation elements made from wound composite tubes

The comparison of the force-displacement deformation characteristic for different layup of composite tubes, according to Tab. 1, can be seen in Fig. 2a. It is clear that the design of optimal layup of the composite is important to maximize the deformation energy, see Tab. 3. The specific energy related to the unit displacement (1mm) were compared. Other comparison of the deformation characteristic, in this case for dynamic and quasi-static tests, gives Fig. 2b.

Table 3. Comparison of the maximum force and the specific energy for different layup of the tubes.

	Impact Tests		Quasistatic Tests	
Specimen Nr.	Max. Force [kN]	Spec.Energy [J/mm]	Max. Force [kN]	Spec.Energy [J/mm]
#1	16.7	14.2	14.7	11.8
#2	10.5	8.4	9.1	6.5
#3	11.0	10.0	11.5	9.9
#4	13.0	11.5	14.6	12.5
#5	12.0	11.3	x	x
#6	14.9	13.1	16.5	13.5
#7	20.4	18.5	22.2	20.3

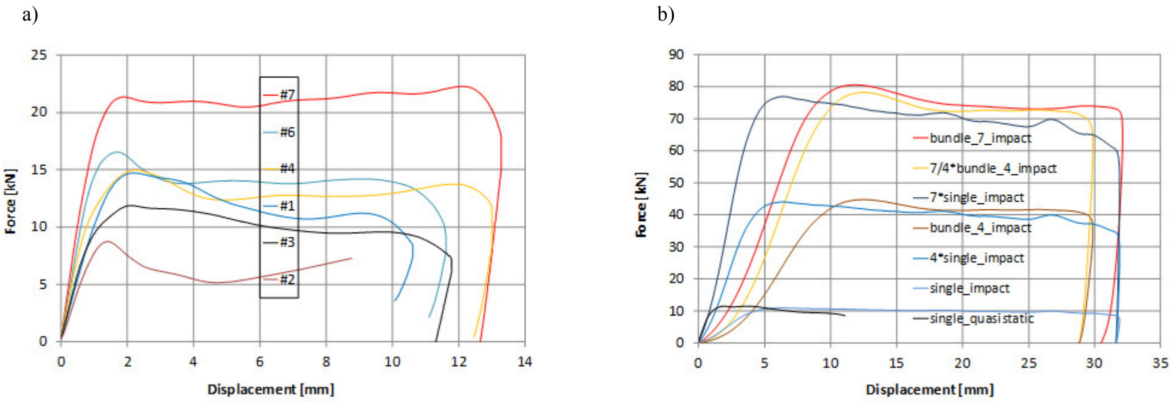

Fig. 2. (a) Quasi-static deformation characteristic for different laminate layup of tubes according to Tab. 1.; (b) Deformation characteristic of dynamic and quasi-static tests for composite tube #3Characteristics for individual tubes and blocks of four or seven tubes.

It allows comparing of the similitude of deformation characteristics for individual tubes and blocks of four or seven tubes. The curves show that the quasi-static and dynamic impact tests of each tube give very similar results during the steady deformation period. The most significant difference is in the beginning of the initiation period. The tubes seem to be stiffer in starting displacement phase by the quasi-static loading in opposite to the dynamic impact loading. It is also interesting that simply multiplying the deformation characteristics of individual tubes obtains good agreement with the experimental curves of blocks of four or seven tubes. This allows determining the deformation properties of multiple blocks consisting of a bundle of tubes.

First attempts to simulate an axial impact numerically by FEM were made using progressive damage model. It can be modelled in two steps. The first step is to define the damage initiation criterion which is based on Hashin's theory. The second step is to apply a damage evolution law, which represents the dissipated energy over an area unit. During damage evolution the stiffness is degrading from its initial value to zero. Described criterion and stress formulation was implemented in VUMAT and UMAT subroutines for Abaqus Explicit and Abaqus Standard solvers [3].

Conventional layered-shell elements with linear interpolation of displacements and with one element per specimen's thickness were used in the basic model. One example of the qualitative comparison of experiment and simulation with improved failure criterion for one type of tested tubes is shown in the Fig. 3.

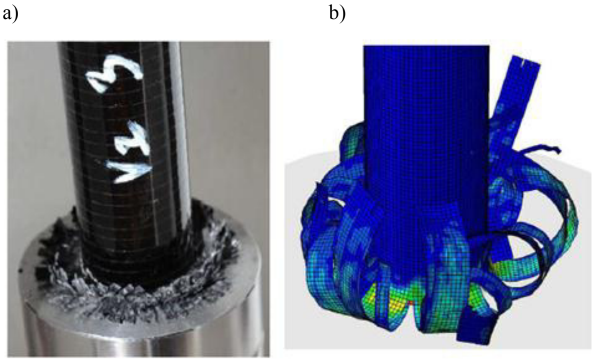

Fig. 3, Qualitative comparison of experiment (a) and simulation (b) with improved failure criterion for specimen type #3.

However, these models were successful in description of impact damage of composite tube specimens only partially and cannot be fully used for failure-modelling of different layups. They also cannot be used as a predictive tool without modification. Especially the mechanism of initiation of delamination and the delay of loss of stability must be co-implemented.

As well, LS-DYNA software was used to simulate composite tube crash problem. Literature research [1], [2] showed that most of the axial impact computations in LS-DYNA software used constitutive material based on Chang-Chang strength criterion. [4] (Model 54). One example of comparison of numerical simulation with the impact test (impact mass 9.2 kg, impact velocity of 7.16 m/s) shows Fig. 4.

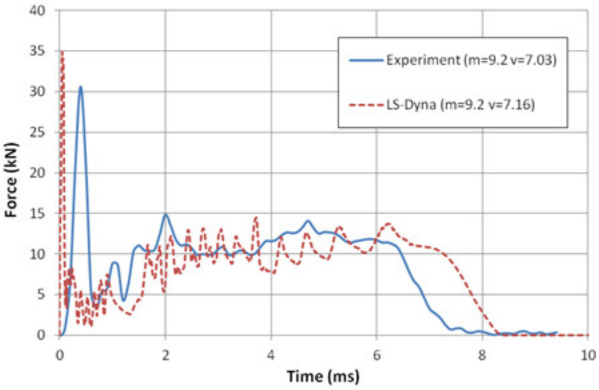

Fig. 4, Comparison of LS-DYNA simulation with the impact tests results (Specimens #4).

Comparison of all results has shown that the LS-DYNA model produces results that are quite close to the experimental ones, from both qualitative and quantitative points of view. In LS-DYNA model no special tuning parameters were used, so obtained results were not specially tuned to match experimental data. This fact means that obtained model may be used as a predictive tool to simulate different layups.

4.2. Results and analysis for deformation elements made from moulded thermoplastic corrugated plates

The measured experimental data of bonded corrugated plate box made from different material (see Tab. 3) during quasi-static test and impact tests are plotted in the graphs in Fig. 5a and Fig. 5b. The maximum magnitude of the force during a test is always higher for the dynamic test than for the quasi-static test carried out on a sample made of the same material. To investigate the energy absorption properties of the materials, comparison of the size of the absorbed energy for a specified displacement for both tests and all three materials was carried out.

The maximal forces and the resulting specific energy for a displacement of 1 mm are compared in Tab. 4. It is evident that the materials VP and VS will increase the strain energy by about 45% in the dynamic test compared to the quasi-static test. However, the material VC shows a 22% decrease in absorbed energy in the dynamic drop-test compared to the quasi-static test. This is mainly due to the fact that during the quasi-static test a steady crushing of the specimen increased by 42% with force than during the dynamic test. Based on the waveforms of the force *F* on the displacement *u* in Fig. 5a and Fig. 5b, it can also be stated that the measured curves of dynamic force oscillate lot more around an average value than during the quasi-static tests.

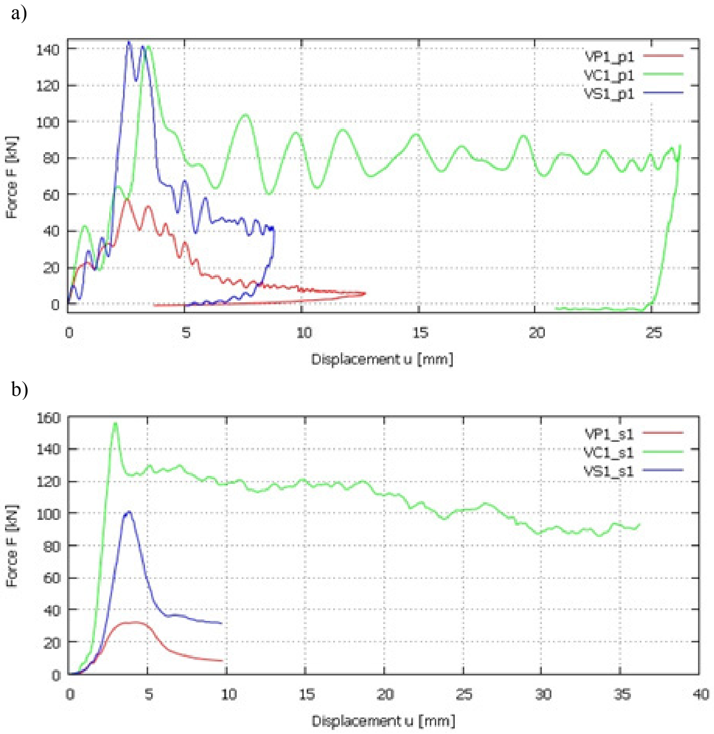

Fig. 5, Deformation characteristic of deformation element box (a) for quasi-static tests, (b) for dynamic impact tests.

Table 4. Comparison of the maximum force and the specific energy for different material of the deformation element box.

	Impact Tests		Quasistatic Tests	
Specimen Nr.	Max. Force [kN]	Spec.Energy [J/mm]	Max. Force [kN]	Spec.Energy [J/mm]
VP	70.6	26.1	32.2	17.9
VC	186.6	76.8	156.2	98.4
VS	162.2	60.2	101.0	42.0

5. Numerical simulation of the bus crash test

The full-scale crash-test simulations were performed in the PamCrash software. The FE model of the bodywork of the low-floor bus (type SOR, made in Czech Republic) was prepared. Deformation boxes were placed into the front part of this bodywork as part of the bumper. The stiffness characteristic of the deformation boxes in different loading modes and directions were evaluated by the FEM calculations on the simple deformation block model and with using presented dynamic response results of the specimens by the impact test. Initially, the bonded corrugated plate box made from carbon thermoplastic sheets (type VC, see Tab. 2) were built-in into the bumper. Crash into a rigid body (see Fig.6) with two different impact velocities of 20 and 30 km/hour were simulated.

Results showed that applied deformation boxes in the front bumper can effectively absorb large percentage of the impact energy in the initial stage of the crash. Basic structure remained undamaged at the speed simulation of 20 km/hour and at the speed of 30 km/hour was deformed only in the main front frame stringers, see Fig. 7a and Fig. 7b.

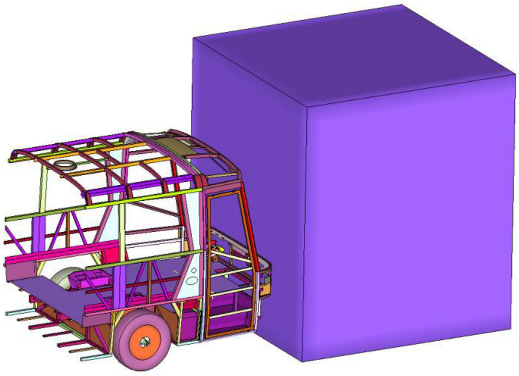

Fig. 6, Model of the crash-test of the bus bodywork.

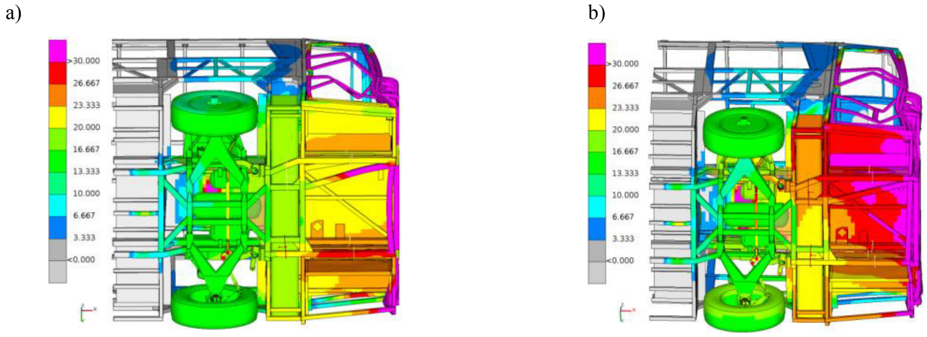

Fig. 7, Displacement field of the bottom part of the bus bodywork after crash (a) at the velocity 30 km/hour (structure with the energy absorber) (b) at the velocity 30 km/hour (structure without the energy absorber).

6. Conclusions

Several series of tests with different types of deformation elements were carried out that investigated not only the suitability of certain materials, but also the technology. Tests showed that there is a difference in material response, mainly in the first stage of deformation, between quasi-static and dynamic impact tests. Tests have shown that the absorbed deformation energy of elements made from filament wound composite tubes depends on the laminate layup. Deformation elements made from moulded thermoplastic sheets are very promising for parts of composite absorbers. But only the fabric made from carbon fibers showed a required degradation mechanism and high specific deformation energy, compared to glass or polypropylene fibres.

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