ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1216478

A FINITE ELEMENT MODEL DEVELOPMENT AS A PART OF PROCESS OF ENERGY ABSORPTION MATERIAL SELECTION

Rafał Jakubowski, Zbigniew Skorupka

Warsaw Institute of Aviation
Department of Transport and Energy Conversion
Krakowska Avenue 110/114, 02-256 Warsaw, Poland
tel.:+48 221883880, +48 221883885
e-mail: rafal.jakubowski@ilot.edu.pl, zbigniew.skorupka@ilot.edu.pl

Abstract

The Warsaw Institute of Aviation major role in the RASTAS Spear project was to design an energy absorption system for the space probe lander. As the system was meant to be unmanned, the main requirement was to use no active solutions like parachute or rocket propulsion (less complexity in application and thus more reliability). A group of various materials was chosen to be tested. Tests campaign was divided into three stages: static compression tests, low speed dynamic tests and high speed dynamic tests. The high-speed dynamic tests were divided into two substages. In the first one simple cube specimens were tested to obtain data necessary for second substage in which full-scale object was tested. Having valuable data from experiments, numerical simulations in LS-DYNA software were carried out and then the results were compared. Based on experimental data several iterations during finite element model developing process were made. That process allowed setting up properly simulation by changing and adjusting properties such: material models, contact types, element formulation and other important constants. The finite element simulation results showed a good correlation with experimental data. The knowledge gained from numerical model optimization in connection with experimental data allowed for creating faster and more accurate energy absorbing material selection methodology. This methodology was successfully used in subsequent projects in which Institute of Aviation took part and also can be used in other future applications.

Keywords: *RASTAS Spear, material, energy absorption, finite element model, LS-DYNA*

1. Introduction

In the years 2010-2013 Warsaw Institute of Aviation (WIA) participated in the RASTAS Spear project. The main task of the RASTAS Spear project was to expand the state of knowledge concerning space vehicles high-speed Earth's atmosphere re-entry, including design of a new passive landing system, which guaranteed safe return of payload. Final result of the project was the full-scale demonstrator of ERV (Earth Re-entry Vehicle) (Fig. 1), which should be sufficient to withstand harsh re-entry conditions [9]. The WIA's Landing Gear Department [5] was responsible for:

- passive landing system definition of Earth Re-entry Vehicle,
- preliminary energy absorption materials group selection,
- testing and simulation of crush phenomenon in laboratory conditions of lightweight materials appropriate for energy absorption during landing [7],
- final selection of energy absorbing material and full-scale demonstrator production (Fig. 2).

2. Experimental energy absorption material data acquisition for FE model development

Preliminary selected materials were tested both quasi-statically and dynamically (Fig. 3) [2]. The quasi-static tests of simple cube-shaped material samples provided force versus displacement curves. Based on those data the stress versus strain curves were calculated (Fig. 4), needed for material model definition during finite element model building.

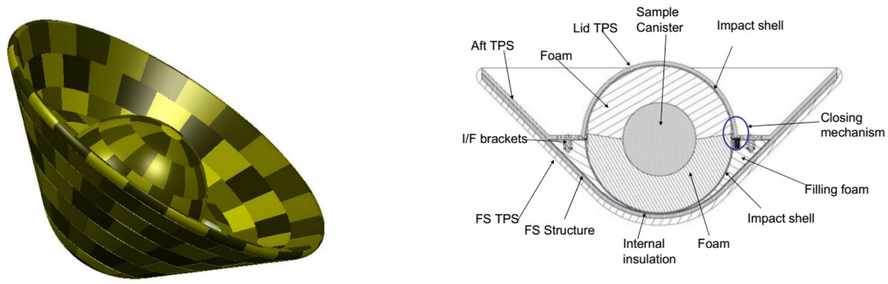
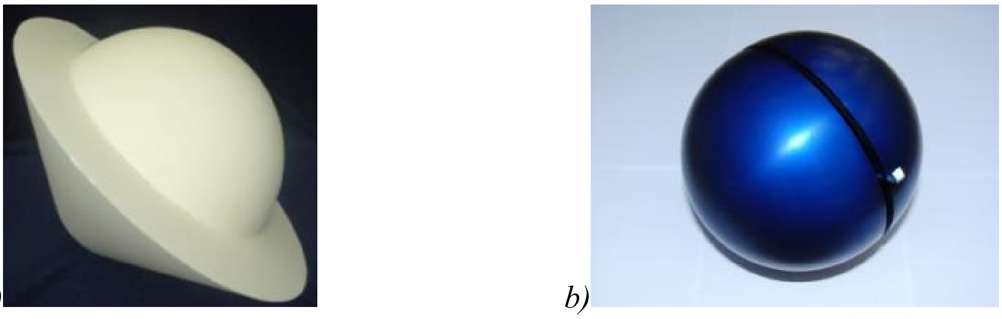
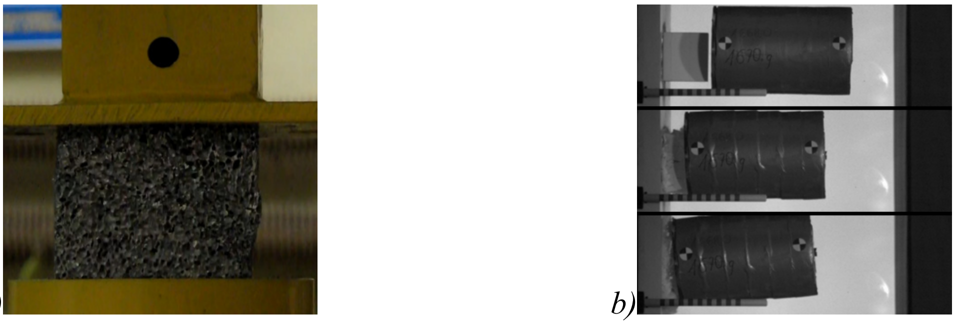


Fig. 1. Earth Re-entry Capsule design for Earth Re-entry Demonstrator mission [2]



a) *b)*

Fig. 2. Full-scale demonstrator of a) Energy absorption material b) Payload [6]



a) *b)*

Fig. 3. Footage taken from a) quasi-static tests b) dynamic tests

Dynamic tests were carried out in two stages: first to assess dynamic behaviour of tested cube-shaped samples (flat bullet head) and second to test full-scale object prepared from chosen materials (sphere shaped bullet head corresponding to the real payload mass). The displacement, velocity and deceleration were measured using high-speed camera and software suite for advanced motion analysis. The basic requirements for tested energy absorbing materials were:

- isotropic structure,
- thermally stability,
- maximum total mass not exceeding 8 kg,
- availability,
- initial ERV collision speed with the ground 45 m/s.
- maximum deceleration during impact not more than 2000 g during 10 ms time interval.

3. Finite Element model development

Numerical simulations reflecting the real tests were performed using the finite elements method implemented in LS-DYNA [8]. Both the bullet and the energy absorbing material were modelled using SOLID elements type (Fig. 5). Full integrated formulation for solid elements (ELFORM:2) was applied to eliminate hourglassing problems. Eroding Surface to Surface contact type was used for all sections. This contact type is useful in the cases where the negative volume in elements can occur due to high deformation of the model. Using this contact type, elements with negative volume are deleted from analysis and calculation can be continued. For the contact between the bullet and the energy, absorbing materials 0.5 coefficient of friction was set. The friction coefficient was calculated using data acquired in aluminium and energy absorbing material pair test.

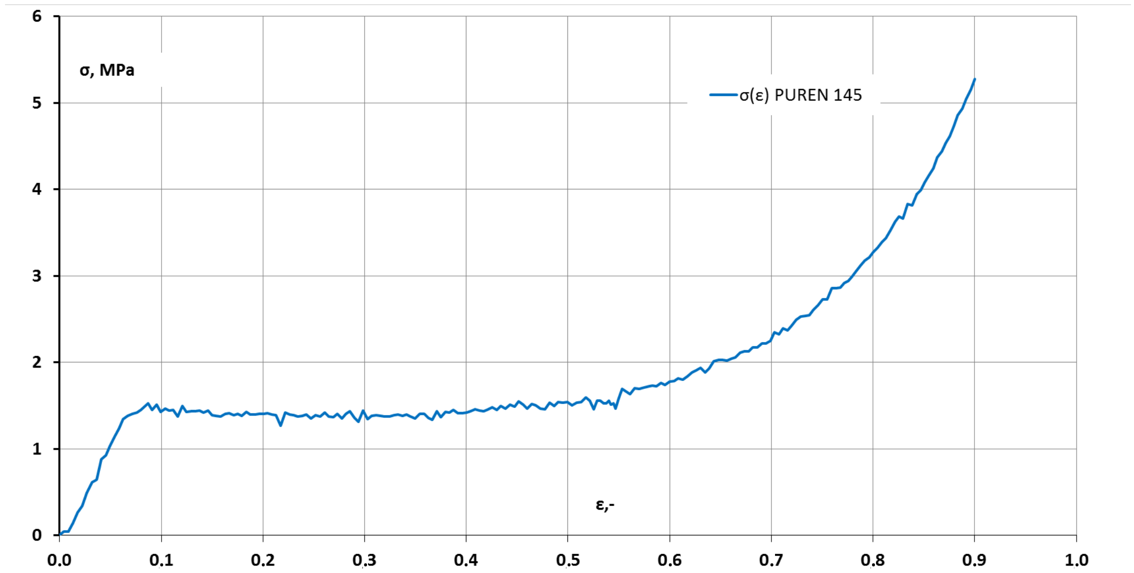


Fig. 4. Stress versus strain curve for Puren145 material used in FE model

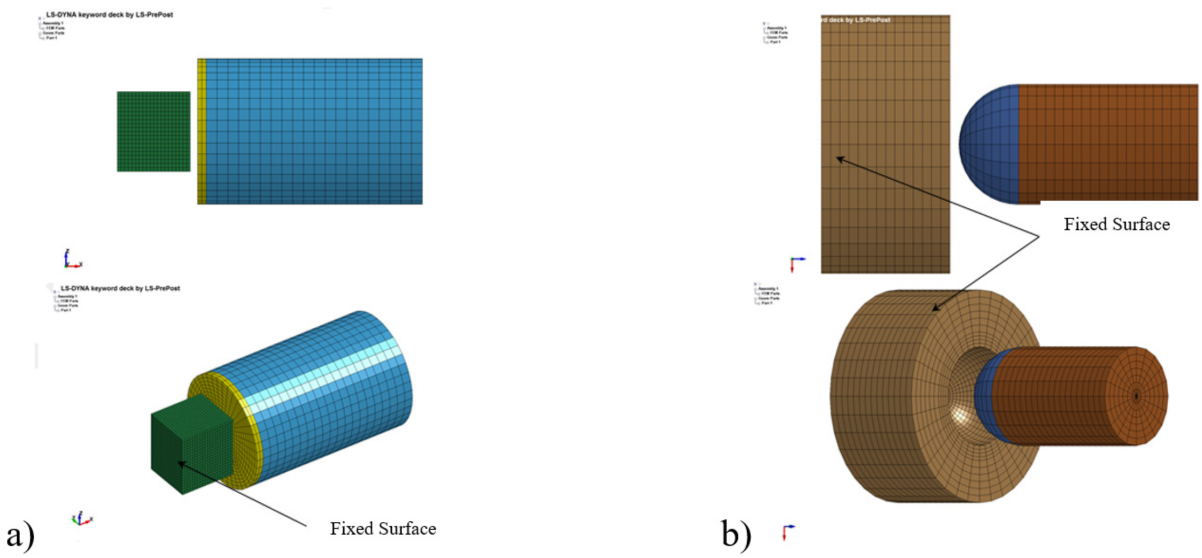


Fig. 5. Finite element models representing tests of a) cube-shaped samples b) full-scale object

For all the bullet nodes initial velocity equal to the one from the corresponding dynamic test was set. The bullet head geometry in both flat and sphere type wasn't exactly the same as in the real object (geometry simplification) so the density of the bullet head material in LS-DYNA was slightly changed to obtain exactly the same bullet mass in LS-DYNA as in experiment what resulted in insignificant change in the bullet's inertia. The energy absorbing material was fixed at the end and for cylinder specimen on the sidewalls as well. Gravity was also included to the simulation.

Hourglass (HGEN), stonewall (rigidwall) (RWEN) and sliding interface (contact) energy (SLNTEN) dissipations were computed and included in the energy balance. For load curve, discretization (LCINT) number of equally spaced intervals equal to n+1 was set where n is the number of points in load curve defined for the energy absorbing material. The time interval between the outputs between both the outputs between both the outputs both for d3plot and ASCII file was the same as in the laboratory test.

There is a number of material models included in LS-DYNA for simulating foam material types used in the real tests so it is important to apply the proper one [1, 3, 4]. Many of them require load curves and number of experimental constants, which are difficult to obtain, hence it was decided to implement the 063-CRUSHABLE_FOAM material model. This material model can be applied in simulation of impact and other phenomena where cyclic behaviour is not important. The 063 material model is robust and requires basic input data, which can be easily obtained. For an aluminium bullet head the 024PIECEWISE_LINEAR_PLASTICITY material model was used.

Simulation results from the nodes corresponding to the measurement points (cross marker placed on bullet) in the laboratory tests were gathered. As in the tests, the data was filtered using f=650 Hz cut-off frequency Butterworth filter. The frequency was estimated using signal power spectrum analysis procedure written in LabView software. Displacement, velocity and deceleration versus time plots from simulation were compared with the ones from the experiment. The results for cubic and cylindrical specimens are presented in Tab. 1. The comparison of the simulation and laboratory test for finally chosen Puren145 material are presented in the Fig. 6. There is good correlation between the test and simulation results. It must be mentioned that in the simulation there were some simplifications implemented, for example the structure of the bullet. The real bullet was also wrapped in the tape, which slightly changed its mechanical properties and could influence the results.

Tab. 1. Comparison between FEM analysis results and experimental data

	Material	Average deceleration [g]		Maximum deceleration [g]		Maximum displacement [mm]	
		Test	Simulation	Test	Simulation	Test	Simulation
cube sample	Puren100	911	740	1976	2205	79	84
cube sample	Puren145	1439	1324	3170	3190	89	82
cube sample	Puren200	1398	1640	2789	2501	64	62
cube sample	CRPF10	1160	1182	1783	1973	80	74
cube sample	SRPF5	657	841	1500	1919	88	87
cube sample	SRPF10	1481	1459	2083	2231	82	75
cube sample	AluFoam	1411	1882	2482	3019	76	68
cube sample	Calcarb	1057	1663	4390	4476	82	89
cylindrical sample	Puren100	1078	1264	3352	3340	131	129
cylindrical sample	Puren145	1368	1495	2369	1999	82	86
cylinder sample	Puren200	2746	2793	4603	4409	44	54

Real-shaped object crash simulation was carried out using the final chosen Puren100 and Puren145 energy absorbing materials. (the laboratory tests were carried out for simplified crushable material geometry due to difficulties with the test boundary conditions). Two cases were considered. In the first case a 5 kg sphere canister hit the fixed, sphere shaped energy absorbing material with zero initial velocity. In the second case, both canister and energy absorbing material had an initial velocity of 45 m/s. In the Fig. 7, the final FE model with boundary and initial conditions is shown.

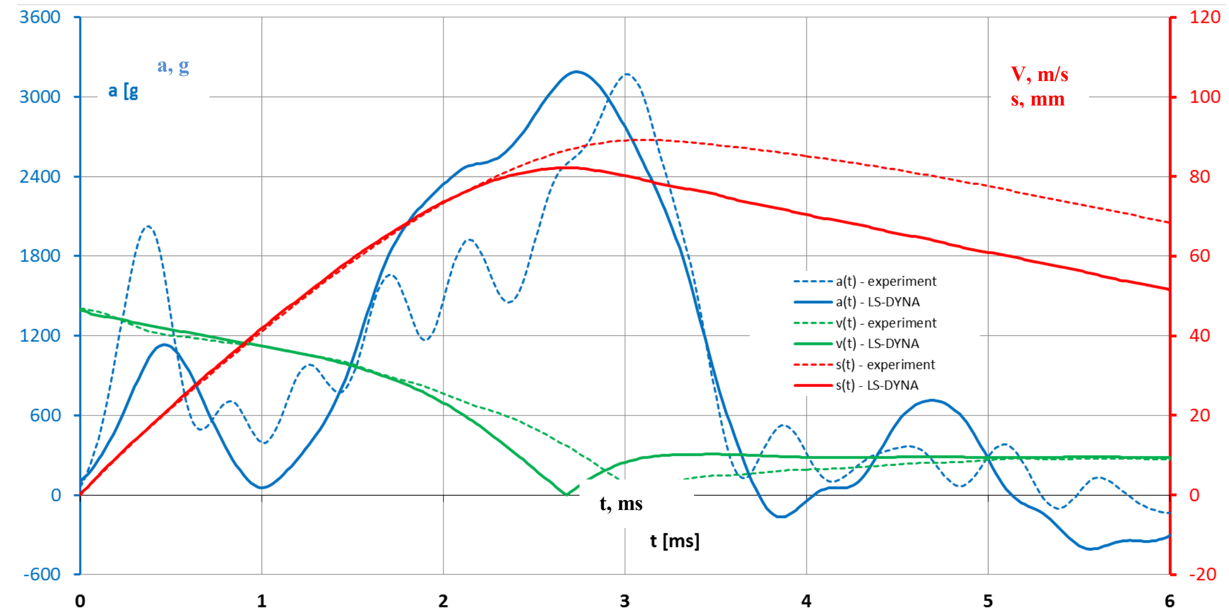


Fig. 6. Finite Comparison of simulation and laboratory test results for Puren145 material

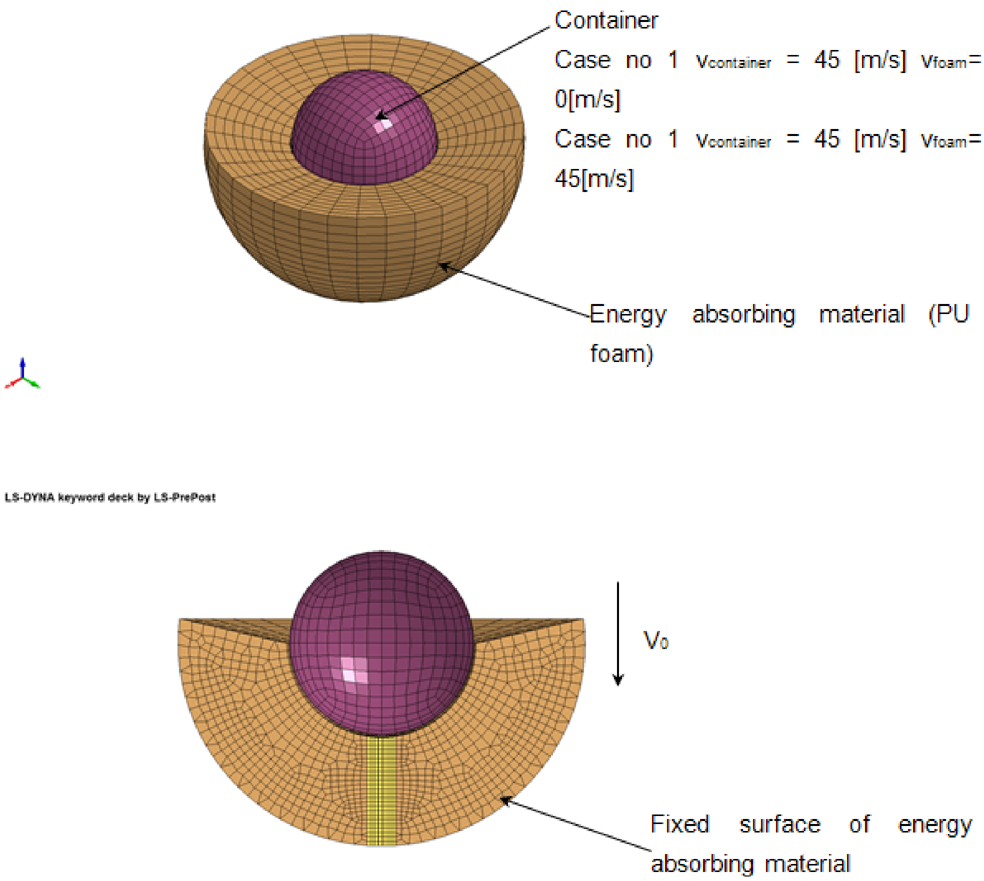


Fig. 7. Finite FEM model of container surrounded by energy absorbing material with initial and boundary conditions shown

The results show that self-collapsing of the energy absorbing material decreases available energy-absorbing distance and this phenomenon can cause unwanted peak of acceleration in the case of Puren100 (Fig. 8) material. For Puren145 material, there is no big effect of the foam self-collapsing on acceleration versus time curve and acceleration does not exceed maximal allowed value at any point of the process (Fig. 9).

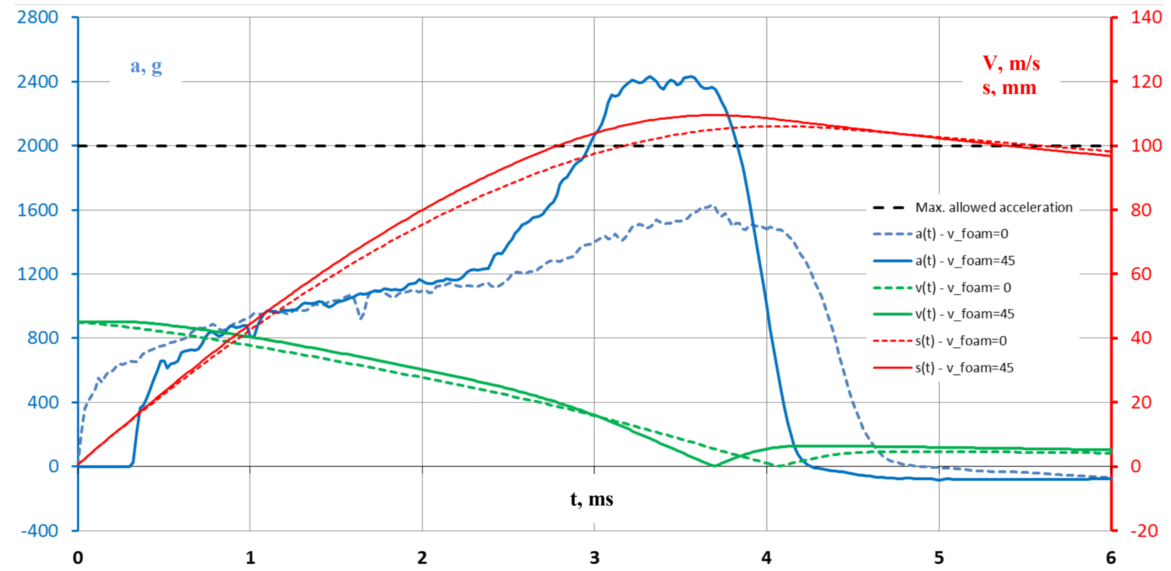


Fig. 8. The results of real shaped object FEM simulation – Puren 100 material

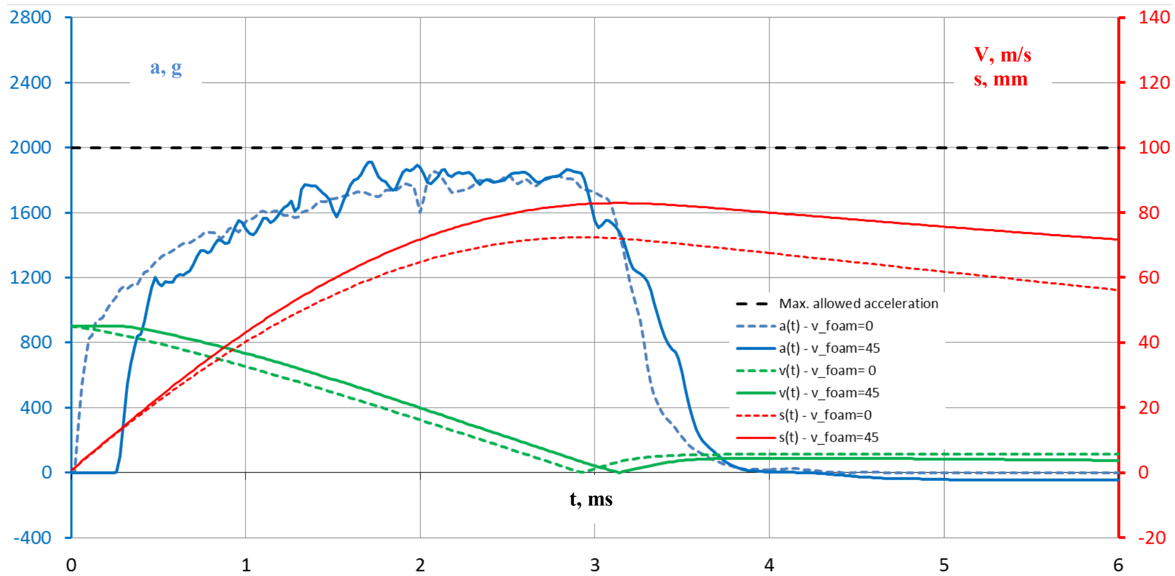


Fig. 9. The results for real energy absorption module FEM simulation – Puren 145 material

4. Summary

In this paper authors presented finite element model development for simulating dynamic energy absorption test of crushable materials. The numerical calculations were a part of energy absorbing material selection process during RASTAS Spear project. The valuable data measured during the static and dynamic tests greatly helped in FE model development. The simulation results were in good correlation with test data both for simple shaped cubic samples and for full-scale cylindrical object. Additionally, the numerical model of real energy absorption module was build and solved. The results showed the module's capability to fulfil one of the basic project requirements (maximum allowed deceleration of payload not exciding 2000 g). The experience gained during FE model development allows making first estimation of material usability without extensive laboratory testing what results in accelerating of material selection process and helps to lower costs.

Presented work was financed from the funds for science in years 2010 – 2012 granted for the international co-financed project.

References

[1] Croop, B., Lobo, H., *Selecting material models for the simulation of foams in LS-DYNA*, DatapointLabs, NY, USA 2009.

[2] Lu, G., Yu, T., *Energy Absorption of Structures and Materials*, NW Boca Raton FL 33431, USA 2000.

[3] Monnich, S., Becker, F., Fellner, B., *Comparison of material models for crash simulation – experimental and simulation work,* German Institute for Polymers (DKI), Germany 2011.

[4] Serifi, E., Hirth, A., Maththaei, S., Mullerschon, H., *Modeling of foams using MAT83 – prearation and evaluation of experimental data*, Germany 2003.

[5] Wiśniowski, W*., Specjalizacje Instytutu Lotnictwa, Przegląd i wnioski,* Prace Instytutu Lotnictwa, 2014.

[6] *D3.6 Crushable Material Tests – Report,* 0037/57/LW/2012/RAP, Institute of Aviation, Warsaw 2012.

[7] *Investigation of experimental techniques and designing test procedure for rastas spear project-Report,* 24/BZ/2011/RAP, Institute of Aviation, Warsaw 2011.

[8] LS-DYNA, *Keyword User's Manual*, Vol. 1-2, Livemore Software Technology Corporation (LSTC), 2012.

[9] Periodic Report – RASTAS SPEAR, (*RAdiation-Shapes Thermal protection investigAtionS for high-SPeed EArth Re-entry*), 2012.