Laboratory investigations on crushable materials as structural energy absorbers for space probe lander

INTRODUCTION

The article consists summary of work done by Landing Gear Department (part of Institute of Aviation in Warsaw - ILot) in European Union project RAdiation – Shapes Thermal protection investigAtionS for high – Speed EArth Re – entry (RASTAS SPEAR), project number: FP7/SPACE/241992.[1] Due to the RASTAS Spear project requirements, it was necessary to create a material based system. Passive (material based) energy dissipating systems as an alternative to active ones (parachute, air-cushion) are less complex in application and thus more reliable. Although the active systems allow to achieve substantially lower deceleration during impact, passive systems can be a better choice for unmanned capsules where the higher deceleration is acceptable. Simplicity and reliability are essential advantages of passive (material based) energy dissipating systems.

1. MODERN (ALTERNATIVE) APPROACH TO SPACE CAPSULE ENERGY DISSIPATING LANDING SYSTEMS EMBEDDED INTO LANDERS STRUCTURE (MATERIAL APPROACH)

Basic requirements for energy absorbing material selection in RASTAS SPEAR project:

- impact velocity up to $v_i = 45$ m/s maximum deceleration of sample canister cannot exceed 2000 g during 10 ms time interval
- selected material should have isotropic mechanical properties
- maximum total mass of crushable material cannot exceed 8 kg
- material must be reproducible and should have the same properties (uniform density, strength)

Having requirements described above, materials selection process was divided into 3 stages:

- quasi-static tests for selected various material samples
- low-speed dynamic tests for materials selected in static tests
- high-speed dynamic impact tests using full scale model for final chosen materials.

Each stage of the material selection process and its results are described in the following sections of this paper.

2. ENERGY ABSORBING MATERIALS SELECTION AND QUASI-STATIC TESTS

The first stage of material selection process was to find a potential group of materials whose density fulfils the requirement of maximum total mass for the established crushable zone geometry inside the capsule [6]. The second major requirement is to provide materials with isotropic mechanical properties. Twenty three different materials were chosen for the static tests (figure 1). The aim of the tests was to check material behaviour during compression and to assess general energy absorption capabilities in connection to each material volume and mass. At this stage some of the materials were excluded from further tests due to unsatisfactory results.
The cubic material sample shape (100x100x100 mm) was chosen to make the preparation process as simple as possible and to have a comparable results for analysis of tested materials. The dimensions ratio is also connected with the nature of the compression test (to avoid undesirable buckling and shearing of specimens). For static tests 40 ton hydraulic press (figure 2) was used. This stand is generally used in landing gear components static trials: wheels, shock absorbers.
The basic function of materials classified as energy absorbers is to take up the kinetic energy by compressing and deflecting with possibly constant stress value. If force applied goes over the crush strength, crushable structure will start to compress with fairly constant stress up to achieve a 50–70 % of strain (figure 3).

Fig. 3 Work zones of crushable material on stress – strain curve[4]

The graph in the figure 3 shows two zones in a typical energy absorbing material. First (dashed) is a basic energy absorption zone presenting the amount of energy which equals to the product of stress and strain. It gives the value of the strain in total mechanical energy per unit volume consumed by the material in straining it to that value:

\[ E = \frac{1}{V} \int P \, dL = \int_{0}^{\varepsilon} \frac{P}{A} \, \frac{dL}{L_0} = \int_{0}^{\varepsilon} \sigma \, d\varepsilon \]  

(1)

Alternatively, energy equals the work done by the force over certain distance, in this case the deflection of the material, therefore assumption can be made that:

\[ \text{Stress} \cdot \text{strain} = \text{force} \cdot \text{displacement} = \text{work}=\text{kinetic energy} \]

As it is shown, the kinetic energy of the object impacting the block of foam equals the work done by compressing that block. By proper calculation of the thickness and the compression strength, selected the block of foam can absorb all the energy of the hitting mass. The first part of the stress–strain curve (figure 3) is a zone covering the energy needed for stopping an object. The second part can be treated as a “backup safety zone”. While designing a crushable structure it is worth to use the newest data in order to compute the stroke needed. The impact parameters can change, due to the fact that they cannot be predicted with perfect accuracy. To eliminate potential hazardous situations like a force peak acting on the payload during the crash it is important to correctly estimate the “backup safety zone” taking into account the worst possible scenario. The safety area is the second part of stress – strain curve.

After testing all the initially chosen materials a result analysis was carried out. For each specimen the following values were calculated:
- total energy absorbed,
- energy absorbed per volume and per mass,
- energy absorbing efficiency.
Energy absorbing efficiency was calculated for 40%, 60% and 80% of the total specimen compression. The efficiency was obtained using the formula:

\[
\eta(\Delta L_z) = \frac{\int_0^{\Delta L_z} F_z \, dz}{F_{z max}(\Delta L_z) \cdot \Delta L_z}
\]

where:

- \( F_{z max}(\Delta L_z) \) - the maximum force occurred between 0 and \( \Delta L_z \) compression distance.

![Sample graph of F(\Delta Lz) (red) and energy absorbed (blue) curves during compression process in quasi-static test.][5]

### 3. DYNAMIC TESTS

For the next test stage (low-speed dynamic) 8 materials were chosen: Puren100, Puren145, Puren200, Cellular Rigid Polyurethane Foam 10 (CRPF10), Solid Rigid Polyurethane Foam 5 (SRPF5), SRPF10, Calcarb and Alporas Aluminum Foam (Alufoam). The material selection was based on the requirements described in section 3 of this paper and after a comparison of the estimated values. Figure 9 shows representative F(\( \Delta L_z \)) curve (red) and energy absorbed (blue) during compression process for Puren145 material specimen.

Initially dynamic tests were divided into two stages, low speed and high speed dynamic tests. However, due to the measurement method used and signal noises caused by Drop Stand (normally used for Landing Gear drop tests) itself, the data acquired was inconclusive. It was decided to focus on high-speed dynamic tests, which were definitely more important for energy absorbing material selection process. Low speed dynamic tests showed general behaviour of materials during compression at impact velocity from 2,5 to 4,5 m/s. Figure 5 shows the Drop test stand for low dynamic tests and the figure 6 shows the representative force F, velocity v, acceleration a and compression L versus time t curve for Alufoam material.

The aim of the high-speed dynamic tests was to check material behaviour under the maximum impact velocity limited to 45 m/s as defined in the project. To be able to carry out the tests an air canon was designed and built in the ILot Landing Gear Department (figure 7).
The test was divided into two phases. During the first phase cubic specimens (the same size as in the static tests) were hit with a 1.5 kg flat bullet head (figure 8). The deceleration was measured using high speed video recording combined with image processing software. For high speed a recording camera was used (50000 frames per second). The image processing software used has several algorithms to track a characteristic point (pixel) or an area (group of pixels) in the high speed camera movie. During analysis quadrant the symmetry algorithm was chosen. There are a few available filters which can be used to improve measured processes. To analyse the data the CFC filter was used.
The CFC filter applies a fourth order phaselss Butterworth filter. All physical data is processed, except for images and calibration sequences. For vector data each component is filtered. The filter is a non-causal IIR (Infinite Impulse Response) filter, i.e. a change in any input sample affects the entire output. Invalid input samples are interpolated and the corresponding output samples are marked as invalid. Input data is re-sampled to an equidistant time base. The CFC parameter determines the cut-off frequency of the filter (f= 650 Hz was set). Frequency was estimated using signal power spectrum analysis procedure written in LabView software. Figure 9 shows displacement, velocity and acceleration versus time curve. The first acceleration peak can be caused by brittle material nature. During compression the specimen rapidly loses its structural integrity and a sudden drop of acceleration is observed.

![Graph showing displacement, velocity, and acceleration versus time.](image)

**Fig. 8** Sample graph obtained in high speed dynamic test for cube shaped test sample.[5]

**Tab. 1** The results of high speed dynamic tests using cube shaped test sample[5]

<table>
<thead>
<tr>
<th>Material</th>
<th>a avg g</th>
<th>a max g</th>
<th>s max mm</th>
<th>v 0 m/s</th>
<th>Bullet mass g</th>
<th>material density kg/m³</th>
<th>Sample mass g</th>
<th>EkJ J</th>
<th>ζ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puren100</td>
<td>911</td>
<td>1976</td>
<td>79</td>
<td>35.5</td>
<td>1636</td>
<td>106</td>
<td>102,8</td>
<td>1031</td>
<td>1.12</td>
</tr>
<tr>
<td>Puren145</td>
<td>1439</td>
<td>3170</td>
<td>89</td>
<td>46.4</td>
<td>1763</td>
<td>151</td>
<td>150,4</td>
<td>1898</td>
<td>0.99</td>
</tr>
<tr>
<td>Puren200</td>
<td>1398</td>
<td>2789</td>
<td>64</td>
<td>44</td>
<td>1763</td>
<td>204</td>
<td>208,4</td>
<td>1707</td>
<td>0.60</td>
</tr>
<tr>
<td>CRPF10</td>
<td>1160</td>
<td>1783</td>
<td>80</td>
<td>43.3</td>
<td>1636</td>
<td>168</td>
<td>165,5</td>
<td>1534</td>
<td>0.21</td>
</tr>
<tr>
<td>SRPF5</td>
<td>657</td>
<td>1500</td>
<td>88</td>
<td>31,5</td>
<td>1750</td>
<td>90</td>
<td>89,5</td>
<td>868</td>
<td>1.51</td>
</tr>
<tr>
<td>SRPF10</td>
<td>1481</td>
<td>2083</td>
<td>82</td>
<td>47,3</td>
<td>1636</td>
<td>162</td>
<td>158,0</td>
<td>1830</td>
<td>0.30</td>
</tr>
<tr>
<td>AluFoam</td>
<td>1411</td>
<td>2482</td>
<td>76</td>
<td>43,8</td>
<td>1750</td>
<td>205</td>
<td>203,2</td>
<td>1679</td>
<td>0.60</td>
</tr>
<tr>
<td>Calcarb</td>
<td>1057</td>
<td>4390</td>
<td>82</td>
<td>37,4</td>
<td>1750</td>
<td>216</td>
<td>188,6</td>
<td>1224</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Table 1 presents the data from the first stage of the high-speed velocity experiments. There is a “ζ” factor introduced in order to estimate the material energy absorption efficiency. In this factor initial the kinetic energy, specimen mass and average deceleration are included. Because mass and deceleration should be as low as possible, the higher the factor is the better should the material energy absorption efficiency be potentially. The next important fact is the observed difference between maximum acceleration and the average acceleration during the compression stage. For example in the case of “calcarb” material the average acceleration is not high but the maximum acceleration is well above the limit of 2000g acceleration (with unrequired initial velocity achieved). Based on the “ζ” factor five potential materials were chosen for the second stage of high speed test but it must be mentioned that it wasn’t possible to test all the materials with the required 45 m/s velocity (possibility
of bullet destruction). Finally for the 2nd stage of the test Puren145 was chosen also due to material block size inaccessibility for CRPF10 and SRPF10 materials concerning required dimensions. Additionally Puren200 and Puren100 were chosen.

The last stage of the high-speed dynamic tests was performed for full scale conditions both considering mass, geometry of objects and impact velocity. During the tests a 200mm diameter spherical head bullet with 5.5 kg of total mass was used (figure 10a). The crushable material specimens were in the shape of a cylinder with a spherical hole in the center (figure 10b).

Fig. 9 Spherical head bullet a) crushable material cylindrical specimen b)

Table 2 presents the results of the tests. It is easy to notice that the value of the “ς” factor significantly dropped comparing to the previous high-speed test results. The kinetic energy increased from four to six times while specimen mass increased about 30 times (that fact explains the decrease of the “ς” factor). However the “ς” factor can still be used to assess energy absorbing capability of materials. Another important aspect is the maximum displacement (s_max). For Puren100 it is equal to 130mm, whereas specimen thickness is equal to 115mm (Table 2). The difference could be explained by the fact that the marker (due to technical measuring issues) was placed on the bullet guide. When the maximum available energy-absorbing material displacement was achieved the bullet foam started collapsing noticeably. This fact leads to the conclusion that when using Puren100 material there is a strong possibility for achieving the maximum energy absorbing distance and for facing a substantial peak of deceleration in the last step of slowing down the probe canister. The best solution then is to use as a front energy absorbing material Puren145 foam which has a lower maximum acceleration and an average acceleration being much below the 2000g limit.

Tab. 2 The results of the high speed dynamic tests using a cylinder shaped with spherical cut test sample[5]
CONCLUSIONS

In this paper the authors presented the energy absorbing material selection process. It was divided into three test stages: quasi-static, low-speed and high-speed. Quasi-static tests as the first step of assessing energy-absorbing capability of material provided the essential data for further FEM calculations and dynamic tests. Low speed dynamic tests allowed to assess the general behaviour of crushable materials during the impact process. The high-speed tests stage was divided into two phases (cubic specimens tests and full scale object test) which allowed the selection two energy absorbing materials which met the RASTAS SPEAR project requirements. Puren145 polyurethane foam as the front energy absorber and Puren100 as the back energy absorber for the probe were chosen.

After the final selection of the materials for crushable structure, a demonstrator of the technology was made. The demonstrator was slightly smaller than the real object and it was manufactured according to the dimensions given by Demokritos in order to fit their part of the Demo. The ILot also made a demonstrator of the Payload, which is an aluminum sphere. In the Figure 11, photographs of Crushable Structure Demonstrator and Payload Demonstrator are shown.

![Crushable Material Demonstrator a), b), c). Payload Demonstrator d), [5]](image)

Fig. 10 Crushable Material Demonstrator a), b), c). Payload Demonstrator d), [5]

Abstract

Energy absorption during landing process is one of the most important processes in space and aviation. Wrong design in this field can cause damage or destruction of the landing object. As for now most of the energy absorption is performed using mechanical systems from parachutes to shock absorbers. Due to mass restrictions and economical reasons, space industry aims to replace mechanical systems with material based absorption. In the RASTAS Spear project ILot Landing Gear Department engineers analysed, tested and calculated possible energy absorption materials in order to check and evaluate their usefulness in space applications. In this paper authors described the entire process which led to the design of the structure capable of efficient and reliable energy absorption in a small space lander.

Keywords: RASTAS Spear; material; energy absorption; laboratory tests.
Streszczenie

Pochłanianie energii podczas lądowania jest jednym z ważniejszych procesów zachodzących podczas lądowania w lotnictwie jak i w pojazdach kosmicznych. Żle zaprojektowane układy pochłaniani energii mogą doprowadzić do uszkodzenia lub zniszczenia lądującego obiektu. Na chwilę obecną większość pochłaniania energii lądowania realizowana jest za pomocą układów mechanicznych poczynając od spadochronów a skończywszy na amortyzatorach. Ze względów masowych oraz ekonomicznych, przemysł kosmiczny dąży do zastąpienia układów mechanicznych przez układy oparte na materiałach energochłonnych. W projekcie RASTAS Spear inżynierowie Pracowni Podwozi Instytutu Lotnictwa dokonali wstępnej analizy, badań i niezbędnych obliczeń w celu oceny i właściwego doboru materiałów energochłonnych spełniających kryteria przydatności w zastosowaniach kosmicznych. W artykule autorzy opisują proces doświadczalnego doboru materiału energochłonnego, który doprowadził do projektu układu pochłaniania energii lądowania lądownika kosmicznego.

Słowa kluczowe: RASTAS Spear, materiał, energochłonność, testy laboratoryjne.

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