Development and Analysis of a Ground Impact Attenuator for the Re-entry Satellite SARA

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Abstract. *SARA - Satellite for Re-entry in the Atmosphere - is a project of a capsule, in partnership between Brazil and Germany, to conduce micro-gravity experiments in an orbit of 300 km. After the launch, the satellite must stay in orbit for approximately ten days and then be re-conducted to Earth. To reduce costs, one of the most important characteristics of this capsule is to be re-usable. In this way, it is necessary to develop a recovery system that protects both payload and the main structure. In this paper, a carbon fabric and epoxy resin tube, at capsule`s nose, for the ground impact attenuator is proposed; experimental and numerical analyses are presented to illustrate its performance.*

Keywords*: attenuator, carbon fabric, crash tubes, crashworthiness, drop tower, re-entry.*

1. Introduction

SARA (**SA**tellite for **R**e-entry in the **A**tmosphere) is a project in partnership between Brazil and Germany, of a capsule to conduce micro-gravity experiments in an orbit of 300 km. The satellite's mission is to be launched and to stay in orbit for approximately ten days and then to be re-conducted to Earth. To reduce costs, one of the most important characteristics of this project is to be re-usable. In this way, it is necessary to develop a recovery system that protects the main structure of the capsule and also that supplies security conditions to the payload.

The first phase of the work is concerned to acquire all the data about the project SARA as well as the requirements for the system to be designed. Also a first analysis of the physical limitations of the system was performed using the basic laws of kinematics, which helped to guide the first ideas for the attenuator.

In the second phase of the work, time was spent with the first ideas of systems that could provide the expected results. Studies were performed to analyse the viability of such systems, till the final idea chosen to follow the project. This idea was based on all the knowledge of DLR - IBK (Deutsches Zentrum für Luft- und Raumfahrt – Institut für Bauweisen und Konstruktionsforschung) about crush structures. An impact attenuator consisting in crash carbon tubes was purposed and superficially designed.

Once a solution for the problem was selected, numerical simulations were performed to find the geometry of the tube that could supply the requirements of SARA. Found the geometry, dynamic tests were performed. It was decided to perform firstly quasi-static tests that served as a way to calibrate the right geometry of the crash tubes and then was finally possible to perform the real impact tests, with a fall mass over the tubes.

2. Description of the Satellite – Structure, Weights and Initial Specifications

The main characteristics of this project were supplied by IAE – Brazilian Aerospace Centre. A sketch of SARA is shown in Fig. 1 as well as its simplified mass distribution. The total mass is estimated in 287.39kg and the gravity centre stays at approximately 819.87mm from the nose, considering 25kg of payload which position is 700mm also from the nose.

The initial specifications for the system to be developed concern to:

a. Deceleration level: acceptable maximum of constant 10 g's at payload and 15 g's at structural parts. Considering that the deceleration will be approximately the same at all the parts of the satellite, the 10 g's are considered to follow on the project;
b. Impact velocities: the parachutes system used in the satellite can guarantee a vertical impact velocity of 10m/s. The horizontal velocity depends on the wind conditions, but will be neglected and the impact will be considered vertical. Then the viability of the attenuator proposed depends on an auxiliary subsystem that prevents any horizontal movement;

c. Land place: Lençóis Maranhenses in the northeast of Brazil, state of Maranhão, was chosen to be the landing place. This is a region with irregular soil, lots of dunes and small lakes;
d. Mass and available space for the attenuation system: considered 15kg the mass of the system, and the available space just the internal space of the nose that consists in a half spherical volume with radius 280mm. Extensions in this volume need to be carefully studied.
e. Soil model: this work as a first and superficial study about the absorber did not consider conservatively any kind of energy absorption capability of the soil.

Weights and position of the components

Item	Name	Mass (kg)	Position (mm)*
1	External Structure	59,76	514,95
2	Internal Structure	14,57	1253,00
3	Back Structure	28,55	1481,37
4	Back Equipments	10,93	1652,80
5	Place of Electronic Equipments	36,40	900,00
6	Recovery System	8,99	1615,97
7	Thermal Insulation Shield	17,20	130,00
8	Experimental Equipments	36,00	666,00
9	PayLoad	25,00	700,00
10	Altitude and Propulsion Systems	35,00	900,00
11	Nose Structure - absorber	15,00	250,00
	SARA - Center of Gravity	287,39	819,87

** The reference is the begining of the nose*

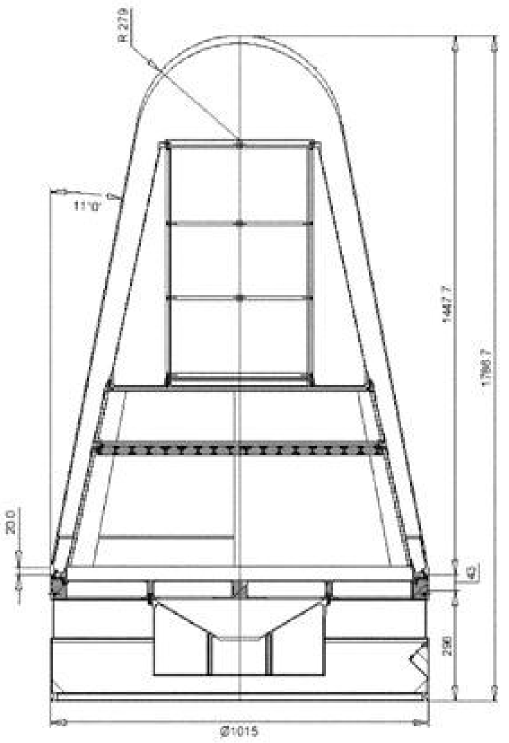

Figure 1. Sketch and mass distribution of SARA

3. Physical limitations

Given the impact velocity and the deceleration level expected, it is possible to estimate the necessary length to stop the satellite. This length is an important requirement for the project because it limits the system to be used. Considering constant deceleration during impact, Fig. 2 brings the relation between impact velocity and necessary length for complete stop.

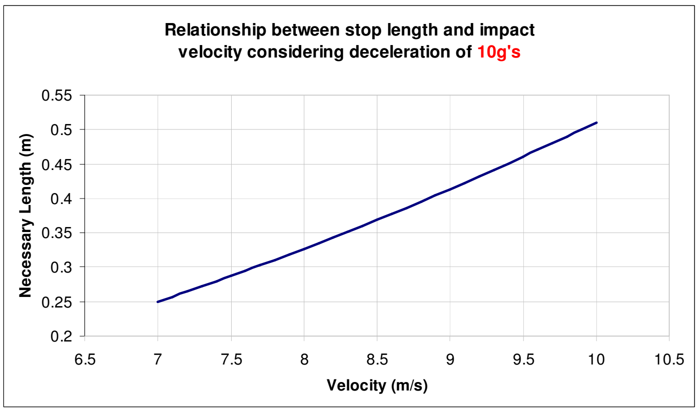

Figure 2. Relationship between available length and velocity, considering 10 g's of deceleration during the impact

As can be seen from Fig. 2, at 10m/s and subjected to 10 g's of deceleration, the capsule would stop after approximately 0.51m of deformation. Of course this is a first estimative and it is conservative, once it is assumed that the soil will not absorb any part of the kinetic energy. By the way, the solution adopted needs a mechanism either to reduce the velocity or to increase the length available to stop the capsule. The g level supplied can not be changed, once this requirement depends on a compromise with the customers, interested in experiments using SARA.

4. SARA – propose of an absorber

Tubes made with carbon fibers embedded in an epoxy resin matrix were adopted as the impact absorbers of SARA, as illustrated in Fig. 3 (b). This solution was adopted due to DLR interest in improving the knowledge of the general behavior of composite aerospace structures.

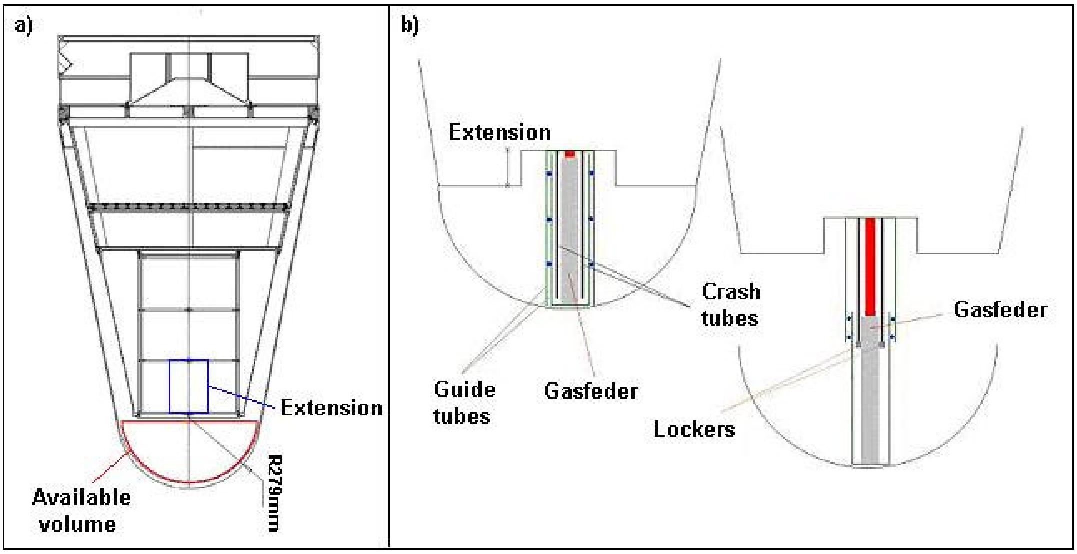

Figure 3. a) Extension for placing the absorber; b) Sketch of the mechanism

The crash tube needs to have, in a first approach, a length of 0,51m, as discussed in section 3. Then a way to store such a mechanism in the nose volume needs to be found. A simple solution is presented in Fig. 3(a), which consists in a cylindrical space in the main body.

The absorber consists basically in a tube made with carbon fabric and epoxy resin. The right failure, it is, without buckling, can be guaranteed making use of a guide-tube around of the carbon tube, and the way to crash the tube is got using an attenuator that can extend. This attenuator is available in the market. A sketch of this system is presented in Fig. 3(b).

As can be seen in Fig. 3(b), the attenuator needs to be equipped with a system to lock the carbon tube in the time of the impact. The way which the system works is described as follows:

a. before the impact, a detector of altitude starts the attenuator and therefore the extension of the nose. This detector of altitude can be the same that is used to open the parachutes;
b. by means of the guide-tube, the nose is completely extended;
c. the attenuator locks the crash tube by means of a mechanism;
d. after the impact, the guide-tube conduce the crash of the carbon tube, until the stop of the capsule.

In this work, the main task is to design the carbon tube, and also to demonstrate that the system works. Details of the other mechanical parts are not discussed and must be presented in further works.

The design of this carbon tube involves three main phases:

1. simulation of a model of the satellite to find the geometry of the absorber element that generates the required g' level curve in the payload;
2. quasi-static test of a range of carbon tubes to find the dimensions which lead to the force-deflection curve already found. In this part of the work, the real mechanical characteristics of the carbon tube with such dimensions are also found;
3. drop test using the geometry found in phase 2 to check the real failure behaviour of the crash tube and the deceleration level generated.

5. Numerical simulations

For this phase of simulation, the computational tool chosen was DRI/KRASH, used in dynamic crash analysis of vehicles impacting in various types of terrain. The vehicle is modelled making use of masses, linear and nonlinear beams and also massless nodes that simulate a rigid connexion. Both references 4 and 5 can be used to formulate the problem and use the software.

5.1. Numerical Model

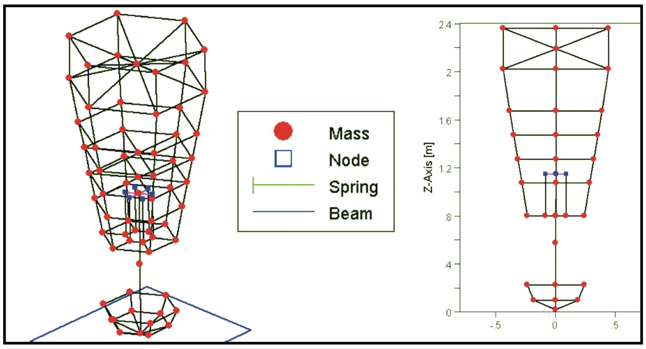

Figure 4. SARA numerical model

This model (Fig.4) is constituted of 66 masses, 145 linear beams and 1 nonlinear beam, counting also with 6 nodes (rigid connections). The masses were radially and symmetrically distributed around the longitudinal axis of the satellite. Until now, there is no detailed information about the structures that supports the pay load and the absorber. They were represented in the model by beams with very high inertia moments values, in an order of a hundred times the inertia moments calculated for the rest of the structure of the satellite. It means that the influence of the mechanical behaviour of that beams during the impact can be neglected.

5.2. Initial Parameters

In general, the crash behavior of composite carbon fibers/ epoxy resin tubes is very sensitive to the geometry, according to Thornton (1979) and Kindervater (1996). In addition, they also depend on the fibres orientation.

For this reason, for the first simulations, the properties of the material needed to be estimated, based on the range of the tested tubes in DLR. So some assumptions were made, and later checked and actualized with experimental tests, foreseen in Phase 2.

With the mass distribution and also the structure properties, it is possible to define a distribution of discrete mass points interconnected by beams. The properties of the beams, it is, the inertia moments and the cross sectional area, can be easily calculated just having in mind what is the structural part of the satellite by that beam represented, as showed in Fig. 5.

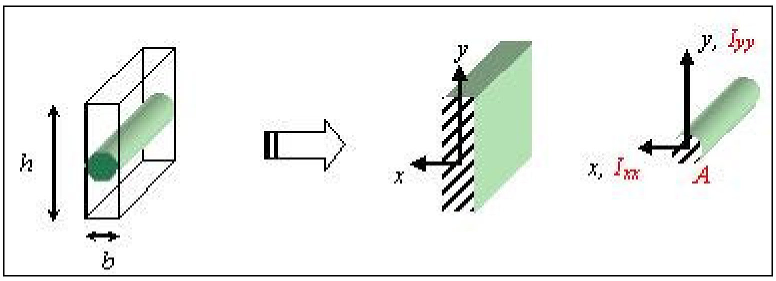

Figure 5. Beam representation of a structure – an example

With respect to the nonlinear beam, that represents the absorber, two very important parameters need to be calculated: *NP* and *LDP*. The first parameter defines the format of the Force-deflection curve while the other parameter defines the deflection at which starts the failure of the tube.

Figure 6 shows how the parameter *NP* can be chosen. The characteristic Force-deflection curve of a carbon fibre tube is showed when $NP = 5$, according to Kohlgrüber (1998). This value was also chosen to continue the simulation. If it is necessary, another curve can also be defined, making use of other tools of the program KRASH.

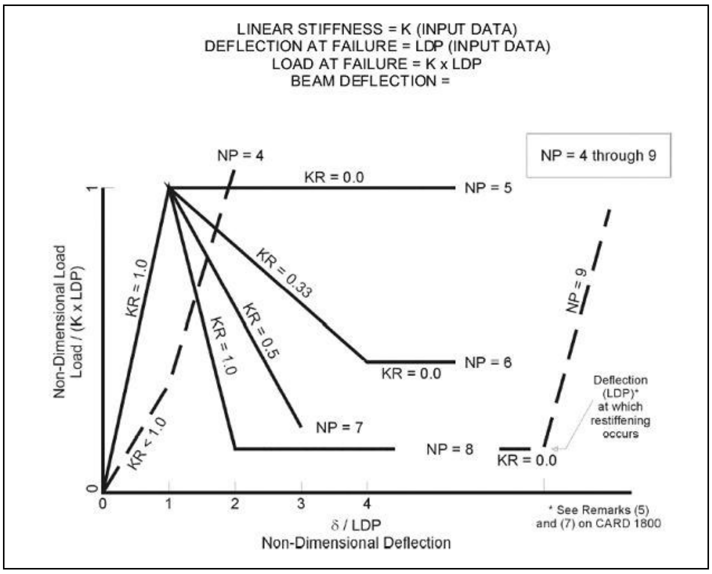

Figure 6. Choosing *NP* parameter

The parameter *LDP* can be calculated as follows:

$$LDP = \frac{F_{fail} \times L}{E \times A} \tag{1}$$

where F_{fail} is the load in the moment of the beginning of the failure of the tube, L and A are the length and the cross section area of the tube respectively, and E is the Young's Modulus of the material.

In this case, the F_{fail} is just the mass of the satellite multiplied by the maximum deceleration accepted during the impact. An estimative of the area is got idealising the Force-deflection curve of the absorber. According to Kohlgrüber (1998), with respect to carbon fibre specimens, the Force-deflection curves obtained in impact tests have always two important properties:

1. the first increase of the load until the failure load is very fast;
2. since the failure load is reached, the value of the load varies around this value, presenting soft oscillations.

In this way, the Force-deflection curve can be idealised by a step curve till F_{fail}.

The next equations show how an initial cross sectional area can be estimated to begin the simulations, based on the total transference of energy from kinetic energy to crush energy.

$$\left| \begin{array}{l} F_{fail} \times \delta_{\max} = \dfrac{m \times v^2}{2} \\ F_{fail} = \sigma_{fail} \times A \end{array} \right. \Rightarrow \sigma_{fail} \times A \times \delta_{\max} = \frac{m \times v^2}{2} \Leftrightarrow A = \frac{m \times v^2}{2 \times \sigma_{fail} \times \delta_{\max}} \tag{2}$$

The last part of the model that needs to be adjusted is the contact spring, which represents the contact between the vehicle simulated and the soil. This spring is responsible to transmit the crash forces that the ground will apply in the vehicle when the contact is established. Important and variable parameters are the spring free length and the force-deflection curve. Reduced values of the spring free length are desired, avoiding big modifications in the model.

Table 1 summarizes some parameters for the first simulation and the last one of a group of many.

Table 1.Parameters for numerical simulation

Parameters		**Simulation 1**	**Simulation 2**
System	Total mass (kg)	289	289
Spring	Length	0.02	0.02
Absorber material	Young's modulus (GPa)	45	63.9
	Yield Stress (MPa)	50	67.7
Nonlinear beam	Area $(m^2)x10^3$	0.579	0.359
	LDP(mm)$x10^3$	0.5908	0.71
	Length (m)	0.5	0.575

5.3. Simulation results

Figure 7 shows the comparison between the two simulations with parameters tabulated in Tab. 1. The simulations between simulations 1 and 2 were used to calibrate the simulation parameters and are not showed here. Once the g level reached at the pay load in (1) is higher than should be, some modifications in the absorber needed to be done: the area needed to be reduced and in the other hand, the length needed to be increased. The values referent to the Young's Modulus and the Yield Stress needed also to be changed, based in the tests with carbon half tubes conduced by DLR as reported by Kohlgrüber (1998). The chosen values refer to the dynamic tests with carbon fibre tubes in epoxy resin, and $0°/90°$ fibres layout. This layout was chosen based in results presented earlier by Thornton (1979) that shows best efficiency of $0°/90°$ layout in terms of energy absorption.

Then the acceleration at pay load during the impact reported in simulation 2 is lower in modulus than that registered in simulation 1. Maximum deceleration registered in simulation 2 was 10 g's and its parameters are used to follow on the experimental tests.

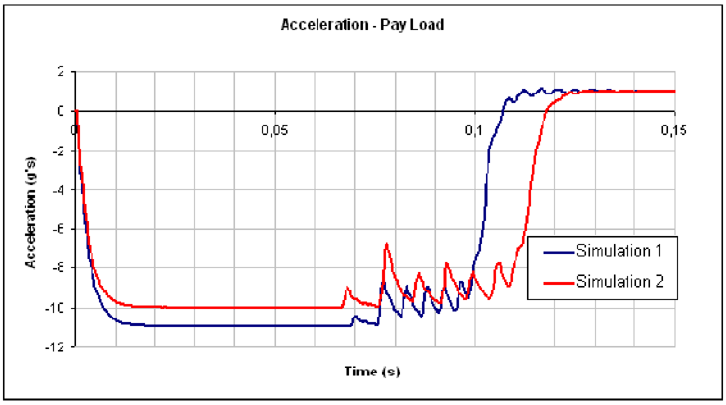

Figure 7. Comparison of reached g'level in both simulations

The available length not destroyed after the impact is bigger in this second simulation. It is a good result remembering that the tube needs to save a portion to deposit the destroyed mass during the impact. Otherwise, if destroyed mass does not find a place to be deposited, it will start being compressed and the load applied in the satellite will increase suddenly, causing therefore an increase of the deceleration level at pay load.

In the first simulation, the non-destroyed tube length was just 37mm while in the second simulation it was 60mm. There is still no information about the percentage of length that needs to be reserved to deposit the destroyed material. This information will be studied with the experimental tests.

6. Experimental tests

6.1. Manufacture process

The tubes tested consist of a carbon fibre fabric and an epoxy matrix. The orientation of the fibres was defined to be $0^{\circ}/90^{\circ}$. The manufacture is manually, making use of a metal cylinder to deposit the carbon fabric. One important precaution during manufacture process is to remove completely the air between two adjacent layers of fabric, avoiding failure by buckling and consequently reduce of tube strength. All the tubes were trimmed with a failure starter (45^{o} trimming). Manufacture process is shown if Fig. 8.

Figure 8. Manufacture process and quasi-static device

6.2. Quasi-static tests

The first tests were done making use of a quasi-static machine. Three groups (Test 1, Test 2 and Test 3 respectively) of three specimens were tested. Dimensions of the tubes correspond to those specified in numerical simulation 2 and variations, and its averages are showed in Tab. 2.

Table 2. Dimensions of the tubes tested in quasi-static mode

Tests (avarage)	Length (mm)	Diameter (mm)		Thickness (mm)	Area (mm^2)
		Internal	External		
1	149.92	50.00	56.93	3.47	582.30
2(1)	149.33	50.00	54.73	2.37	389.36
3	149.60	50.00	53.48	1.74	283.11

(1) : In test 2, the third tube presented lots of irregular regions, result of air inside the walls wall.

A quasi-static test does not supply the same results expected in a dynamic test. However the results can be corrected by a factor to estimate the results of a dynamic test. Kohlgrüber (1998) appoints that in case of carbon fibre tube with layout $0°/90°$, the average crushing force acquired in the dynamic test with velocity 10m/s is almost 36% lower than that acquired in the quasi-static test. So Fig. 9 brings g level results corrected by this factor, it is, the expected results in a dynamic test.

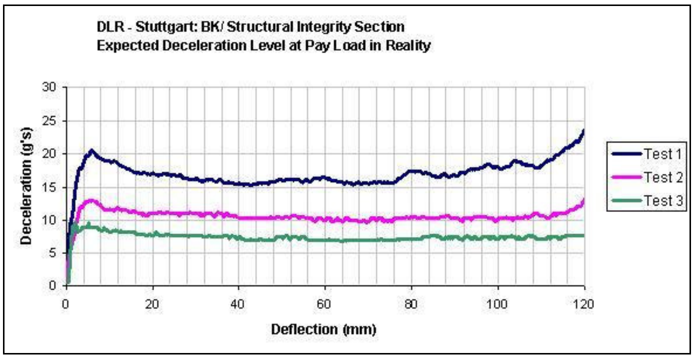

Figure 9. Estimation of the deceleration level in reality

A g level between 7 and 12 was observed in tests 2 and 3. These tubes will be used to perform dynamic tests. Figure 10 shows the evolution of failure.

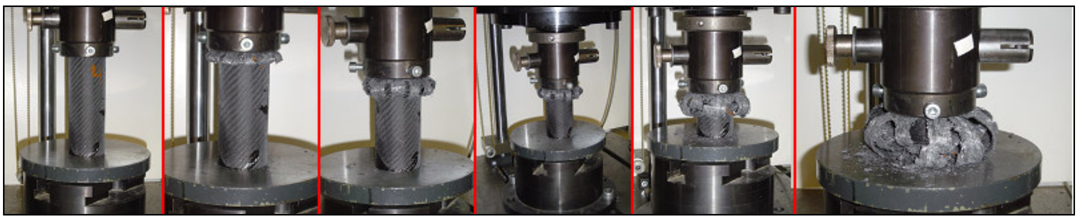

Figure 10. Evolution of failure in a quasi-static test

Finally, Fig 11 shows the influence of air bubbles on the behavior of the third tube of test 2

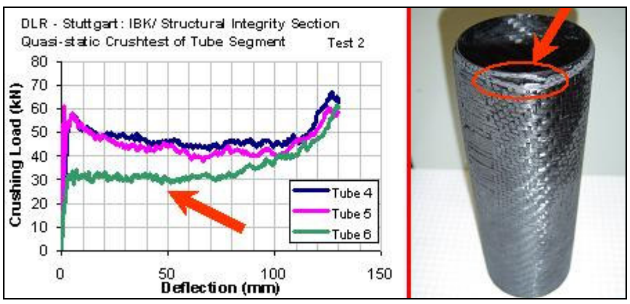

Figure 11. Result of imperfections in tubes

6.3. Dynamic tests

Six specimens with reduced length and cross section dimensions between those defined by quasi-static tests 2 and 3 were tested. So the energy to be absorbed by them needed to be proportionally reduced. Trying to evaluate the effect of differences in velocity and fall mass, two groups of tests were executed: one reducing fall mass and the other reducing velocity. A safe factor of 10% was applied to guard drop tower. The results are showed in Fig. 12 a).

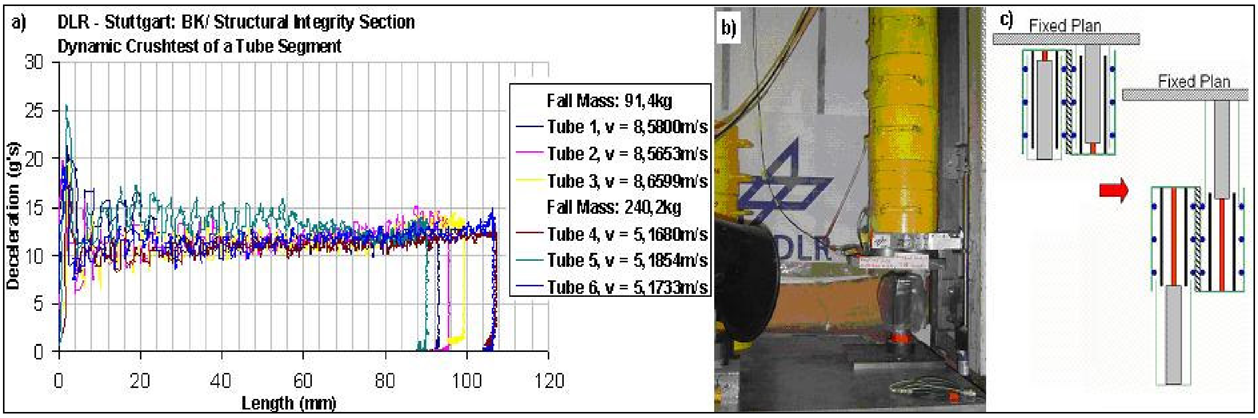

Figure 12. a) Deceleration level at the payload; b) drop tower facility; c) mechanism proposed

In general, a g level plateau was observed between 10 and 11 g's. Exception for tube 5, that indicates a probably not perfect axial alignment of tube and machine. The length necessary to absorb the fall energy was between 90mm and 110mm, less than 75% of the total length of the tubes, conservative result once in quasi-static tests 80% of the tube length could be crashed without a load increase.

An average of 3.2kJ of energy was absorbed, 22% of the total energy of the satellite at the impact. It means that the necessary length of the crash tube to absorb all the kinetic energy would be 675mm, and problems like buckling and storage space come up. Figure 12 c) brings a solution dividing the tube in two. In this case, two pneumatic attenuators are used in parallel, each one corresponding to one crash tube. Close to the soil, the system would be started through a sensor. The crash tubes would need to have different thickness then one would crash just after the other.

Considering that each tube needed to have a length of 340mm, and that the total length of the system was 450mm, the extension in the main body would be just 170mm and not 395mm, representing a reduction of almost 60%.

7. Conclusion

An attenuation system that is designed to afford the impact of SARA generating a g'level around 11 g's was purposed and analysed. An extension in the main body is necessary and the last efforts were in direction to reduce it. The system presented is considered optimum in this way, once the extension could be reduced in almost 60% compared to the initial proposal. However, more tests are necessary to reach the required 10 g's.

The horizontal impact velocity was neglected, and no safe factor was considered in the formulation.

Nowadays this project has been developed in DLR as part of the study work ("Studienarbeit") of Daniel Leiss, undergraduate student of Aerospace Engineering at Universität Stuttgart, Germany.

8. References

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9. Responsibility notice