Development and Evaluation of a New Configuration of a Landing Impact Protection System for Stratospheric Balloon Gondolas

FREDRIK HAIDER
Utveckling och utvärdering av en ny utformning av landningsskydd för stratosfäriska ballonggondoler

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Abstract—This thesis presents analyses of the landing impact of stratospheric balloon gondolas and two of the current systems used for protecting a gondola during landing. From the analyses a new system for sizing the protecting crashpads was developed. The new system provides better protection compared to the old method for sizing the crashpads. Finally recommendations on further work on the subject is given.


Index Terms—crashpad, stratospheric, balloon.

I. INTRODUCTION

STRATOSPHERIC balloons have been in use since the 1930s for observing earth, the atmosphere and space. In the early days they were the only way of going to the edge of space, while today they are often used as a cheaper alternative to satellites. One of the current flight providers is the Swedish Space Corporation (SSC) who have flown over 600 stratospheric balloons from Esrange Space Center (ESC). Under these balloons hangs a gondola that carries the research equipment which can weigh up to 2500 kg.

In between the gondola and the balloon sits what is called the flight train where communication systems and the parachute are located. When the flight is terminated it descends with the parachute at a vertical speed of up to 8 m/s. High crosswinds can sometimes bring it to even higher horizontal speeds. The current system provides further protection on landing with a set of cardboard crashpads. These perform well when there is no crosswind, but with crosswinds the pillars are sheared off and the gondola tips over. SSC is in need of a better system that provides better protection in these conditions and gondolas. The method for accomplishing this task is threefold. First a literature review of past and current solutions is carried out to gain an overview on how engineers have tried to resolve the issue, while also gaining more information on the problem. Secondly with the gathered information from the literature review a couple of load cases are formulated and analysed in the FEM (finite element method)/CAE (Computer aided engineering) software suite ABAQUS. Finally, a new system is proposed and discussed. Suggestions for further work are provided based on the new system, analysis and literature review.

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II. BACKGROUND

Historically research into the protection of the gondola have focused on the improvement of the current system (discussed in later sections), development of reusable systems and the ability to chose the landing zone more accurately.

Reusable systems have proven difficult to make reliable and reusable and this includes the use of airbags. Airbags have been shown to be unreliable and often too expensive [1]. Instead the development of systems to improve landing conditions have been in focus. One of these systems is PAROR which is a software package developed by CNES (Centre national d’études spatiales) which uses weather data to make more accurate predictions of the landing site given a time of release from the balloon [2]. Making it possible to avoid landing in lakes or other dangerous terrain. For more accurate landings some research have focused on the development of guided parachutes. These have however proven difficult to make reliable [3].

An alternative for energy absorption is that of composite tubes used in the automotive industry. These tubes have an inner layer of metal (for example aluminum) and a outer composite layer providing the energy absorption characteristics of both metal and composites [4]. Another alternative is the use of adaptive structures, AIA (Adaptive Impact Absorption) [5]. The basics of an AIA system is that the energy absorbing structure adapts its characteristics (stiffness, yield strength) to the impact thereby reducing impact force and maximizing energy absorption. This is usually done using a combination of sensors and actuators, but a similar effect can be achieved with passive structures [5]. A common material used in the
Another aspect to consider, is the risk of the gondola tipping over. This can happen because of the parachute pulling it over or because of a high centre of mass making it unstable. The parachute tipping the gondola is likely to happen when \( v_x > v_y \) since this means that the flight train is stretched out faster than it folds during landing, resulting in the parachute pulling on the gondola. To determine if the position of the centre of mass is such that there is an increased risk of the gondola tipping over the following method is used. The moment of force around the centre of mass from Fig. 1 results in

\[
I \ddot{\omega} = Hh - Vb
\]

where \( H \) is the horizontal force, \( V \) is the vertical force from the collapse of the system, \( I \) is moment of inertia of the gondola and \( \dot{\omega} \) the resulting angular acceleration. Figure 1 shows the gondola landing uphill therefore tipping over clockwise. This is the most risky scenario since counter clockwise rotation would allow the second crashpad on the other side to provide extra cushioning. Equation (4) can be rewritten for when the gondola tips clockwise as:

\[
Hh \leq Vb
\]
B. Crashpads

An example of the crashpads in use is seen in Fig. 2, it is no more complicated than a couple of stacked cardboard honeycomb sheets. For sizing this system for a given gondola the kinetic energy and minimum stopping distance $S_{\text{min}}$ are calculated by equations (1) and (2) respectively. Since the full pad height cannot be used, the actual height $S_c$ required is calculated ($\tau = 0.7$ is a correction factor for usable height)

$$S_c = \frac{S_{\text{min}}}{\tau} \quad (6)$$

Then the number of sheets $N$ of cardboard this corresponds to is calculated, where $T_i$ is the sheet thickness.

$$S_t = NT_i > S_c \quad (7)$$

which results in an actual stopping distance

$$S' = S_t \tau \quad (8)$$

with which the necessary area of the pad can be calculated ($\sigma_c$ yield strength perpendicular to the liner). For when $F_{\text{def}} = \sigma_c A$, the area $A$ can be calculated by equation (3):

$$A = \frac{K_E}{\sigma_c S'^t} \quad (9)$$

Furthermore, the risk of buckling needs to be taken into consideration. This means that each crashpad needs to have a pyramid shape with an angle of at least 10°. For further information how this specific angle is calculated the reader is refereed to [8]. To reduce the mass of the system and to further decrease the risk of buckling data from Figs. 3 and 4 are used. These show that for example a heavy gondola, the material be3005 or be2005 would be the most suitable options.

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C. Crashrings

For normal payloads and landing conditions CNES is using the same crashpads as SSC which they consider the most efficient system for normal conditions. However, in the case of the EUSO (Extreme Universe Space Observatory) experiment which was likely to land in water, the use of crashpads made out of honeycomb cardboard would risk sinking of the gondola. Therefore they designed the aluminium rings which can be seen in Fig. 5. This system was also used on the CLIMATE experiment, where the use of cardboard crashpads was not possible since the dust and outgassing of the adhesives would interfere with the onboard experiment [7].

For sizing the aluminium rings the same method as for the crashpads are used. Kinetic energy and minimum stopping distance are calculated with equations (1) and (2). Calculating the deformation force is done using equation (10), where $\kappa_c$ is a correction factor of 1.31, $\sigma_r$ the yield strength of the aluminium alloy and $D$ is the ring diameter and $b, h$ are the width and thickness of the rectangular cross section.

$$ F_{\text{def}} = \frac{\kappa_c \pi bh^2 \sigma_r}{3D} \quad (10) $$

Finally equation (3) is solved to calculate the size of the rings. Relation between $b$ and $h$ is obtained by looking at available sizes of aluminium band. Furthermore, side bracing is added as seen in Fig. 5 to prevent the rings from buckling out-of-plane and provide protection from rocks.

Equations (10) and (11) do not take the kinetic hardening of the aluminium into account and they are thus not very accurate for large deformations.

For all simulations done in ABAQUS (explicit dynamics), the same gondola model was used. The gondola is considered a block with dimensions $1.5 \times 1.5 \times 1.2$ m$^3$ and a mass of 250 kg. These parameters are chosen so that they have some resemblance to an actual gondola of the same size, i.e the BEXUS (Balloon Experiments for University Students) gondola [13]. This block is considered infinitely rigid which resembles the same conditions used in [14]. The centre of mass of the block coincide with its geometric centre.

The ground is modelled as a rigid plane which has a coefficient of friction of 0.4 [14]. Since the ground is usually not flat it is also given an angle of $10^\circ$. Finally two load cases are chosen based on the work in [14]. The first case is that the system is deformed and dragged along the ground. This means that some energy is absorbed by friction. In the second case the system is “stuck” to the point it first hits and is not allowed to drag along the ground. This is to represent the case in which the ground is so soft that the system digs in and is not able to drag without being torn apart.

The initial velocity before impact is 7 m/s vertically and 5 m/s horizontally. The choice of vertical speed is based on the fact that this is the speed that almost all gondolas travel at, thanks to the sizing of the parachute. The choice of horizontal speed is based on two sources, one is by recommendation of Esrange engineer Per Baldemar and the second on the median wind speeds of Kiruna seen in Fig. 6.

Therefore it can be considered a reasonable estimate for this application.

$$ F_{\text{def}} = \frac{4bh^2 \sigma_r}{\sqrt{3}D} \quad (11) $$

Figure 5: EUSO experiment with crashrings mounted [11].

V. Method

Initial analysis was done with a MATLAB program developed by the author. This was used to calculate the mass-to-performance ratio for a wide range of gondola sizes and allowable loads on the gondola. As previously mentioned, the crashpad system is in general a better system and therefore a more advanced analysis of the crashrings with ABAQUS was deemed unnecessary. However, verification of equation (10) is necessary. Should the load case be considered as a ring being crushed between two planes equation (11) is applicable according to [12]. Equation (11) is close to equation (10).

The choice of horizontal speed is based on two sources, one is by recommendation of Esrange engineer Per Baldemar and the second on the median wind speeds of Kiruna seen in Fig. 6.

Figure 6: Mean wind speed in the different regions, all at the same latitude [15].
Gravity was also added to the model. The assumption is that the parachute no longer supports the gondola when it first makes contact with the ground, although this is not strictly true since the parachute would still cause a drag force as mentioned in section IV-A. In [14] the force of the flight train was considered, but here the collapse of the parachute was not considered. Should the parachute actually stay fully deployed by the cross wind the high risk of dragging the gondola along the ground makes any other impact absorption calculations irrelevant, since the gondola would be destroyed anyway.

Young’s modulus for the honeycomb cardboard was calculated with equation (12) using data from Fig. 7 ($T_i$ is the sheet thickness and $\delta$ displacement) [16]. This resulted in a value of approximately 3.2 MPa, with data from Fig. 7, $\sigma_c = 100$ kPa, $T_i = 80$ mm and $\delta = 2.5$ mm.

$$E = \frac{\sigma_c T_i}{\delta}$$

(12)

Figure 7 provides engineering data for the strain-stress curve. This is then converted to a true-strain-stress curve (see red line in Fig. 7) using the method described in [17]. This curve was used in ABAQUS. The gondola and crashpad were meshed with 10-node tetrahedral (C3D10M) elements of the size that the student licence limitations allowed. The element type was chosen because of it being quadratic meaning better accuracy when there are large strains [18]. Finally the size of the crashpads was calculated using the method described in section IV-B.

![Figure 7: The non-linear behaviour of a honeycomb structure collapse [8].](image)

Figure 8 shows the yield strength of the honeycomb sheets depending on the angle of the force. This data is based on [10] with configuration lh2525 as honeycomb. This behaviour is universal for all the honeycombs tested in [10]. This data was not used for the simulations, but it is of interest for the subsequent discussion.

![Figure 8: Yield strength profile for honeycomb lh2525.](image)

VI. RESULT

Starting with the comparison between the two current systems the result can be seen in Fig. 9. This is for 7 m/s initial velocity. This was done using the methods described in sections IV-B and IV-C for a wide range of gondola sizes, where a maximum of 10g of acceleration was allowed.

![Figure 9: Comparison between the two systems.](image)

Figure 10 shows that the line of action (red) of the force $F$ should not exceed the edge of the crashpad (blue). Should this happen the crashpad will either buckle or shear off. This theory is similar to that of [8]. To prevent this the angle of the crashpads can be set such that they are facing the most likely load case. This angle $\beta$ can be determined with equation (13). In which the angle $-10^\circ$ is used to take terrain topography into consideration. Choice of angle is based on [14] and discussion with SSC engineer Simon Westerlund.

$$\beta = \arctan\left(\frac{v_x}{v_y}\right) - 10^\circ$$

(13)
As seen in Fig. 11 (with the rotation of the crashpads) another problem is introduced. Although the initial impact results in a force that is favourable to the deformation of the front crashpad, the back crashpad (see force vector \( B \)) is at an unfavourable angle and is at risk of being sheared off.

As stated previously there is risk of buckling and the crashpads being sheared off, this is also different depending on the mass of the gondola. The risk decreases as the width-to-height ratio increases which can be seen in Fig. 12, which uses the same data as in Fig. 9.

Figure 10: Relation between angle of attack \( \theta \) and angle of crashpad \( \beta \) and how this is set so that the line of action (red) does not exceed the crashpads edges (blue), which can cause shearing and/or buckling.

![Figure 11: Force direction when landing uphill.](image)

Figure 11: Force direction when landing uphill.

![Figure 12: Width-to-height ratio dependent on gondola mass and initial impact velocity.](image)

Figure 12: Width-to-height ratio dependent on gondola mass and initial impact velocity.

See appendix for Figs. 14, 15 and 16. In these figures red is for the new rotated crashpad configuration and blue is for the current straight crashpad configuration. As seen in Fig. 14 none of the systems tips over and they both provide adequate protection. When studying the deformation of the crashpads it can be observed that there should be no risk of crashpads buckling or shearing off. In Fig. 15 this is not the case, as the straight configuration does not provide adequate protection since it tips over. This is resolved with the new configuration. Figure 16 shows when the landing occurs uphill. It should be noted that in real life the crashpad seen in Fig. 16-(1c) would not deform so heavily horizontally, but would instead be sheared off.

VII. DISCUSSION

In this section a discussion of the results, further work and sustainability aspects are presented. Starting with a discussion of the results.

A. Results discussion

As stated previously, the ABAQUS model used is a major simplification of reality. This was done because of the difficulty in describing the complex honeycomb structures and the lack of available nodes the student license provides. The major difference between real life and the model is that the model does not allow individual sheets being sheared off. A consequence of this can be seen in Fig. 16-1a-c where the landing would have been even more violent since the sheets would have been sheared off. Another limitation of the model is that it does not necessarily show if the buckling seen in the upper section of Fig. 14-2c would compromise the crashpads' integrity. The simulations does however show that the use of the new configuration (rotated crashpads) does provide better protection. This is not just because of the rotation, but it is also because of the fact that the width of the gondola has increased, which as equation (5) shows, means that the tipping risk also decreased. This has been achieved without a substantial increase in mass. The consequence being that it is...
at bit more difficult to mount the crashpads.

There are however a couple of concerns with the rotation of the crashpads which the results was not able to show because of the simplified model. The first major concern is the integrity of the back facing crashpads. Figure 11 show that they will experience a more dominant horizontal force, increasing the risk of the crashpads being sheared off. The simulations results show no hint of this happening. This could however be because of the simplified model. Should this be proven to be a problem, top side bracing could be a possible solution. This could for example be an added aluminium plate to create a structure similar to that in [4]. The last concern is the angle of the crashpad relative to the sides of the gondola rather than to the bottom (see angle $\theta$ in Fig. 13). In the simulations it was set to 45°. This angle might not be the best since it could mean high torque load when landing at certain angles. To counteract this, side bracing as seen in Fig. 5 could be a possible solution. This would spread the side load between multiple crashpads it could also add protection from rocks and trees.

Other than the rotation of the crashpads this thesis has also considered three other aspects when sizing the crashpads, which previously have not been considered. This being the expected wind speeds at the landing site, the stability in terms of buckling of the crashpads and the risk of the gondola tipping over. Figure 6 shows expected wind speeds for a couple of regions. Although taking the different wind speeds into consideration is important for both the angle of the crashpads and the pads being able to absorb all of the kinetic energy it does introduce a couple of problems. First of all is that this increased speed increases the angle of the crashpads, see equation (13), of up to 45° which could mean a substantially increased risk of the crashpads being sheared off when the wind speeds are lower than expected. This problem is amplified by the data in Fig. 8 which shows that the compressive strength is decreased substantially when the angle is in the range of 30–40°. To reduce the risk of this causing any problems there are two remedies. The first approach is to use the side bracing (see Fig. 5) as previously mentioned. The second is moving the crashpads closer to the gondolas centre so that they have more support. Doing this will however increase the risk of the gondola tipping over as seen by equation (5).

Now switching focus to that of the width-to-height ratio, which is also affected by the wind speed as seen by Fig. 12. What is shown in Figs. 3 and 4 is that in some cases a different material might be needed for some gondolas where the width-to-height ratio is low. A choice of honeycomb with worse energy-to-mass performance could in some cases actually be a better performer. Whether to go for stability or decreased mass the results in Fig. 12 should be considered. There are two parameters to consider: the mass of the gondola and the expected speed at which it will land. For heavier gondolas stiffer and stronger honeycomb sheets such as be3005 (see Fig. 4) could be suitable, however this might not be the case for landings where higher speeds are expected. Something that has not really been explored in this thesis is the possibility of combining multiple types of honeycomb sheets to reduce mass and improve the width-to-height ratio.

Just as there is a difference in wind speed there is also a difference in terrain at the different landing sites, marshland, e.g. wooden areas, etc. All present a need for side protection. However sometimes the gondola is at risk of tipping over and destroying vital equipment even when landing in favourable terrain. This is where equation (5) is to be considered. Although the forces $H$ and $V$ can vary a lot, a rule of thumb is to consider side protection when $h > b$ and especially when landing in windy areas, but how much protection should be added and where? This can be answered by Figs. 15-1 and 16-1. Although they tipped over in both cases it can be seen that in both cases most of the energy had been absorbed prior to the gondola tipping over. It can be observed that side crashpads capable of absorbing 10% of the total kinetic energy should be enough to provide adequate protection. These should be placed on each side above the gondolas’ centre of mass. The user should however be reminded that the gondola might not necessarily be able to take the same load from the sides as from the bottom. Should there be a problem with placement of large crashpads, the use of crashrings should be considered. This is since they take up less space and as seen in Fig. 9 they have similar performance to crashpads in the lower energy ranges (remember lower mass equals lower kinetic energy). The user should however also be reminded of the risk of the rings blocking transmitters and transceivers.

Looking back at the case of landing in a wooded area. There are two things to be done about this case: increasing the side protections energy absorbing capability or adding side bracing as previously mentioned on both the side crashpads and at the bottom. This is to be done since trees can be thin and without side bracing the crashpads are at risk of missing the tree and the gondola hitting it directly. Therefore connected side bracing should be considered.

![Figure 13](image-url)


B. Suggestions for further work

One of the major problems is that we do not know on which side the gondola will land. If this could be decided both mass, reliability and performance could be improved. This could possibly be achieved by the use of a different parachute or other orientation system. The system should however not be an active one since previous work has proven that such systems are difficult to be made reliable. The ability to orient the gondola in a known direction would eliminate the risk of the backward facing crashpads being sheared off when landing since they could be oriented in the optimal orientation. This is something that requires further work, both finding a suitable solution to this orientation problem and how to orient the solution in such a situation. Although the forward facing crashpads could be oriented as in Fig. 11, the back crashpads might need a different orientation (other than facing the same direction as the front crashpads).

In the interest of reducing the mass of the system further work should also be focusing on using side bracing such as that of the crashrings to spread the load across multiple crashpads allowing a reduction in size of the crashpads while still providing the same protection. This could be achieved with a AIA system [5] although as stated this would have to be passive to be reliable and to keep cost low. A mechanical solution would be the best approach. The mechanical approach should however not rely on any complicated moving mechanism since this has the possibility of cold welding or fail because of any of the other environmental concerns.

For any further work there should be more focus on the improvement of the material model for the honeycomb structure since a more accurate model would allow faster prototyping and better understanding of the ability and limitations of the material. The work of this thesis has confirmed that the use of honeycomb cardboard sheets is currently the best way to protect a payload given its ease of use, low price and high performance. There are however some foams that might be able to provide better protection because of the way they behave when collapsing. These foams does however present an environmental concern since they can be difficult to clean up after impact.

Finally one possible improvement could be a simplified version of the system [3]. Where, instead of guiding the parachute to a specific location it could be a timed mechanism which at the last part of the descent steer the gondola into the wind reducing the horizontal speed.

C. Sustainability

The use of stratospheric research balloons is an important part of climate research. One example is CLIMATE which is used to study concentrations of the main greenhouse gases (H₂O, CO₂ and CH₄) and characterize the stratospheric aerosols [19]. Research such as this is important for making it possible to find the best approach to tackling climate change. Being able to protect equipment such as this and making it possible to fly more often has been the aim of this thesis work. Besides reducing resources spent on repairing the equipment the lowered down time enables research to be accelerated. This accelerates the way forwards toward passing the thirteenth goal of the UN sustainability goals [20].

VIII. Conclusion

The new crashpad configuration has been proven by analysis to be able to provide better protection compared to the current configuration. A short summary what should be considered and how to use the method described in this thesis is as follows:

1) Gather crosswind data from [15].
2) Calculate crashpad angle with equation (13).
3) Make a choice of honeycomb material using Figs. 3 and 4, see section VII for further detail.
4) Calculate crashpad size as described in section IV-B.
5) Approximate centre of mass, if \( h > b \) add side mounted crashpads above centre of mass. Size pads to absorb 10% of total kinetic energy.

For any further work on the subject the following systems and subjects should be considered.

- Change of parachute type or other solution to be able to choose the gondola landing side.
- Crashpad orientation outwards when choice of gondola landing side is possible.
- An improved model for dynamic collapse of the honeycomb structure. This would include onboard measurements on upcoming flights.
- Optimization of the crashpads size and mass using a mix of honeycomb materials and or combination of entirely different materials such as foams and metals.

Acknowledgements

I would like to thank my supervisors Dr. Gunnar Tibert and Simon Westerlund for their guidance and feedback. Finally I would like to show my gratitude to SSC for the opportunity to visit Esrange Space Center.

References


APPENDIX
ABAQUS SIMULATION RESULTS

Figure 14: Simulation with 7 m/s vertical velocity. Blue is for the current configuration and red is for the new configuration.

Figure 15: Simulation with 7 m/s vertical and 5 m/s horizontal velocity, moving downhill. Blue is for the current configuration and red is for the new configuration.
Figure 16: Simulation with 7 m/s vertical and 5 m/s horizontal velocity, moving uphill. Blue is for the current configuration and red is for the new configuration.