Design, Analysis and Manufacturing of a Re-Entry Capsule made by Inflatable Structures

E. Carrera\textsuperscript{a}, L. Montefiore\textsuperscript{a}, E. Beruto\textsuperscript{b}, G. Augello\textsuperscript{b}, M. Adami\textsuperscript{c}, A. Hromadková\textsuperscript{c}, E. Gabellini\textsuperscript{d}

\textsuperscript{a}Aerospace Department, Politecnico di Torino, Italy
\textsuperscript{b}Alenia Spazio S.p.A., Torino, Italy
\textsuperscript{c}Aero Sekur, Roma, Italy
\textsuperscript{d}Samtech Italia, Milano, Italy

Abstract

The construction of an efficient and reliable re-entry capsule has played and continues to play a fundamental role in the space activities. Current applications include International Space Station sample return, the delivery of networks of small stations to the Martian surface, and the return to Earth of launcher upper stages. Recently \cite{1}, \cite{2} attention has been paid to the possibility of building a re-entry capsule by employing inflatable technologies. The inflatable technology offers great advantages due to its low volume and mass and it is therefore of interest to many potential users, ranging from the Space Station to planetary science, and even possibly launcher or technology developers. However, the analysis and design of an inflatable re-entry capsule consists of a cumbersome subject. So many different and difficult problems arise in its design process: aero-thermodynamics, material sciences, shield design, multi-body mechanics, inflatable structures blow up simulation and stress analysis, etc.

Introduction

This work focuses on design, structural analysis and manufacturing of an inflatable re-entry capsule that has been partially developed in the framework of a joint study made for ESA by Alenia Spazio and Aero Sekur Companies.

The finite element model used for simulation of the considered inflatable structure has been developed in the framework of a scientific collaboration \cite{3} among the Aerospace Department of Politecnico di Torino, Alenia Spazio and Samtech Italia. Samcef software was, in fact, employed for the blow up process simulation and stress analysis. The numerical code investigated and used for the analysis was Samcef Mecano: this is a fully coupled FEA and MBS code for non-linear analysis of structures and flexible mechanisms, in transient dynamic and/or static conditions. Mecano is well suited for the analysis of inflatable structures because of its rich library of structural elements, such as membranes, cables, etc., and also for some specific elements and boundary conditions dedicated to inflatable structure applications, like a specialized thin shell element and volume control technique. The fully coupled formulation of Samcef Mecano, which is simultaneously a FEA and MBS solver, allows the modelling of structural components (Mecano Structure library of finite elements) that are connected by kinematic joints (Mecano Motion
library of rigid and flexible joints), in order to obtain a hybrid inflatable-deployable structure, for example to analyse inflatable structures having an internal deployable skeleton too. The field of validation of the Samcef Mecano Code has been the design and the analysis of an Inflatable Re-Entry Capsule. Obtained results have shown the capability of the employed software along with the suitability of the proposed solutions. Further details of the performed numerical simulation along with the description of the both manufacturing process and obtained performances will be given in next sections of this paper.

Non-linear static analysis

A non-linear static analysis has been performed in order to assess the suitability of the inflatable re-entry capsule to withstand the loads arising from the re-entry and descent environment as well as the structure pressurization. First of all, a preliminary study has been carried out on two possible models, which form only the pressurized part of the whole structure of the capsule; the scope was to assess which of the two had shown a better structural behaviour, in terms of stiffness and strength. Results of the non-linear static analysis, performed during this phase of preliminary study, have shown that Aero Sekur model, subjected to the same condition of imposed load, shows a higher suitability to limit deformations and stresses, i.e. a better stiffness and strength. Therefore, Aero Sekur model was chosen for design and analysis of the capsule; structural symmetry properties (geometric, material, loads and constraints symmetry) have been also considered and so a portion of 1/8 of the whole CAD model has been imported into CAE room. After shape repairing actions, made in order to obtain a shape that has been able to satisfy meshing requirements, the finite element model of the structure has been built; Figure 1 and Figure 2 show FEM models of the tubular part and of the Thermal Protection System respectively. For the tubular part, hypothesized by prevailing membrane stiffness, have been used linear quadrangular and triangular membrane elements; the membrane thickness is 0.26 mm. The Thermal Protection System, hypothesized by prevailing membrane stiffness too, has been modelled by special linear triangular shell elements, which do not have rotational dof. So, if the structure becomes very thin, the stiffness matrix will be identical to the one of a membrane element, but it will not be ill-conditioned as for classical shell element with rotational dof.
The element is a triangle defined by 3 nodes. The unknowns are the three displacements \((u, v\) and \(w)\). It is a superposition of a membrane element and a Kirchhoff plate element. For the membrane behaviour there are two options. The first one is very classical: the displacement is linear over the area of the element and the membrane strains are constant. In the second option, the membrane strains are computed from a patch of elements and the behaviour is similar to a 6 node triangular element. For the plate behaviour, we consider an element with transverse displacements at nodes and rotations of the edges; the rotations of the edge are computed as a function of the displacements of a patch of elements. In case of no neighbouring, the edge is considered either clamped or free. The use of this special triangular membrane element has been able to solve the big problems of convergence arising from Mecano analysis: in fact, the strong non-linearities of geometry, the large flexible/flexible contact and the prevailing membrane behaviour shown by the structure have given rise to so many different and difficult problems during the simulation. The material of the tubes, which are the pneumatic structure of the capsule, is kevlar: for this material, hypothesized by non-linear elastic behaviour, the variation of the Young Modulus, as well as the variation of the Ultimate Strength, with respect to the temperature change has been considered as shown by Figure 3 and Figure 4 respectively.

![Figure 3: Variation of Kevlar Young Modulus vs. Temperature](image1)

![Figure 4: Variation of Kevlar Ultimate Strength vs. Temperature](image2)

The Thermal Protection System is made by a multilayered structure, which consists of four isotropic plies, as shown in the Figure 5.

![Figure 5: Multilayered Thermal Shield](image3)

The material of the inner ply (near the tubes) is kevlar; for this material, hypothesized by non-linear elastic behaviour, the variation of the Young Modulus, as well as the variation of the Ultimate Strength, with respect to the temperature change has been considered as shown by Figure 3 and Figure 4 respectively. The material of the other plies (Conductive Insulation Material, Ceramic Textile Fabric Material and Ablative Insulation Material) is hypothesized by linear elastic behaviour and so Young Modulus has been considered constant with respect to the temperature change.
The boundary conditions applied to the model are external constraints, symmetry constraints and contact constraints. The position of the external constraints on the model is shown in Figure 6, where the group of nodes, on which the boundary condition (clamp) is applied, is highlighted by red colour. Figure 7 shows the position of the symmetry constraints on the model: the group of nodes, on which the boundary condition is applied, is highlighted by red colour too. The contact constraints are boundary conditions that assure the connection between tubes and TPS; a large contact has been hypothesized between a group of nodes of the tubes and a group of elements of the TPS.

The chosen contact model is the flexible/flexible contact between a group of slave nodes and a group of master facets, in case of large relative displacements. The group of slave nodes, highlighted by green colour in the Figure 8, is a group of nodes of the tubes; the group of master facets, highlighted by red colour in the Figure 9, is the group of all elements of the TPS.

The load conditions used to perform Mecano analysis are the following:

- **First Load Condition**
  - A Delta pressure of 0.125 MPa applied internally to the tubes
  - A Dynamic pressure of 0.007 MPa applied externally to the Thermal Protection System
  - A Constant Temperature Value of 1271°C imposed to the outer ply (Ablative Insulation Material) of the TPS
  - A Constant Temperature Value of 14°C imposed to the inner ply (Kevlar Material) of the TPS
  - A Constant Temperature Value of the 0°C imposed to the tubes
Second Load Condition
A Delta pressure of 0.125 MPa applied internally to the tubes
A Dynamic pressure of 0.007 MPa applied externally to the Thermal Protection System
A Constant Temperature Value of 614°C imposed to the outer ply (Ablative Insulation Material) of the TPS
A Constant Temperature Value of 122°C imposed to the inner ply (Kevlar Material) of the TPS
A Constant Temperature Value of the 65°C imposed to the tubes
Pressures and temperatures have been applied to the model according to the time histories shown in the Figure 10.

Figure 10: Load Time Histories

Two cases of analysis have been obtained from the combination of the set of physical properties, loads and constraints; the post-processing of the obtained results, in terms of displacements magnitude and mean Von Mises stress, has been performed by using Samcef and Samcef Field software. The results of the only second load condition will be considered in the next description. Figures 11 and 12 show the deformation of the tubes and of the TPS respectively, in terms of displacements magnitude. The maximum value of displacement magnitude is found in the TPS and it is 41.773 mm. Figure 13 shows the overall displacement field in the whole model: an amplification of the deformation coefficient of 3 has been considered in order to highlight better the contact constraint between tubes and TPS.

Figure 11: Deformation of the tubes
Figure 12: Deformation of the TPS

From the previous results it is possible to evaluate the displacement of the TPS relative to the pneumatic structure (tubes). In order to compute this relative
displacement, a node is chosen in the zone of maximum deformation of the TPS (Figure 14); another node is chosen in the zone of maximum deformation of the tubes (Figure 15). The difference between the displacements of these nodes is the looked for relative displacement. From these two last figures it is possible to see:

- Displacement magnitude of node 20796 on TPS = 41.773 mm
- Displacement magnitude of node 20780 on tubes = 30 mm
- Relative displacement = 11.773 mm

Figure 13: Deformation of the whole model

The subsequent Figures 16 and 17 show the history of the displacements of these two nodes during Mecano analysis. Figures 18 and 19 show the overall stress field in the tubes, in terms of mean Von Mises stress.

Figure 14: Node 20796 chosen in the zone of maximum deformation of the TPS
Figure 15: Node 20780 chosen in the zone of maximum deformation of the tubes
Figure 16: Displacement history of node 20796 on TPS
Figure 17: Displacement history of node 20780 on tubes
The maximum value of mean Von Mises stress is found in some connections between tubes and it is concentrated in much localized areas; this value is 320 MPa. A stress value less than 150 MPa is also found in other connections between tubes. This problem can be easily avoided by local stiffenings in these positions of the tubes. The overall stress field, with a few exceptions for the localized areas, shows anyway a value less than 60 MPa. Assuming an Ultimate Safety Factor of 1.5, the Ultimate Strength of the tubes kevlar material must be: $\sigma_{\text{ULTIMATE}} > 1.5 \times 60 = 90$ MPa. Remembering the variation of the kevlar Ultimate Strength with respect to the temperature, as shown in the Figure 4, the condition $\sigma_{\text{ULTIMATE}} > 90$ MPa allows a temperature value, for the kevlar tubes material, of maximum 260°C. Figures 20, 21, 22 and 23 show the stress field in each ply of the composite Thermal Protection System, in terms of mean Von Mises stress.
The maximum value of mean Von Mises stress, in each ply of the TPS, is:

- $\sigma_{\text{EQUIVALENT}} = 0.95 \text{ MPa}$ for ply 1 (Ablative Insulation Material)
- $\sigma_{\text{EQUIVALENT}} = 97.42 \text{ MPa}$ for ply 2 (Ceramic Textile Fabric Material)
- $\sigma_{\text{EQUIVALENT}} = 0.002 \text{ MPa}$ for ply 3 (Conductive Insulation Material)
- $\sigma_{\text{EQUIVALENT}} = 66.27 \text{ MPa}$ for ply 4 (Kevlar Material)

Assuming an Ultimate Safety Factor of 1.5, the Ultimate Strength of the ply 4 material must be: $\sigma_{\text{ULTIMATE}} > 1.5 \times 66.27 = 99.40 \text{ MPa}$. Remembering the variation of the kevlar Ultimate Strength with respect to the temperature, as shown in the Figure 4, the condition $\sigma_{\text{ULTIMATE}} > 99.40 \text{ MPa}$ allows a temperature value, for the ply 4 kevlar material, of maximum 250°C.

**Technology and materials design**

In line with ESA policy in favour of non-prime and small medium companies, the IRT program was initiated to develop equipment for the future use of Automated Transfer Vehicle (ATV) as a cargo retrieval system.

The inflatable technology offers advantages when it is applied to large re-entry vehicles, and for such applications as ATV system enhancements for the return of cargos from the ISS. It offers important advantages with respect to conventional systems as it is lightweight, low-cost and non-bulky. Based on this a team was formed under the lead of Aero Sekur S.p.A as prime contractor. The study was aimed to the development of IRT system in two main components: Inflatable Structure and Thermal Protection. The capsule is slowed-down from 8 km/s to 0.9 km/s in less than 200s, with a deceleration peak of more than 15 times the Earth’s gravitation. During the re-entry phase, the capsule is decelerated and heavily heated by the surrounding hypersonic flow.

The Thermal Protection System has to withstand very high temperatures (up to 1700°C with a maximum heat flux in the range of 500 kW/sqm) and significant dynamic stresses. The scope of it is to protect the inflatable structure after it is deployed during the re-entry phase, which slows the speed down from 8 km/sec to 0.9 km/sec in 200 second approximately; instead the inflatable structure has to hold a payload capsule, which must be landed. Furthermore the inflatable structure gives the desired shape and the structural resistance to the whole system. The maximum temperature at which the inflatable is able to sustain is the main requirement of the heat shield. The inflatable is made by a coated fabric and an adhesive. Therefore the working temperature range is the lower one of those two of the involved materials (about 170°C).

Aero Sekur developed and qualified the multilayer flexible TPS structure. The TPS model (scale 1:5) was tested two times in Plasma Wind Tunnel (PWT) at CIRA in Capua premises. The test conditions were set up to fit them to the re-entry environment. Both tests gave very satisfactory results; the TPS developed by Aero Sekur was able to shield about 1300°C and so to guarantee the interior temperature of about 100°C. In the Figure 24 is shown the plasma test effect and in the Figure 25 is given the tested TPS instead.
The desired effect of TPS is obtained by assembling of different layers with very peculiar functionalities. The adopted multilayer concept is based on the utilization of single materials according to their specific property in order to reduce the TPS total mass, the TPS total thickness and then to increase its folding capability. There are layers which “passively” protect the attached plies by their physical properties (for example thermal conductivity); then there are layers which “actively” contribute to the whole system by their endothermic decomposition which occurs at temperature significantly lower vs the exterior one. By this chemical reaction a huge amount of the total received energy is dissipated and wasted by the resultant gas escape. To give the needed stiffness to TPS structural plies are also included. The TPS stiffness is a very fine tuned design as it is the best balance among two critical aspects. The first one is the need to maintain the right shape during the re-entry phase in order to avoid local increases of temperature on the outer surface of the shield. The second one is the need to allow TPS to fold and pack inside of the dedicated capsule stowage volume which is rather small (less than 200 litres). The second aspect is therefore linked to the TPS flexibility or in other words it is a “non-stiffness” aspect. The materials design was approached in several steps. The main development phases were started with a requirements review. Then the available materials were selected and tested both qualitatively and quantitatively. Some dedicated test tools were built in Aero Sekur premises. The promising multilayer structures were also tested in the Small PWT in University of Napoli “Federico II”. After an initial phase, where a deep materials trade was performed, some materials were selected and further investigated. This experimental phase was run parallel to the assessment phase of the assembling technology. So, at the end of the experiment, the final configuration was defined in terms of materials and assembling technology. In the Figure 26 is shown the sample tested in the Small PWT and in the Figure 27 is given the trial plant for models assembling.
The key point of the above-cited combination is the assembling of different material plies and mainly the physical integration of different material families. The interface between interior TPS and inflatable is also critical for its performance. The definition of this interface is probably the most important phase of the whole project. Furthermore it has rather empirical and practical approach allowed thanks to Aero Sekur’s long experience in the manufacturing of inflatable emergency aeronautical products. In fact, this has put the company in the position to be selected by ESA as a candidate provider of Inflatable Re-Entry Technology in the years to come. The inflatable truss structure model (Figure 28) was built by a trial material and the first fitting test was also performed. Currently the truss structure is under construction by the design materials. The inflatable truss will be qualified according to the given requirements.

![Figure 28: Inflatable Truss](image)

**Conclusions**

Inflatable Re-Entry Technology is an innovative concept which offers great advantages if it is applied to space applications. This new concept allows both mass and volume savings compared to conventional technology, and it is easily reconfigured. One of the possible future applications of this technology foresees its utilization in the manufacturing of an inflatable re-entry capsule, which will return to Earth payloads from the International Space Station with an ATV spacecraft as the carrier. Aero Sekur S.p.A. has a long experience in the manufacturing of textile composites and inflatable structures; so this company was selected by ESA as a candidate provider of inflatable re-entry technology in the years to come. The chosen materials have tested and investigated as well as the assembling technologies. From results it has been seen that the thermal shield developed by Aero Sekur is able to satisfy the main requirement of the maximum temperature at which inflatable structure can sustain. Moreover the multilayered concept allows a significant reduction of the total mass, of the total thickness and an increase of the folding capability. Instead the inflatable structure, at first built and tested by a trial material, is now under construction and it will be qualified according to the given requirements. About the evaluation of the stiffness and of the structural strength of the re-entry capsule and then of the goodness of its design proposal, the results of the performed non-linear static analysis have shown that, from the overall point of
view, the structure of the capsule appears to be suitable to withstand the loads applied to it and so to be able to survive in the environment encountered during the re-entry and descent phases. The much localized high stress areas are easily manageable by design, i.e. local stiffenings. Then it is possible to conclude that the structure of the capsule, being able to limit deformations and stresses if subjected to the imposed loads, shows stiffness and strength such as to assure to the capsule to successfully accomplish its mission.

References


