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Modelling, simulation and testing of inflatable structures applied to re-entry in the EFESTO-2 project

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Abstract

Inflatable Heat Shields (IHS) are poised to revolutionize space travel, enabling missions that prioritize both increased payload capacity for scientific instruments and resources, and reusable spacecraft for sustainable exploration. However, unlocking this potential requires maturing key technologies. This is precisely the focus of the European projects EFESTO and EFESTO-2, funded respectively by H2020 (grant nr. 821801) and HORIZON EUROPE (grant nr. 1010811041).

EFESTO Projects are based on an innovative Inflatable System architecture developed by the Canadian company This Red Line Aerospace.

EFESTO, attempted the initial challenges of developing the core elements of an IHS: the inflatable structure and flexible thermal protection system. This project significantly advanced the Technology Readiness Level (TRL) of these components. Building upon this foundation, EFESTO-2 focused on consolidating critical technical aspects and adopting a broader system engineering perspective.

In particular, the EFESTO-2 project focused on implementation of a sound testing effort to improve knowledge of this peculiar systems with respect to the topics of aero-shape and structure.

A Fluid Structure Interaction (FSI) investigation was executed to retrieve deformation of the inflatable structure under aero-loads and then understand impact of shape deformation on both aerodynamic drag and aerothermal loads, by means of CFD and wind-tunnel tests.

The structural and mechanical characterizing was appointed through numerical modelling and analysis first, then with extensive testing of a meaningful-size ground demonstrator of the inflatable structure, and then again with cross—correlation of test data with FEM results.

This paper focuses on two of the many activities carried on in the frame of the project: The FSI and the dynamic characterization, carried on by CIRA with the significant support of SRSED srl, an Italian SME, part of the ALI consortium. A dedicated effort has been also made by ONERA to model and simulate morphing behavior of the inflatable structure during folding and unfolding, aimed to reproduce the actual folding process.

Keywords : *inflatable heat shields, inflatable structure, morphing, fluid-structure interaction.*

Nomenclature

Computational Fluid Dynamic (CFD)
Concept of Operations (ConOps)
FEA (Finite Element Analysis)
IAD (inflatable Aerodynamci Decelerator)
Finite Element Method (FEM)
Fluid Structure Interaction Loop (FSI)
Inflatable Heat Shields (IHS)

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1. EFESTO-2 main elements

The EFESTO-2 project, funded by the European Union's Horizon Europe program (grant agreement Nr.1010811041), is a collaborative effort managed by a European consortium led by Deimos Space (ES) (see Fig. 1). Other participating organizations include ONERA (FR), DLR (DE), CIRA (IT), POLITO (IT), DEIMOS ENGHENARIA (PT), and PANGAIA-GRADO-ZERO (IT).

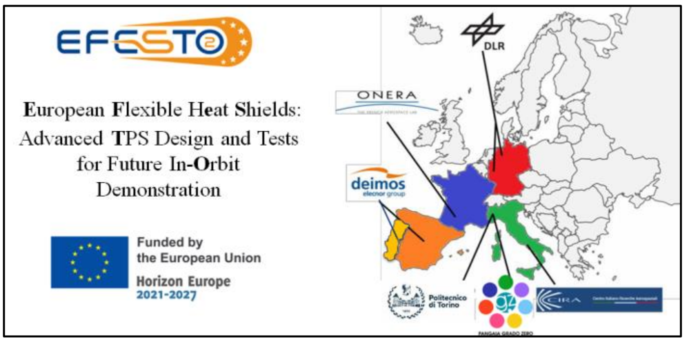


Fig 1. EFESTO-2 project consortium

The project focused on four main tasks:

1. Business case analysis (BCA), evaluating the commercial viability of Inflatable Heat Shields (IHS) technology and fundamental starting point to make the outcome appealing and valuable for concrete exploitation. A reference use-case chosen for the Inflatable Heat Shield exploitation is the recovery of a Firefly Alpha vehicle upper stage.

2. Reference mission and system engineering, defining a representative mission scenario and the corresponding IHS system design. After the BCA investigation, the definition of the ConOps is done identifying two main segments as the Launch and Early Operation Phase (LEOP)/Orbital phase, where the launcher executes its typical tasks like launching and injecting the main payload into orbit, followed by the Recovery phase, which focuses on retrieving the Launch Vehicle (LV) stage [1].

3. Extensive ground testing, comprising testing of IHS Ground Demonstrator and components to validate their performance. Cold flow wind tunnel testing of subscale models investigates the dynamic and static stability of capsule-like bodies, particularly focusing on deformed shapes at relevant flow regimes while the mechanical characterization of the Inflatable Structure at CIRA facilities will delve deeper into the structural behaviour of these structures through modal surveys, static test and morphing observation.

It is worth mentioning that a great and valuable support is being ensured by CIRA subcontractor “ALI Scar” (IT) along with partners “SRSED srl” (IT) and “Thin Red Line Aerospace” (Canada) for all is about the inflatable structure technology.

Near-future activities identification, recognizing promising avenues for future research and development in IHS technology.

2. Fluid Structure Interaction

Inflatable Heat Shields (IHS) pose unique challenges due to their inherent deformability during re-entry. As reported in [2], the combined extreme aerodynamic heating and loading, acting on the capsule, produces complex interactions between the flow dynamics, and structure. In terms of testing capabilities, the hard task to test aero-elastically scaled models in wind tunnels, implies that Aero-elastic (AE) simulations are critical for the hypersonic regime. Due to the complexity of the Aero-thermo-elasticity (ATE) problem, simple, but quite accurate, numerical tools that make use of linearized analytical solution, can reduce the cost of the test campaign and give valuable information in order to prepare high-fidelity numerical models.
The interaction with the fluid flow causes continuous deformations, dynamically changing the vehicle's shape and impacting its aerodynamics, the deformed shape alters the flow characteristics, affecting the forces and moments acting on the vehicle; the aerothermodynamics as the changing shape influences heat transfer, leading to variations in the heat flux experienced by the shield and the trajectory ,so long as the combined effects on aerodynamics and aerothermodynamics alter the vehicle's trajectory and mission profile.

An extended review of the FSI approaches for AE applications has been investigated by Kamakoti and Shyy (REF). They have identified three types of FSI coupling:

1. **Fully Coupled**: the governing fluid and structural equations are combined, solved and integrated in time simultaneously.
2. **Loosely Coupled**: the structural and fluid equations are solved using two separate solvers. Only external interaction between the fluid and structure modules are performed. Therefore, the information is exchanged after partial or complete convergence of each module.
3. **Closely Coupled**: the fluid and structure equations are solved separately using different solvers but are coupled into one single module with exchange of information at the interface using an interface module thereby making the entire model tightly coupled.

Considering the phase of the EFESTO-2 project, and the complexity of the ATE problem, a “Loosely Coupled” algorithm for FSI has been addressed. This approach couples computational fluid dynamics (CFD) and structural mechanics (FEM) analyses, enabling:

- Analysis and prediction of the system's behavior under FSI effects.
- Design optimization of IHS by understanding how flow-induced deformations influence:

The investigation involved a 1-way CFD/Structural mechanics coupling procedure:

1. ONERA conducted 2D axisymmetric Navier-Stokes simulations to determine the surface pressure distributions acting on the reference IHS geometries during their reference trajectories.
2. CIRA-ALI used these pressure distributions as input for the structural solver to calculate the resulting deformed shapes.
3. This process quantified the impact of the deformations on the wall heat flux experienced by the shield.

This simplification of the ATE problem is named “one-way coupling”, and relies on three important assumptions:

1. Thermodynamic coupling between heat generation and elastic deformation is negligible.
2. The characteristic time of the aero-thermal system is large relative to the time periods of the natural modes of the AE system, which means that the dynamic AE coupling is small.
3. Static AE coupling is insufficient to alter the temperature distribution from the reference condition.

The chosen method involves iterative information exchange between separate CFD and FEM models.

1. CFD simulation calculates the flow field around the initial undeformed shape and determines the wall pressure distribution.
2. The pressure data is transferred to the FEM model to calculate the resulting deformed shape through static analysis.
3. The deformed shape is fed back to the CFD model for a new flow field simulation, generating a new pressure distribution.
4. Steps 2 and 3 are repeated iteratively until both fluid and structural solutions converge.

This loop ensures the mutual influence of fluid flow and structural deformation is considered during the analysis, leading to a more accurate representation of the system's behavior.

The key outcomes to be represented and compared at each iteration are:

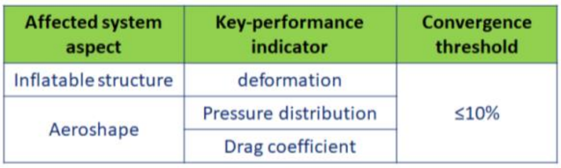
a) the pressure distribution and the drag coefficient of the shape on the one hand,
b) the geometry profile of the shape under the pressure pattern produced by the CFD.

The former two are an outcome of the CFD results; the latter is an outcome of the FEM results after application of the new flow-field around the deformed shape of the previous iteration.
Therefore, it was straightforward to identify as key parameters to be monitored at each iteration during the FSI loop the following ones:

- The pressure level on the conical region of the shape
- The displacement or deformation of the shape
- The drag/axial coefficient (CA) of the shape

As far as it concerns the convergence criterion, the logic was based on stopping the iterations when the delta or change of the absolute value of any key parameter, from an iteration to the next one, is such to exhibit a negligible difference.

A reasonable threshold under which a change of a key parameter can be assumed as negligible is about 10%, Figure 3.



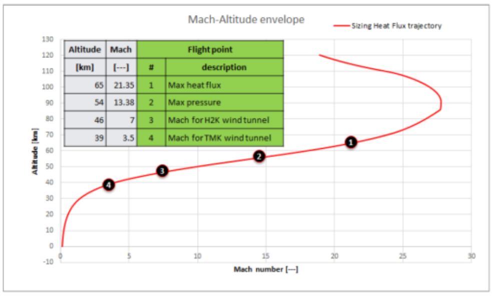
Affected system aspect	Key-performance indicator	Convergence threshold
Inflatable structure	deformation	≤10%
Aeroshape	Pressure distribution	
	Drag coefficient	

Fig 2. Key Performance Parameters

The interaction between the inflatable heat shield (IHS) and the surrounding airflow was performed in particular conditions,mainly focusing on critical points as:

- Maximum heat flux: When the heat entering the IHS is highest.
- Maximum pressure: When the force exerted on the IHS is strongest.

Furthermore, taking into account that thew the chosen points should also be achievable in the wind tunnels available later in the project. At the end the focus was set on four meaningful flight points as shown in Fig 3.



Altitude	Mach	Flight point	
[km]	[---]	#	description
65	21.35	1	Max heat flux
54	13.38	2	Max pressure
46	7	3	Mach for H2K wind tunnel
39	3.5	4	Mach for TMK wind tunnel

Fig 3. Strategic flight points for the FSI loop implementation

2.1. FE model

The FE modelling, carried on by SRSED srl (CIRA Subcontractor) adopted for the implementation of the FSI loop has leveraged extensively on the heritage of EFESTO-1 project.
A FE model of the Dual Body configuration realized by means of axisymmetric SAX1 elements has been realized.

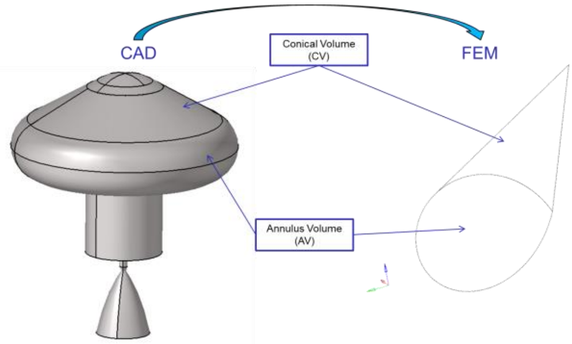


Fig 4. From CAD to FEM model

In order to simulate the reduction of the in-plane behavior of fabric elements, the fabric material has been simulated as a 3-layer composite material.
The aforementioned simulation approach gave good results in terms of experimental/simulation comparison as show in figure below during EFESTO project static test campaign.

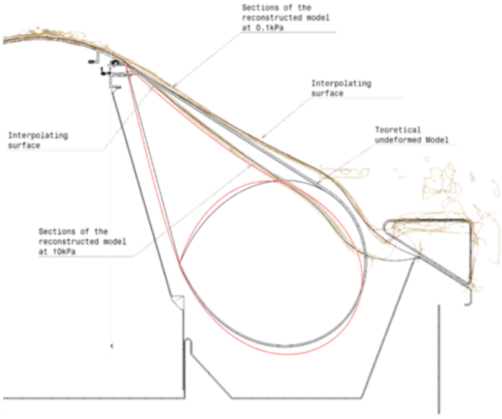


Fig 5. Numerical (red line)/Experimental (brown line) comparison results

In order to simulate external pressure during re-entry, the node at the nose location has been pinned, while the node representing the Dog-Ring location has been radially constrained.
Furthermore, the external pressure profile has been applied on the red line shown in figure below.

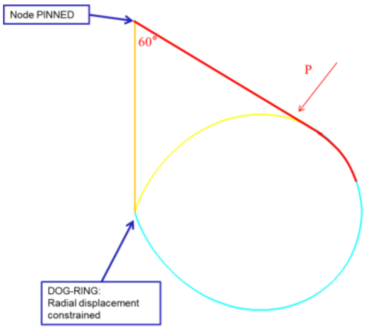


Fig 6. FE model BC's and Load Case

In order to replicate re-entry configuration, the pressures of 27 kPa and 5 kPa have been applied into Annulus Volume and Conical Volume respectively.

2.2. FSI Results

An iterative process simulates the deformation of an object at high speed (Mach 7). Iterations continue until minimal further deformation occurs (convergence). The following charts synthesize the 'Loop A' evolution form the undeformed shape to the last deformed at convergence, respectively:
In order to obtain an adequate database of results for the trajectory during re-entry of the EFESTO-2 inflatable capsule, two flow conditions have been investigated, at Mach 7 and Mach 13 respectively. In following paragraphs results obtained have been summarized.

2.3. Results at Mach 7

As reported below, three loops of iteration have been enough for calculating the equilibrium shape and pressure profile of the IS, in order to match the threshold of 10% as shown in Fig 2. Following, the pressure profile provided by ONERA at Mach 7 after the three loops of iteration.

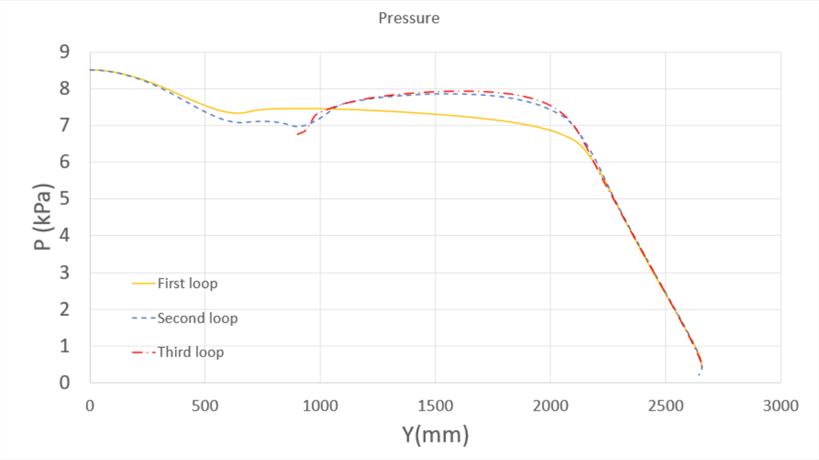


Fig 7. Third loop of pressure profile (at Mach 7)

Following, the deformed shape of the IS under the aforementioned pressure load has been depicted and compared with each loop.

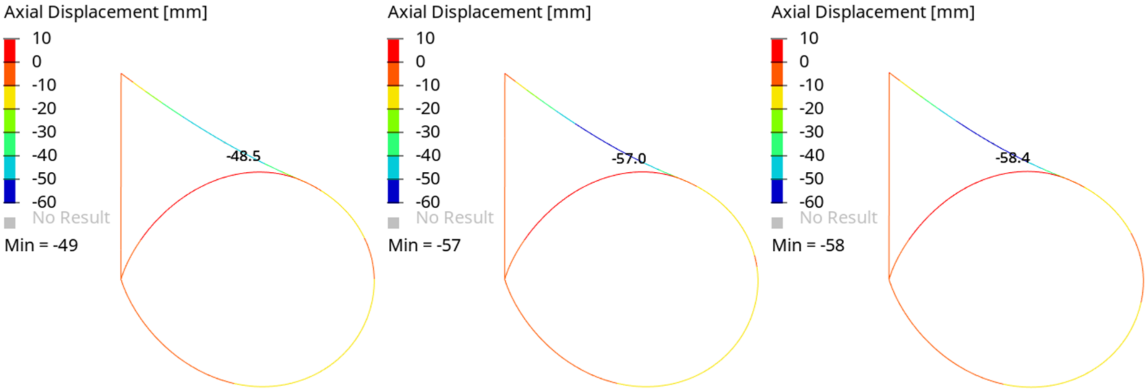


Fig 8. FE model deformation results: First loop (left); Second loop (center); Third loop (right)

2.4. Results at Mach 13

As reported below, three loop of iteration have been enough for calculating the equilibrium shape and pressure profile of the IS, in order to match the threshold of 10%. Following, the pressure profile provided by ONERA at Mach 13 after the three loop of iteration.

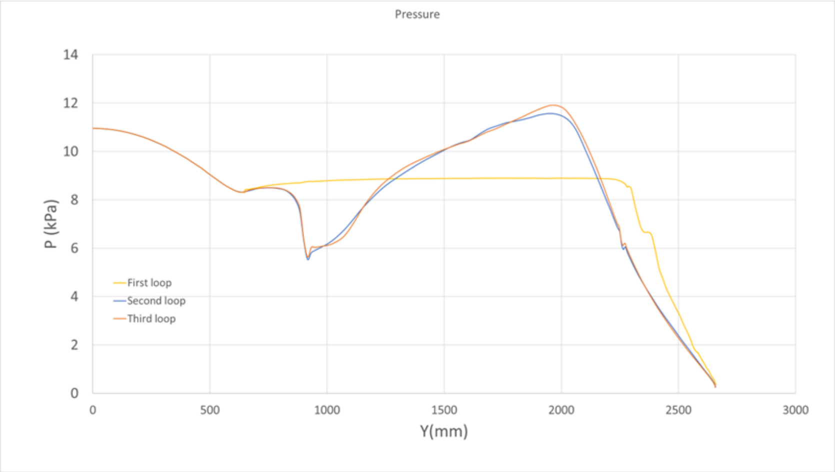


Fig 9. Third loop of pressure profile (at Mach 13)

Following the deformed shape of the IS under the aforementioned pressure load has been depicted and compared with each loop.

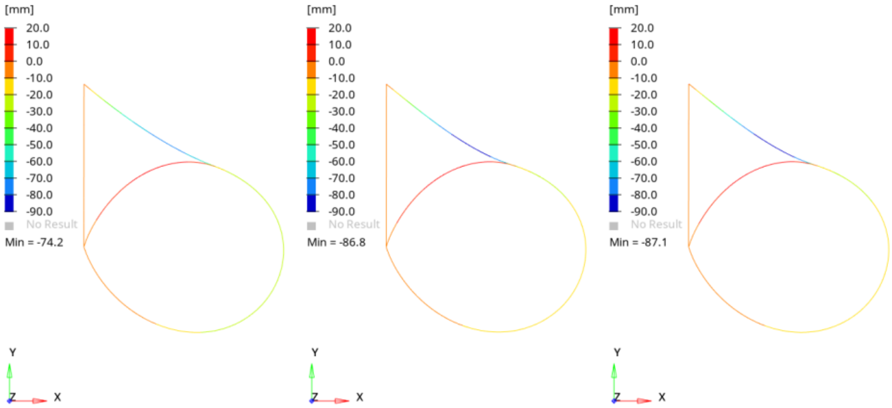


Fig 10. FE model deformation results: First loop (left); Second loop (center); Third loop (right)

3. Dynamic test campaign

3.1. 3D FE model

As aforementioned, in order to identify the best setup for experimental dynamic test campaign, a numerical simulation of the Ground Demonstrator IS has been carried out. To this end a FE model of the Ground Demonstrator IS has been realized by means of membrane (2D) and truss (1D) elements, in order to simulate the presence of the Carrier and Tendons respectively.

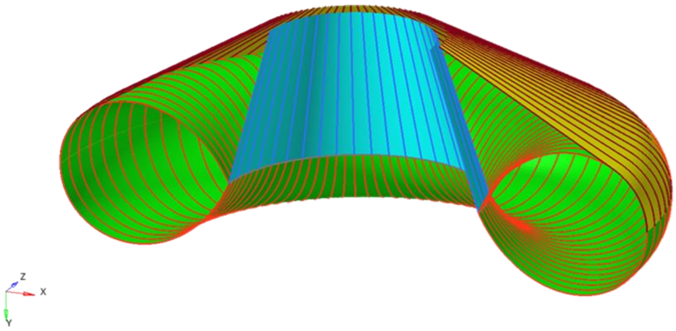


Fig 11. Ground Demonstrator IS 3D FE model

Material properties have been applied considering test results carried out on carrier and tendons specimens during EFESTO project.

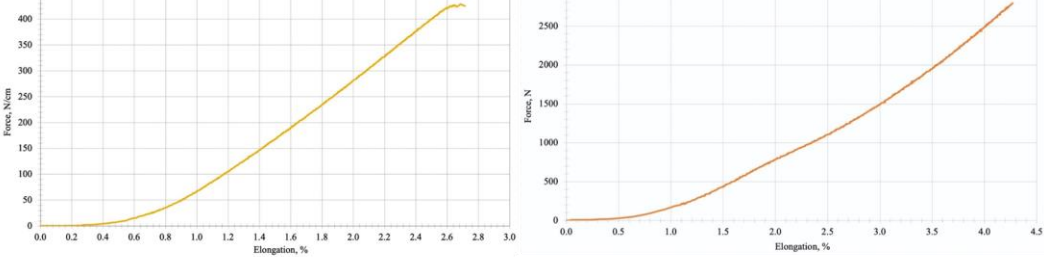


Fig 12. Experimental Force vs Elongation curve for Carrier (left) and Tendons (right)

Furthermore, the BC's have been applied as shown below, with only nodes at tendons top location pinned, in order to simulate the presence of the rigid flange.

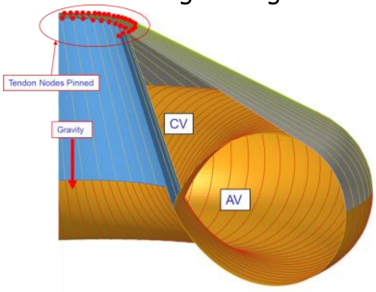


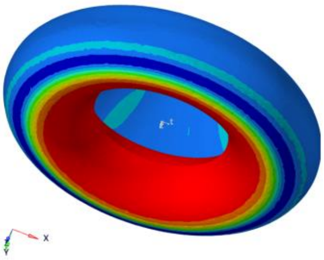
Fig 13. Ground Demonstrator IS 3D FE model BC's and Loads

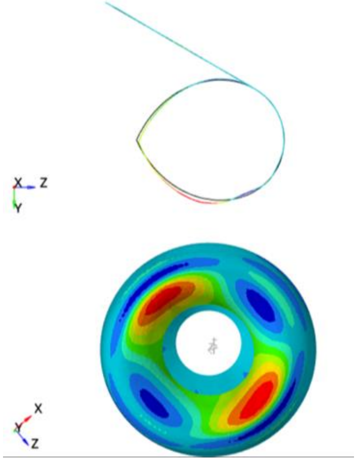
Finally, two steps of calculation have been performed:

4. the first step, aimed at achieving the equilibrium inflated configuration of the IS, was an explicit analysis with a pressure of 0.1 kPa and 18 kPa in the CV and AV respectively, and the application of the gravity load to the IS;
5. the second step, aimed at obtaining modal shapes and frequencies of the IS, was a linear perturbation modal analysis.

3.2. 3D modal analysis simulation results

As aforementioned, this preliminary modal analysis is aimed at preparing the setup for the dynamic test campaign. The goal is to identify modes shapes and first global frequencies of the IS.
Following some pictures of the modal shapes calculated.





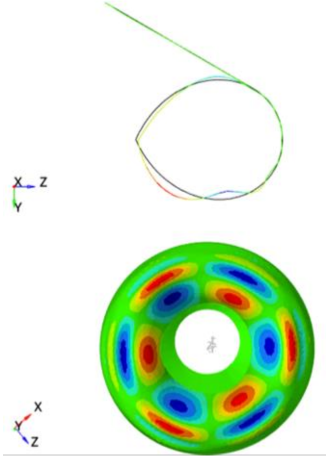


Fig 14. Natural modes of the IS: First axial mode (left); 4-lobes elastic mode (center); 6-lobes elastic mode (right)

3.3. Dynamic test campaign

During the EFESTO project, the integrity of the IAD Ground Demonstrator was successfully verified under simulated re-entry pressure loads. Subsequently, in EFESTO 2, the same demonstrator was used to investigate the dynamic behavior of the Inflatable Structure (IS) through experimental modal tests performed at CIRA. Modal tests allow for the identification of modal parameters (natural frequencies, mode shapes and damping). Non-linearity aspects were also considered during dynamic tests, by evaluating modal parameters exciting the structure at different excitation levels.

Modal testing is a crucial technique for understanding the dynamic behavior of all structures. Inflatable structures present unique challenges due to their lightweight and flexible nature (that makes them susceptible to large deformations and complex vibration patterns) and their highly damped response (that make it difficult to accurately measure and excite the structure's natural frequencies) as highlighted in Danesh Pazhooh et al. (2011) [3]. Furthermore, inflatable structures often struggle to maintain their shape during testing. They can quickly develop wrinkles and sag, before a complete set of measurements can be taken. Considering all aspect, CIRA designed and manufactured a dedicated inflating system (Fig 15) able to maintain the pressure on the two chambers of the IS during tests.

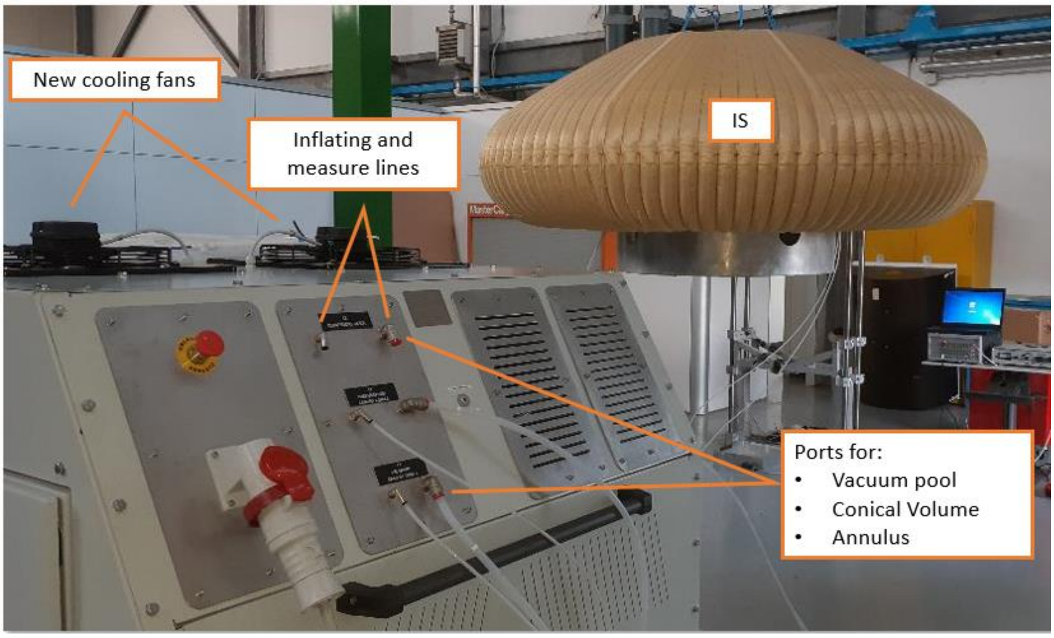


Fig 15. IS Inflation System

Many researchers have tackled with inflatable structures in past decades. Ruggiero et al. (2004) [4] conducted an experimental modal analysis on inflated self-rigidizing torus using an electromagnetic shaker and many accelerometers (SIMO configuration). This study measured three out-of-plane and one in-plane mode frequencies. Song et al. (2006) [5] instead, employed a subwoofer for acoustic excitation (SISO configuration) on a Torus. They captured three out-of-plane and two in-plane modes. The ground vibration test of the IS has been carried out at the technologies plant of CIRA. The test site environmental conditions, in terms of temperature, pressure and humidity, have been verified compatible with the operating characteristics of the test equipment. Such conditions allowed to minimize the transducers sensitivity variation due to thermal fluctuations. To perform modal tests on the EFESTO 2 demonstrator, a suspension system made of 8 elastic ropes were used to realize the free-free ideal condition for the test. The "in plane" suspension frequency (pendulum like) was about 0.3 Hz, while the "vertical" suspension frequency was about 2 Hz. Test measurements were performed after the springs were allowed to creep for several days. In Fig 16 the suspension system is shown.

Fig 16. IS Suspension System

The test article has been instrumented with a set of 32 mono-axial accelerometers. The measurement mesh has been designed considering the numerical predictions of the FE model in order to choose the optimal location for sensors, shakers and suspension system, and allow the optimal control and observation of the selected target modes. Any possible spatial aliasing of the experimental modes has been minimized. The Modal Assurance Criterion (MAC) has been used to evaluate the quality of the selected mesh of measurement. The accelerometers have been installed half of them on the maximum "in plane" circumference, the other half on the circumference located at the bottom of the annulus of the IS, as showed in Fig 17.

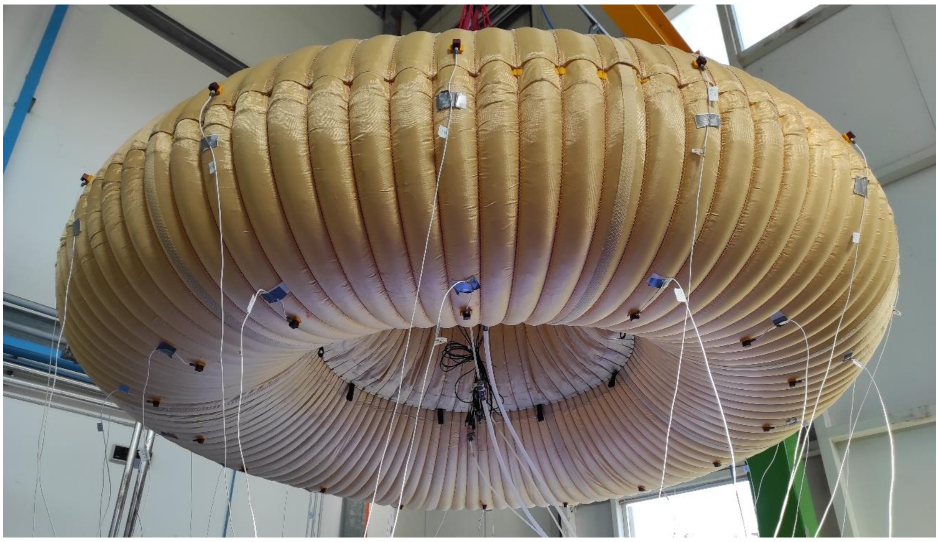


Fig 17. Accelerometer sensors positioning

The measurement mesh is shown in Fig 18.

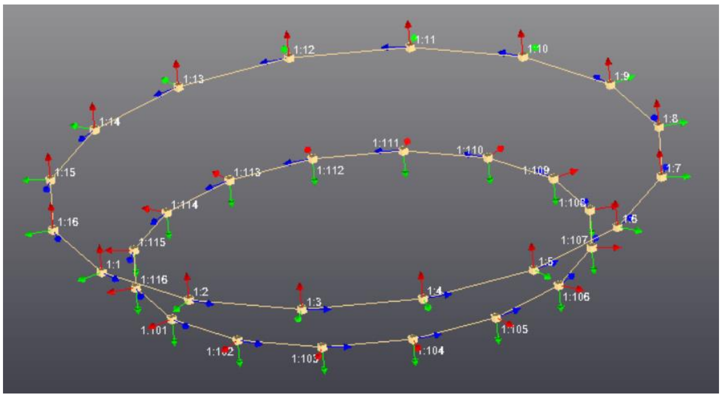


Fig 18. Measurement mesh

Experimental modal characterization of the IS has been performed by using Phase Separation technique. Global excitation of modes of the structure with a SIMO broadband random excitation signals has been carried out in order to identify the structural resonances and derive an overview of the basic modes within the frequency range of interest. Modal parameters have been extracted by the measured FRFs, using Frequency Domain MDOF modal analysis technique: Siemens LMS Test-Lab Polymax Plus algorithm (Peeters et al. (2012)[6]) have been employed to identify modal parameters: frequencies, damping and mode shapes. Thus, the modal characterization of the structure has been performed as follows:

- Step 1 – Measurement of the structural FRFs by means of Random broadband excitation signal in the frequency range 3-100 Hz
- Step 2 – Modal parameters extraction from the FRFs measured in step 1 (resonance frequency, damping and mode shape)

In order to measure the natural modal parameters of the IS (inflated at a pression of 18 kPa) one point of the structure has been excited by means of an electro-dynamic shaker. The shaker has been grounded by means of a pantograph system. An aluminum plate carrying the load cell has been attached to the IS through a bi-adhesive tape and connected to the shaker through a stinger (push-road) as shown in Fig 19. The shaker has been placed in correspondence of accelerometer N° 1.

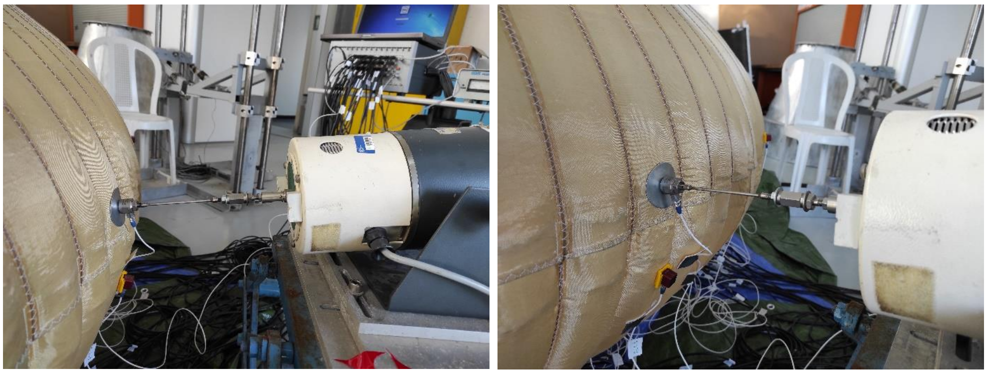


Fig 19. Shaker excitation system

For each measured normal mode (in the frequency range 15Hz-78Hz), test results have been reported as follows:

- Resonance frequency (Hz)
- Modal damping (in percentage respect to critical damping)
- Generalized Mass
- Mode shape plot

	Frequency	Damping	Generalized Mass
	[Hz]	[%]	[Kg]
Mode 1	19.277	7.93	2.86194
Mode 2	27.167	5.55	3.12598
Mode 3	39.116	3.15	1.33622
Mode 4	43.704	4.56	1.04849
Mode 5	53.868	3.46	0.46424
Mode 6	60.982	3.14	0.34299
Mode 7	71.481	2.58	0.59918

Table 1 - Modal parameters in Frequency Range 15Hz-78Hz

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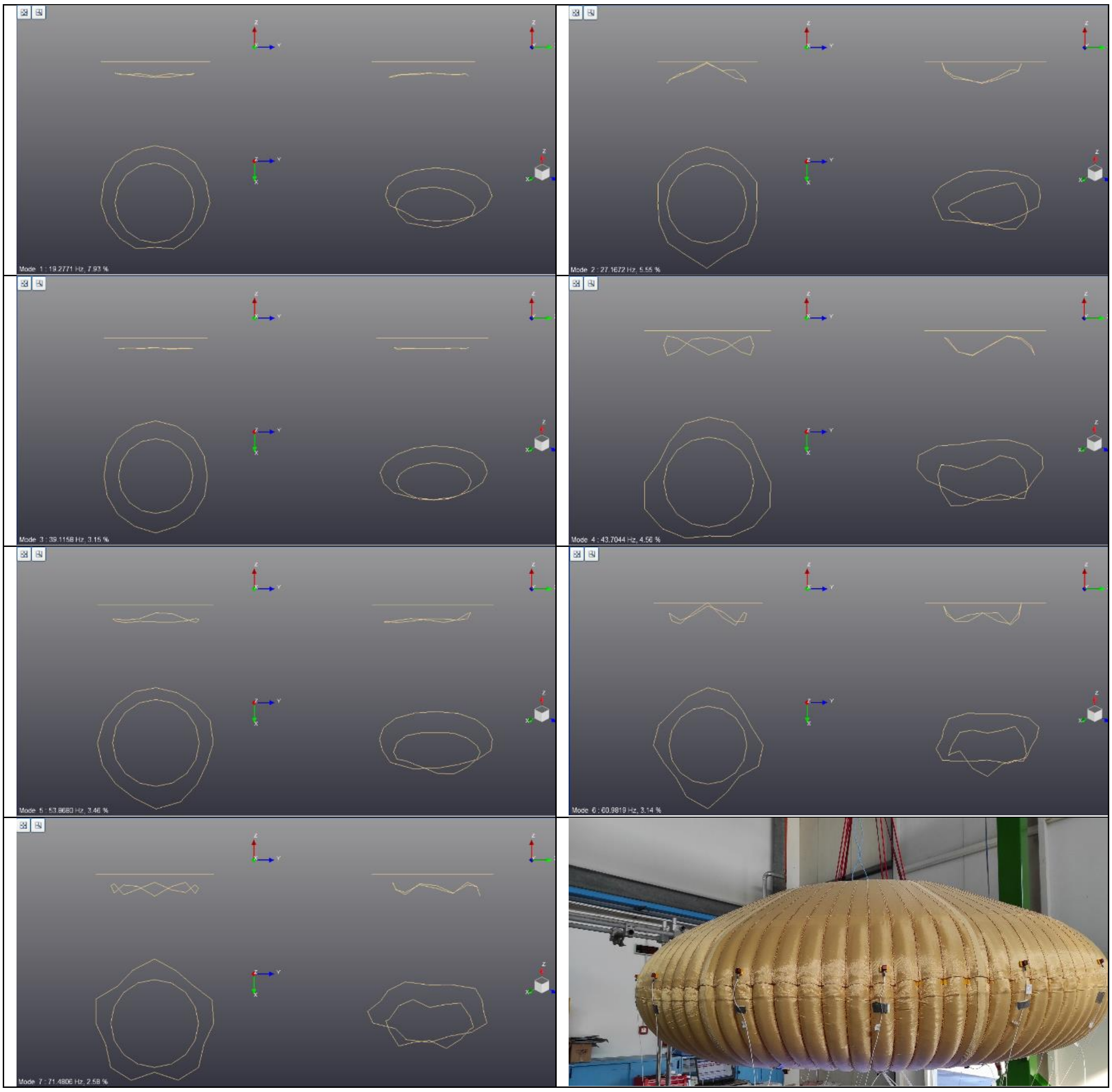


Fig 20. IS Mode Shapes in Frequency Range 15Hz-78Hz

4. Morphing analysis

A dedicated effort has been made to model and simulate morphing behavior of the inflatable structure during folding and unfolding. During the parent project EFESTO, a folding and inflation analysis process was designed and set up, relying on the FE explicit software RADIOSS. This allowed to describe the folding phase in a way similar to the process developed by CIRA on the test rig, but also to give a prediction on the shape of the inflated shape.

As part, of the extended spectrum with respect to EFESTO, the activities were reviewed in EFESTO2, and several areas of improvement were identified, in the definition of the FE model, the characterization of the materials, as well as the folding hypotheses and strategy.

First, the FE model was rebuilt entirely, based on the new geometry of the EFESTO-2 test case (Fig 22) In particular, one of the major improvements is the addition of the tendons, which are now modelled explicitly as truss elements running along the generators of the cones, and around the annulus (Fig 23a) These axial tendons provide additional rigidity to the cone and are deemed essential to ensure that the aerodynamic shape is preserved, which was not the case for EFESTO (see Fig 21c). In terms of boundary conditions, both the upper and lower connection to the rigid payload were improved in realism. In the upper area, a loose connection realized through additional ropes (Fig 23b), while the boundary conditions corresponding to the dog ring placed at the inner edge of the annulus are now correctly enforced.

Additionally, material modelling was refined. The dependence of the material properties to temperature, when available, will be taken into account for the inflation analysis, in order to acknowledge the fact that the IS would deployed in outer space. The analyses will be focused on the behavior of the IS at first, with the same material properties used in other disciplines.

Finally, the folding strategy was also reviewed, and lessons were learned from the demonstrator activities in EFESTO. Indeed, while folding the IS in a petal-like pattern (See Fig 21b) was proved beneficial, the first steps were cumbersome and difficult to simulate. As a result, the new folding strategy makes use of the increased height of the rigid payload, and the IS will now first be pressed against the walls of the payload in a downward movement, before forming the petals. This is expected to reduce the internal stresses in the material, as well as the amount of wrinkles, which are particularly critical as far as the flexible TPS is involved.

Precisely, future works will have to focus on the introduction of the flexible TPS in the overall strategy described here. Indeed, both the significant thickness of the stacked layers of thermal protection, and the stiffness of the materials themselves, increase massively the bending stiffness of the overall structure. It is then important to verify if the folded shapes predicted with the IS are achievable with the flexible TPS, and whether or not the materials are damaged. Additionally, let us note that all the activities described above make use of material properties that are not fully known (especially in the out-of-plane direction). Thus, additional effort will have to be put in characterizing these missing properties through a dedicated test campaign.

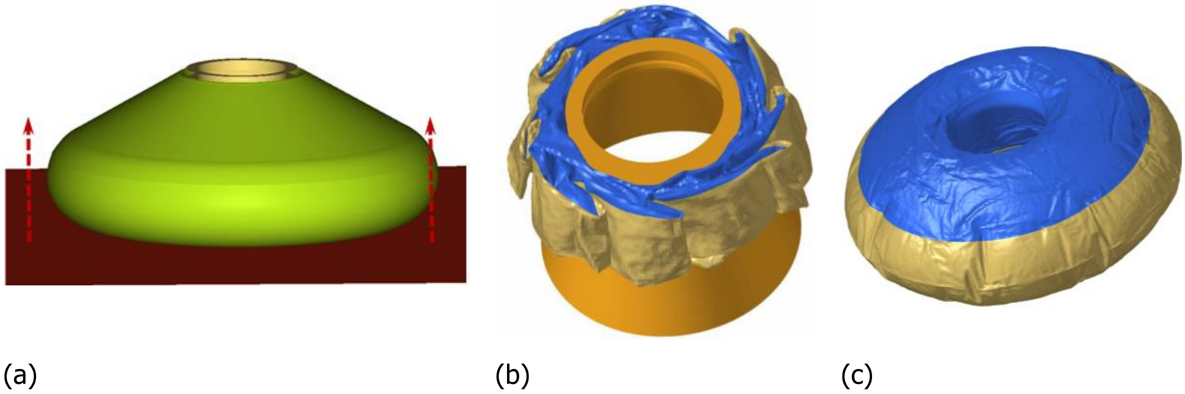

(a) (b) (c)

Fig 21. Folding and inflation analysis: contraction (a), folded shape (b), inflated shape at nominal pressure (c)

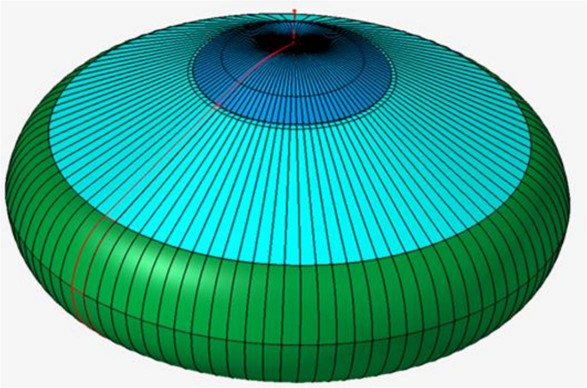
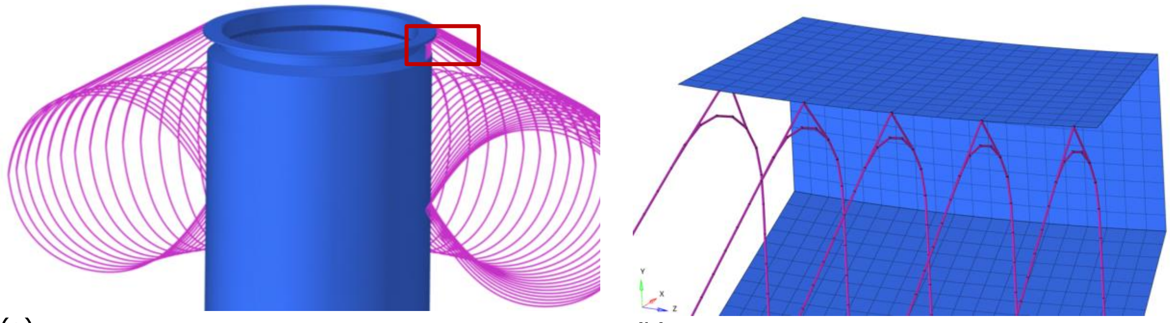


Fig 22. view of the updated EFESTO2 FE model



(a)
(b)

Fig 23. Global view of the tendon array (a) and detail of the upper connection to the rigid payload

5. Conclusions

The presented activities challenged the researcher involved in the project. The numerical modelling of the system revealed to be a non-trivial matter. Many approaches and validation strategies have been implemented, even if not shown here, for achieving a reliable model.

Experimental activities are still ongoing on the Inflatable System, but a good amount of data have already been acquired, with different boundary conditions, at different inflation levels and loading the structure with different load patterns and directions.

The so far acquired data, and the extensive hands-on executed on a fully representative ground demonstrator, have increased the all-around knowledge and understanding of these innovative inflatable structures. The overall feeling is of a very reliable and effective IS architecture, fully suitable for future real flight tests.

Next activities will be focused on acquiring additional experimental data from the structure in other different configurations and in tuning the numerical model in order to reproduce the experimental data in all the tested configurations.

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- Journal article

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