# ANISOGRID PAYLOAD ADAPTOR STRUCTURE FOR VEGA LAUNCHER

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## ABSTRACT

In the framework of a development project promoted by the European Space Agency (ESA/ESTEC), Airbus Defence & Space (EADS CASA Espacio, ECE) has designed, manufactured and tested a technology demonstrator representative of the payload adaptor (PLA) of VEGA Launcher, by using an anisogrid concept, called anisogrid payload adaptor (APA).

This lattice technology of CFRP grid structure is a promising weight saving solution for some structural applications, both satellites and launchers applications, compared to the traditional sandwich and/or monolithic concepts. The manufacturing process developed by ECE for the APA, based on Automated Fibre Placement (AFP) technology, allowed achieving all the requirements of the payload adaptor in a competitive manner in terms of mass and cost.

This paper outlines the design, manufacturing and testing of the APA demonstrator, as well as the logic of the development, with some previous trials and smaller demonstrators to identify and understand the key points of this type of anisogrid structures.

## 1. INTRODUCTION

The lattice technology in CFRP is a new engineering approach to develop light structures with potential benefits for the launch vehicle performance capability. Although there are currently in flight service some CFRP lattice structures for launchers [1] [2], they have been developed to be manufactured by Filament Winding (FW) process, which involves substantial differences with AFP.

ECE within the framework of ESA/ESTEC development project has demonstrated the feasibility of the lattice AFP process for its potential application in future structures, developing a technology demonstrator based in the current VEGA 1194 adaptor under similar specifications.

Critical issues associated to the design, analysis, manufacturing, verification and testing processes have been identified, trying to assure a robust design concept that could be manufactured in a repetitive and simple manner by AFP, reducing cost and time.

The manufacturing processes used for this project have been based on previous ECE internal work and studies performed, where several lay-up techniques and procedures were developed and tested in order to verify the feasibility of this design approach. All the technologies used for the manufacturing of the APA technology demonstrator are today flight approved, thus all materials and processes are space qualified.

## 2. LOGIC OF THE DEVELOPMENT

The global logic of the activities is based on a building block approach structured in three phases:

- Exploitation of the heritage from previous ECE projects.
- Based on the previous analysis, to perform a specific development campaign at sample level, identifying the optimal solution from a mechanical and manufacturing point of view for the APA technology demonstrator in the nodes areas.
- Manufacturing and testing of two cylindrical demonstrators using the selected design from the samples. The objective is to consolidate the design, analysis and fabrication process before the APA production.

### Heritage from previous projects – basic structural components

ECE has developed the manufacturing of CFRP lattice structures by using AFP in the last years, specifically for FLPP and ICARO projects [3] [4]. In those projects, several technological demonstrators were produced, “Fig.1”.

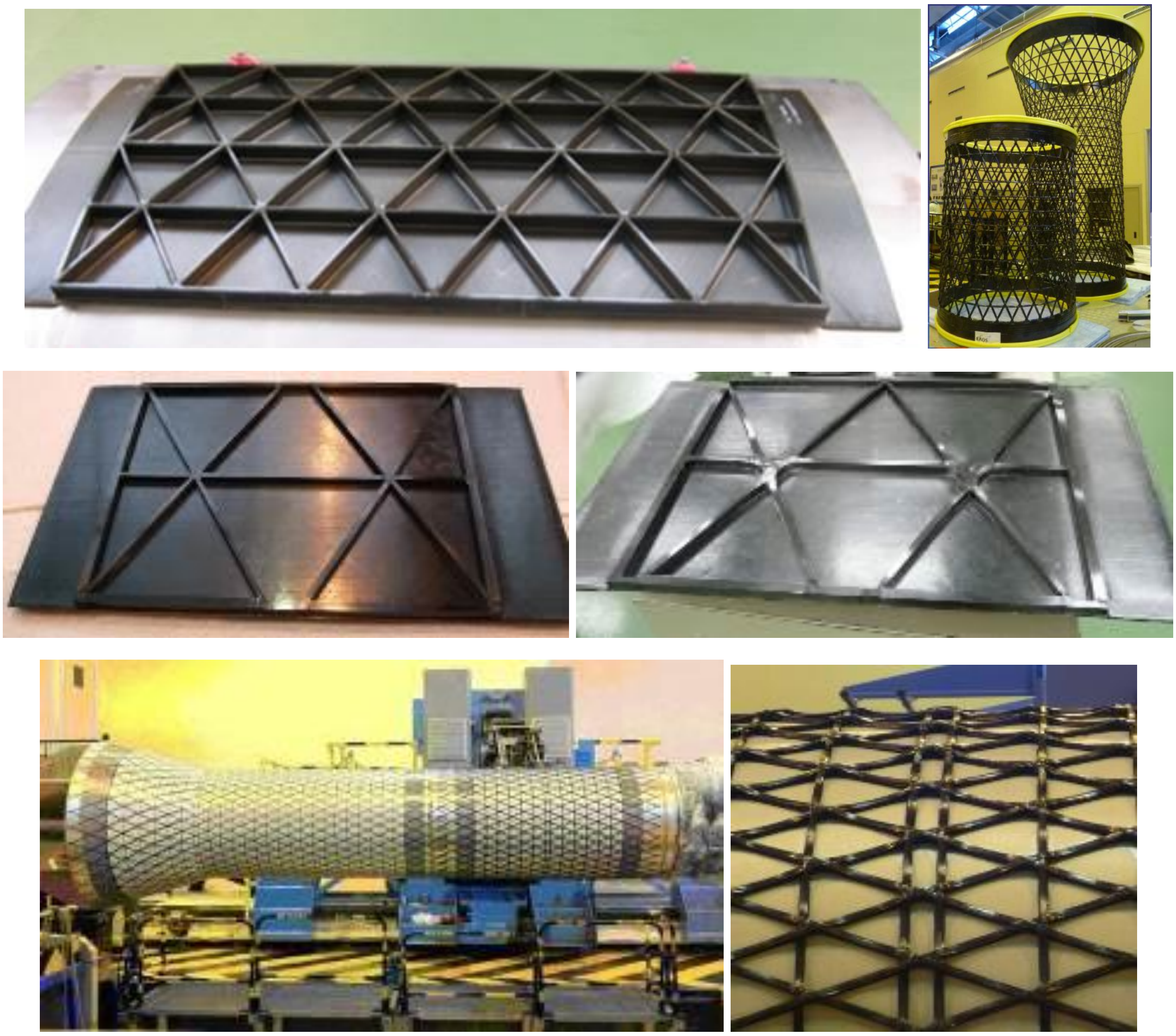

Fig. 1. FLPP and ICARO lattice technological demonstrators for aerospace applications

From those projects, three main constitutive and differential elements were identified: nodes, stiffener elements and skin. The characteristics of each one have been analysed from the point of view of manufacturing and analysis.

- The node concept, which does not have relevant importance for isotropic metal structures, plays an important role in composite parts due to the high influence of the manufacturing method, the conception of the structure and the mechanical connotations that are derived from them.

- Stiffeners have different behaviour depending on how the structure is manufactured. They provide stability and strength to the structure with a skin, however they constitute the structure itself when there is no skin. Then, all mechanical performances are strongly related to their geometry and pattern disposition.

- For the APA there is not foreseen a skin for the structure, according previous studies performed along the ICARO project. The skin does not offer remarkable advantages from the mechanical point of view, compared to the associated drawbacks for the manufacturing, mainly in the intersection zones.

Once concluded that the lattice structure would be without skin, it was assessed the role of the remaining structural components, which are driven by the geometry of the node and the pattern disposition of the stiffeners. These structures present intersections with crossed stiffeners of varied geometries distributed and based on design parameters.

Several trials were made in previous ECE projects [3] [4], in order to analyse from the manufacturing point of view how to deal with over thickness issue in the nodes. Different topologies for nodes are discontinuous nodes “Fig.2”, displaced overlapped nodes “Fig 3.” and steering nodes “Fig.4”.

The main characteristic of discontinuous nodes is having a constant thickness in the all stiffener elements that converge in the node. In this case, it is necessary to alternate cuts in the carbon strips that cross the node. The main drawback is the discontinuity of the fibre in the entire stiffener.

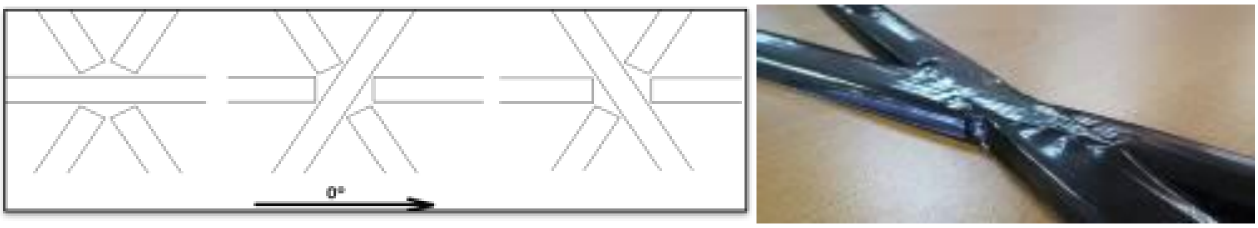

Fig. 2. Example of discontinuous nodes (constant thickness)

Concerning to the overlapped nodes, the main issue is the layers bending. In order to minimize the effect of the over thickness due to the tows that merge in the same area, steered and straight displacement were analysed. The final objective is not having more than two piled up carbon strips in nodes surroundings.

Depending on how many crosses are displaced, some triangular geometry with the presence of bigger or lower triangular gaps can appear. This node topology requires a special control on the local compaction because thickness transition is produced sharply, without existing an approximation area.

Fig. 3. Example of displaced overlapped node

Steering nodes are an advanced type of node that can be produced by AFP technology. Moreover, this type of solution is flexible to produce nodes with less, more or equal nominal thickness as the stiffener, depending on how is made the steering process.

This concept has an important drawback, due that the fibre misalignment decreases the strength capability of the stiffener. The buckling factor is considerably lower because the thickness of each pack of fibres is lower than the thickness of the complete stack of straight stiffener. Non-linear effect associated to the bending effects during the compression load cases have to be taken into account, and it should be assumed than they can appear during the test, reducing significantly the final performance of the specimen.

Also, as the node size is substantially bigger, this effect limits the application of this approach when the distance between nodes is lower than certain value.

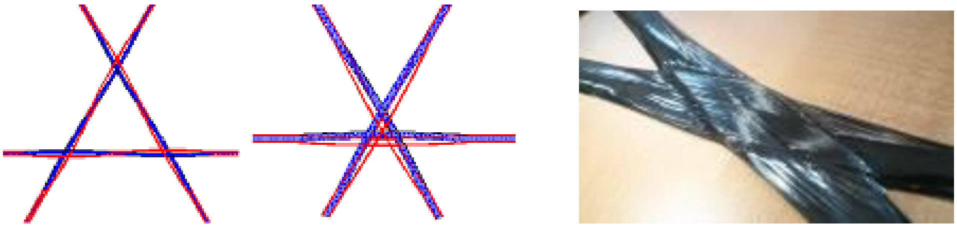

Fig. 4. Example of steering node

## Feasibility trials at sample level

In order to gain understanding of the node behaviour in terms of mechanical performance (strength & stiffness) different design verification parts (DVPs) representative of the geometry of the APA were manufactured and tested in both, tension and compression loads, “Fig. 5”, at Aerospace and Advanced Composites (AAC) facilities. Three different nodes topologies were produced: discontinuous, overlapped, and steering nodes.

Fig. 5. Constant thickness node (left), overlapped node (centre), steering node (right)

Once tested the previous DVPs, the results are analysed. The overlapped node topology was selected for the APA design, because it has some advantages with respect to the other alternatives, in terms of manufacturing and mechanical behaviour.

According to the conclusions extracted from the previous first tests, a second batch of DVPs was produced “Fig. 6”, based on the overlapped node with some variations, as smaller free stiffener length in order to avoid a potential buckling, or some manufacturing particularities and enhancements, like the use of expansion tools for curing.

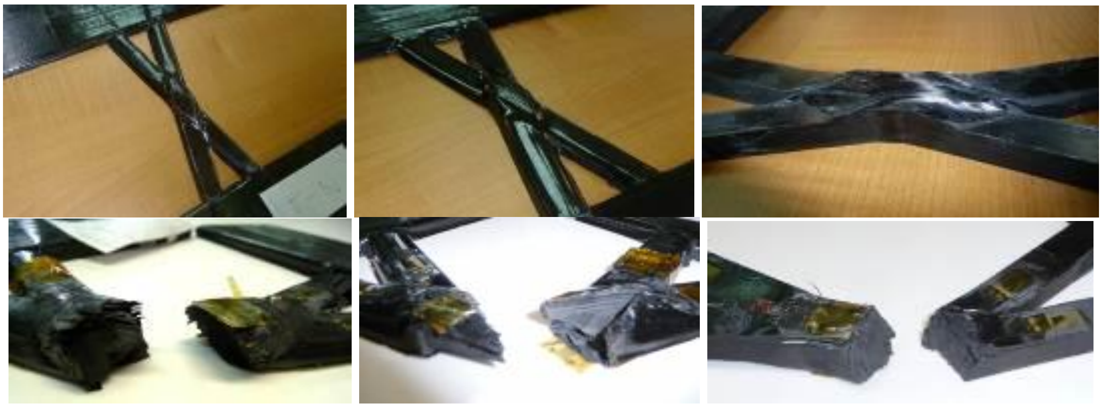

Fig. 6. Second batch of DVPs with overlapped nodes with different manufacturing solutions

The main conclusion of the study is that using of expansion tools increases the mechanical strength performance a 20% compared to the ECE developed curing system without expansion tools. Besides, the rupture mode shape is more clean and consistent.

The main drawback of this approach is the higher complexity in the manufacturing process, increasing the time and the non-automatic operations in the production. For a hypothetic future industrialization of this concept in AFP, the use of expansion tools seems not feasible.

### Cylindrical demonstrators study

According to the previous results and other similar demonstrators produced in ICARO project [3], the topology of node selected for the APA it is the overlapped node concept, without using any expansion tool during the curing.

Two anisogrid cylindrical demonstrators were produced before the manufacturing of the APA, with the following objectives:

- To select the most appropriate CFRP material, from the mechanical and manufacturability point of view.
- To mature the manufacturing process and the selected design for the nodes. The topology for cylinders is fully representative of the APA.
- To consolidate the analysis method and to correlate the test results

Both demonstrators were identical except for the thickness of the stiffeners and CFRP material, one with a high modulus (HM) fibre and the other with ultra-high modulus (UHM) fibre, “Fig. 7”.

Fig. 7. Cylindrical demonstrators HM fibre (left), UHM fibre (right)

Once produced, those demonstrators were tested in tension and compression, in order to obtain the local and global stiffness, the buckling performance and, finally, the failure load and the rupture mode. The specimens were tested by means of a universal testing machine, "Fig. 8", at Testing and Engineering of Aeronautical Materials and Structures (TEAMS) facilities.

Fig. 8. Cylindrical demonstrator test

The correlation of the stiffness behaviour and the strength capability with the performed analysis was good for both cylinders, except a lack of stiffness performance detected in the UHM fibre cylinder. The conclusion was the validation of the analysis methodology, the same that would be used for the APA.

Taking into account those results and the manufacturing constraints, the material selected for the APA was the HM fibre one, due to a higher robustness in its global behaviour.

## 3. APA TECHNOLOGY DEMONSTRATOR – DESIGN

The VEGA 937/1194 APA design concept is a technology demonstrator based of the PLA family for satellites that are located in the upper part of the launcher VEGA. It is located on the top of the AVUM stage, for satellites until 2000 kg and centre of gravity (CoG) location of 2 m, "Fig. 9".

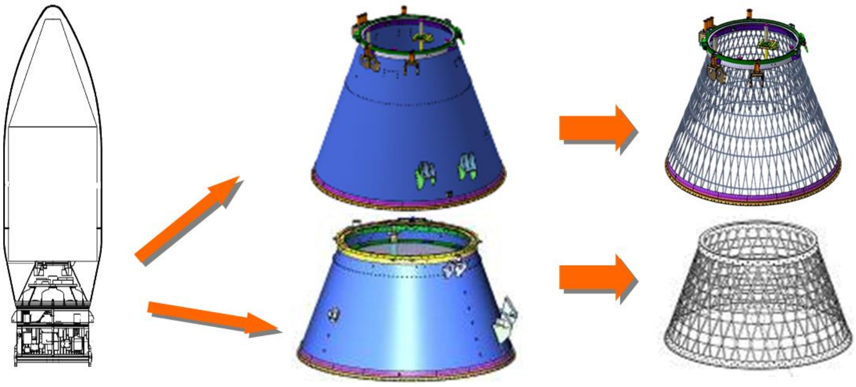

Fig. 9. VEGA P/L Adapters, 937 (up) and 1194 (down) and its respective lattice concepts

### Global model study

One of the most important issues of the development is to stablish the optimal topology of the structure. It is necessary to know what could be the best design approach taken into account not only the geometrical variables and/or constraints, but also the manufacturing ones.

The goal behind the parametric modelling of a VEGA PLA is to have available a computer aided-design (CAD) model capable to be easily modified according to updating of specifications during the preliminary design phase.

In this case, the parameters are the helicoidally stiffeners number, its section (height and width) as well as the angle of positioning with respect to the cone mould. Concerning the horizontal ribs, its number, positioning, and section height and width are also considered as variables, "Fig. 10".

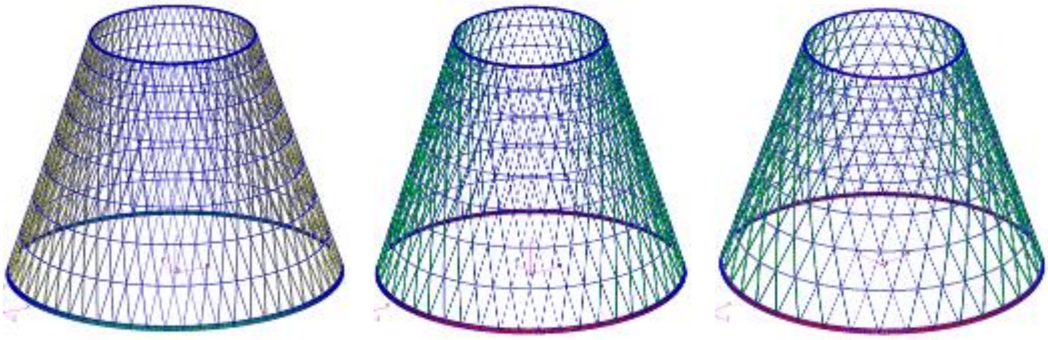

Fig. 10. Lattice distribution 120, 96, 72 stiffeners

During the initial finite element method (FEM) calculus of the different configurations, each of them had a separated CAD model. The parametric model is able to change between these and other configurations simply by activating or de-activating certain Boolean parameters, as well as being able to change every design dimension.

The basis of the parametric model is the isogrid configuration. Conical shells, circular frames and spars following the generatrix are fairly easy to parameterize. However, because of considerations relating to the ease of generating the FEM and manufacturing constrains, the isogrid spars must maintain a constant angle relative to the generatrix. This helical curve, when projected on the horizontal plane (the YZ plane following the launcher's axis system) results in a logarithmic spiral.

The CAD program used to create the APA models does not have a tool to create logarithmic spirals. Then, it is needed to create a curve the most approximate to these spirals. To accomplish this objective, a script is created in Python that generates the basic conical support geometry, the control parameters, and then over a hundred points belonging to the exact logarithmic spiral as well as their radiuses.

In this way, the model is divided in several solid elements, independent in relation with each other, but all governed by the control parameters the user can modify, such as lengths and thicknesses, angles or number of spars. Some of the parameters are common to all or most of the solids, like the cone angle or the base diameter, while others are specific to only one of them, like chamfer angles.

The principal solids of the structure are the conic shell, the helical spars, the circular frames, the generatrix-following stringers and the sandwich and outer shell. There are also secondary solid sets for the filling elements and bounding tapes at the ends of the helical spars. Finally, warnings were included to warn the user of the limitations of the model and what were considered as incongruent combinations of parameters.

The analysis is performed modelling the whole cone introducing the upper and lower interface (I/F) rings, in order to simulate a more realistic behaviour of these areas. The stiffeners intersection nodes are ideally supposed, and potential over thickness in the stiffeners junctions are not considered.

Three different versions of APA were compared, modifying the position of circumferential ribs. The first is placing the ribs at level of stiffener intersection, generating a triangular path. The second is with the ribs in the middle of stiffeners intersection, generating a hexagonal/triangular path. The third is placing vertical ribs instead horizontal one, “Fig.11”.

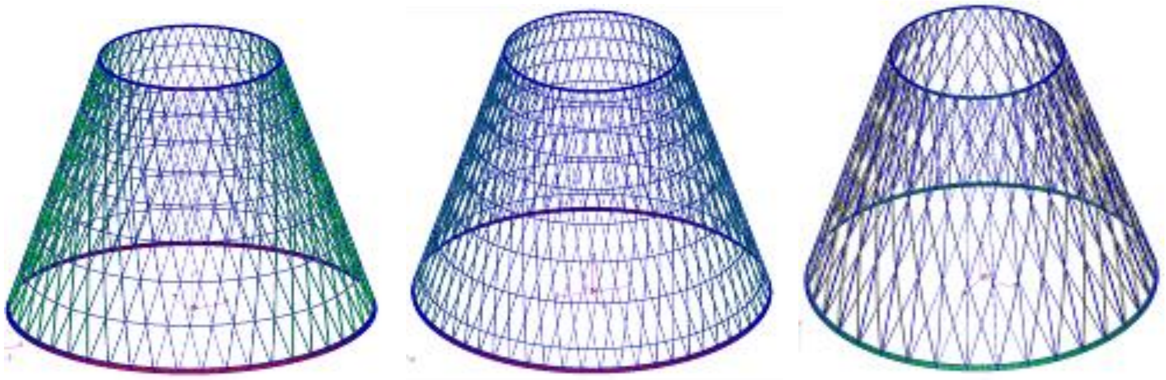

Fig. 11. Lattice topology triangles (left), hexagons (centre) vertical ribs (right)

The main conclusions of the study was to stablish the optimum helicoidally stringer angle, number, width and height of the stiffeners, and the better dimensioning, and positioning of the circumferential frames.

## Final Design

The final design of the APA demonstrator has been fixed taking into account a balanced optimization between mechanical performances, mass and manufacturing feasibility:

- The thickness for APA stiffeners was stablished according the AFP manufacturing process.

- The angle between the helices and the horizontal plane is defined taking into account a mass optimization but balancing it with a suitable stiffness, buckling and strength performance, and maintaining the established margin of safety (MoS).

- The relative position of the helices among them is defined avoiding over thickness areas or bumps inside the upper and lower stripes.

- The width of each helix and circumferential ribs is compatible with the AFP process.

- The number of helices is compatible with the launcher I/F attachments distribution, in order to assure a homogeneous behaviour and controlled overfluxes around the whole structure. For that reason, only configurations of helices compatible with the 72 pairs of I/F points were considered. Finally, it was selected 36+36 helices.

- The number of circumferential stiffeners is compatible with the AFP process and with the helicoidally distribution of the stiffeners, to assure the buckling performance.

- This parameter is conditioned by three factors, over thickness in the nodes, buckling along the “X” axis of the structure and distance of them near the upper and lower stripes.

- Integral CFRP rings close the lattice by its upper and lower areas, filling and covering the lattice stiffeners.

- The assembly between the APA and the payload/launcher is achieved through metallic rings rigidly joined to the conical CFRP integrated rings, supporting a VEGA clamp-ring separation system in the case of a payload and a standard bolted I/F in the launcher side.

## 4. APA TECHNOLOGY DEMONSTRATOR – MANUFACTURING

The APA technology demonstrator is manufactured by ECE with a Viper-3000 AFP. Virtual lay-up simulations were performed in order to optimize AFP head displacements and layering trajectories.

After the AFP lay-up process, the APA is vacuum bagged and cured in autoclave, following the same process previously used in the cylinder demonstrators. After the demoulding and machining of the I/F area, the metallic rings for the I/F are assembled and the APA is finished, “Fig. 12”.

Fig.12. APA manufacturing and assembly

## 5. APA TECHNOLOGY DEMONSTRATOR – ANALYSIS, TESTS AND RESULTS

### APA Analysis

An exhaustive analysis wok has been performed during the development, in different steps.

- The first stage was a viability study, in which it was studied the behaviour of the stiffeners with unidirectional layers topology. In order to identify the appropriate bending capability, a detailed solid model was analysed determining the true bending stiffness in order to fix the preliminary helices dimensioning.

- Next, a similar study was made, but considering the beams with a slight curvature, trying to simulate the real shape of the lattice cone adaptor, due that using a conical curing tool is not possible to have discrete straight stiffeners, because the line between two nodes is curve.

- Besides a detailed study of the node areas was needed. The team had the certainty that it should be the critical zone of the structure, by previous experience in ICARO project and by the intrinsic complexity of the manufacturing process to perform this shape by FP techniques.

In order to know the load gradient along the node, a detailed FEM model covering this area was built, “Fig. 13”. Near the node region there is a discontinuity in the spreading of the strains due the overlapping of the crossing stiffeners. The external fibres are bent, and then most of the axial compression load is bore by the inner fibres.

This effect generates a load concentration on this area, producing a loss of stiffness, by that is it must be quantified due to the relevance in terms of stiffness and strength performance reduction.

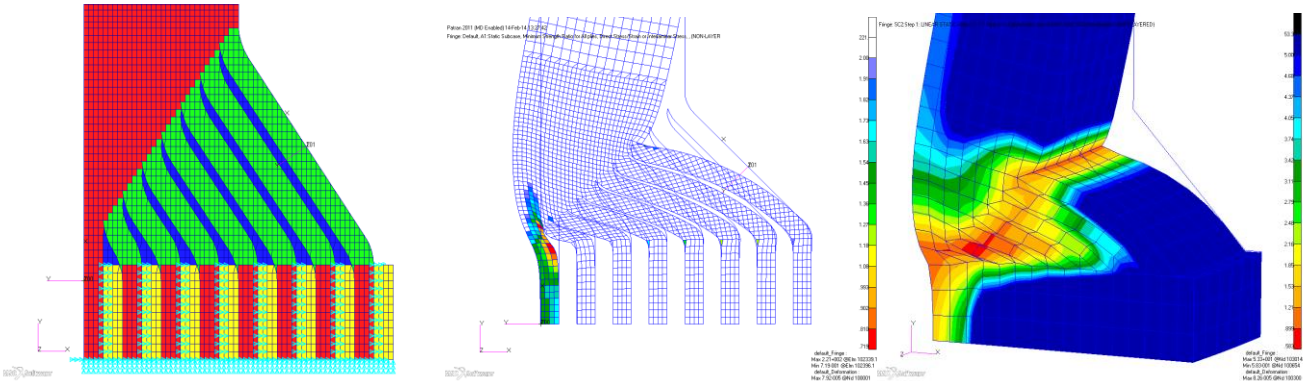

Fig.13. Detailed study of the node area

Once determined the maximum distance between nodes as function of the beam area and load applied, a global preliminary study of the whole structure was get down in order to assure the bucking capability.

This work was made in parallel by two teams in order to fix the dimensioning of the structure by means of two different approaches. The results were compared assuring the credibility and therefore the validity of the analyses, “Fig. 14”.

The combination of different methodologies has been of paramount importance to assure enough level of confidence in the results, taking into account the complex topology of the anisogrid design.

The analysis was performed using different FEM software for the simulation, Ansys, with solid elements modelling at Componeering Inc. facilities and Nastran, using model of shells, in Airbus Defence & Space. ESAComp software was also used in the definition of material properties and material data processing.

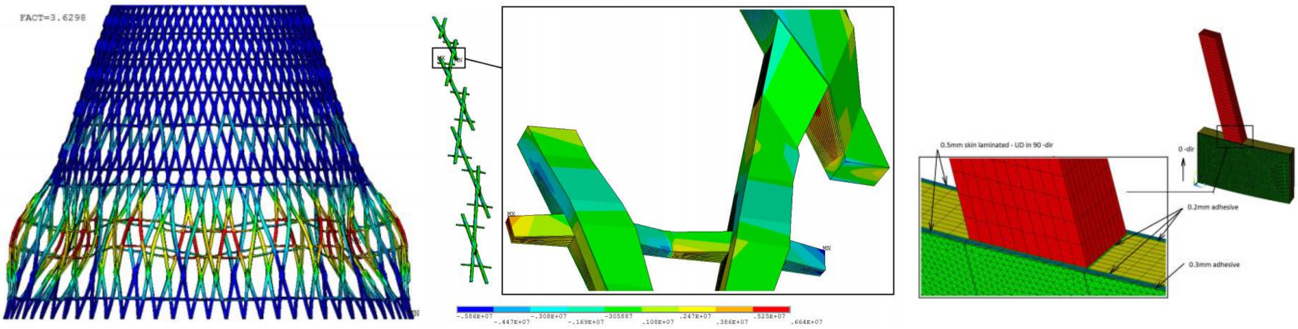

Fig.14. APA preliminary analysis (global model and local details)

Once stablished the preliminary global model, and with the test results obtained from DVPs and technology demonstrators, it was reached a sufficient confidence level to fix and freeze the final lattice cone design.

A detailed model of the complete structure was made, “Fig.15” with of more than 400000 elements. Analysis of stiffness, buckling and strength were made, focusing the work in a fidelity modelling of the I/F areas, between rings and bars, including bonded parts and bolts.

A parametric study, taking into account the variation of the bars and circumferential frames thickness between the theoretical design value and the real one obtained by the manufacturing process was performed.

Later on, an exhaustive damage tolerance analysis at three levels was made, studying the behaviour of the structure under different degraded conditions: removing nodes, introducing delamination patters and using linear fracture mechanics to introduce cracks.

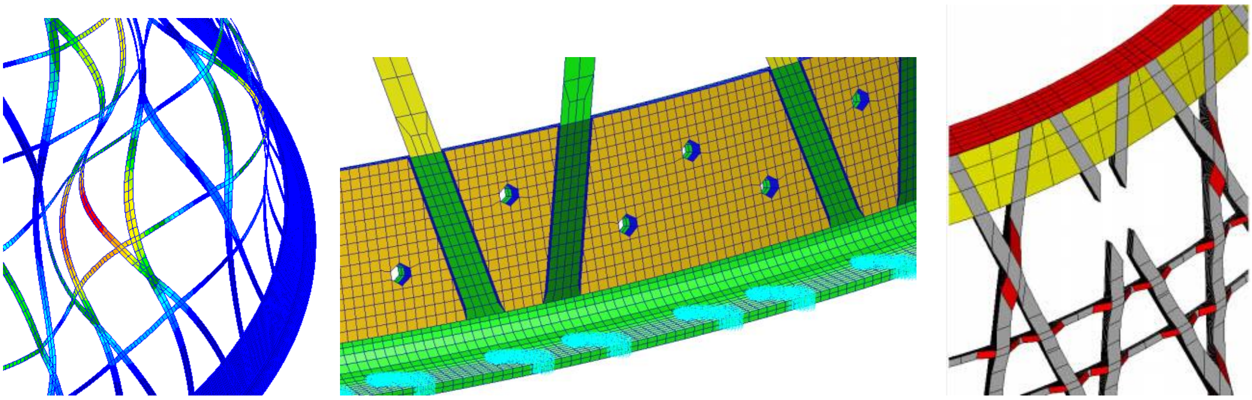

Fig.15. APA final structural analysis and damage tolerance study

The main conclusion obtained from the analysis, and afterwards confirmed by the tests, is that the lattice concept is a robust design solution.

The main advantage with respect to other designs is the intrinsic “fail-safe” behaviour. This design is tolerant to manufacturing defects, shape imperfections or local cracks, since the structure is able to distribute the loads to adjacent areas, without a catastrophic failure.

## APA Tests and results

The testing of the APA has been performed at Instituto Nacional de Técnica Aeroespacial (INTA) facilities. The test set-up is presented in "Fig.16".

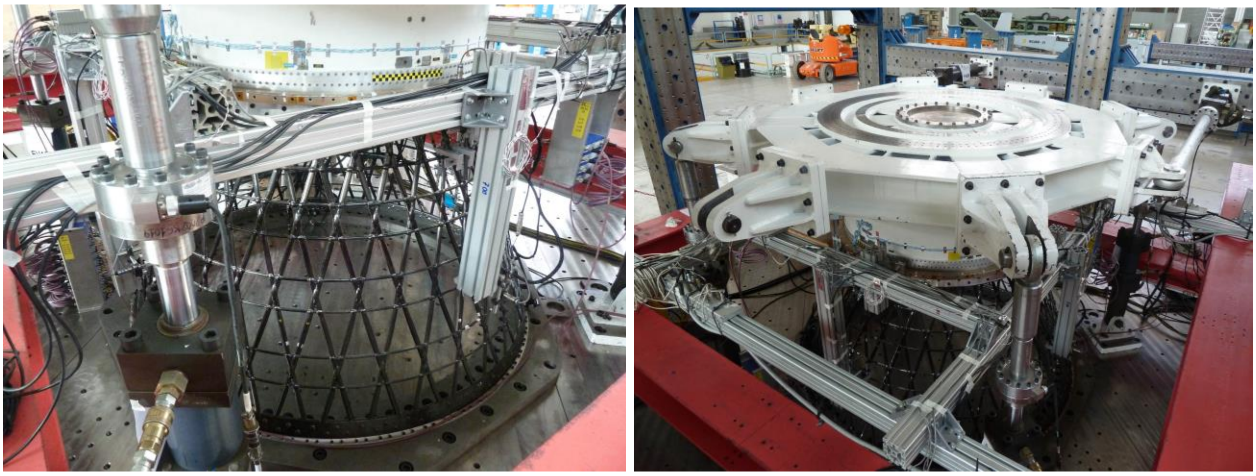

Fig.16. APA test set-up

The objectives of the test campaign are the following:

- To fix the degree of correspondence between the complete structure behavior and the analysis predictions, in order to ensure the validity of the mathematical model used for the predictions by means of a correlation work.
- To derive the real stiffness and strength of the APA demonstrator, representative of the VEGA 1194 adapter.
- To validate also the VEGA 937 configuration with respect to the current flight model.

A complete predictive analysis was previously made, introducing the entire set-up in the model, "Fig. 17", in order to adquire a level of accuracy according to the development needs.

In addition, a set of displacement transducers, inclinometers and strain gauges were installed to run and control the test.

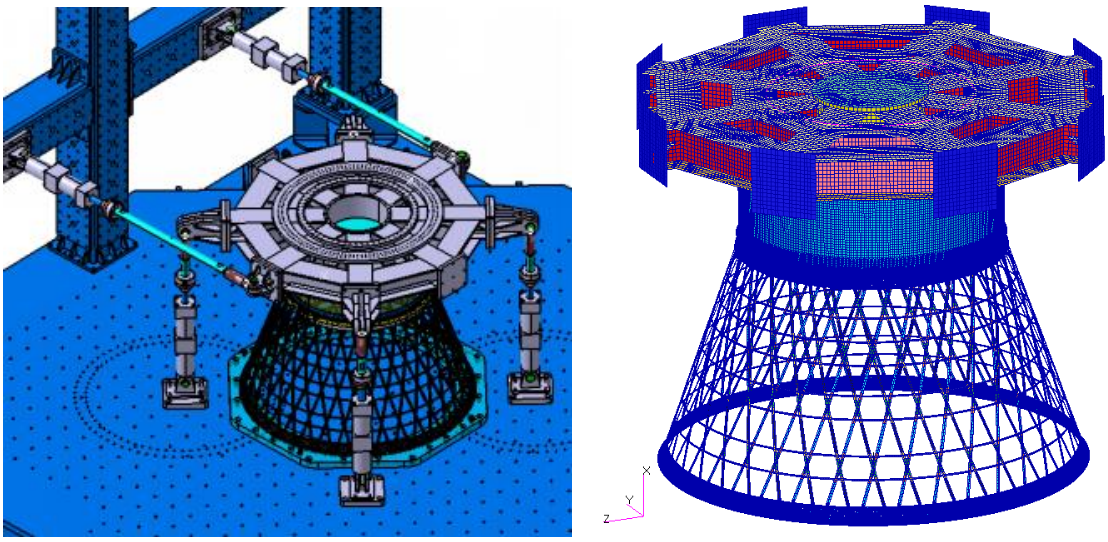

Fig.17. APA Test FEM model

Different load cases of compression, tension, shear and bending moment were defined in order to obtain the flexibility matrix of the structure, comparing the obtained results with the current ones coming from the flight model.

In addition, several load cases were defined to verify the strength performance. Those loads combined axial loads with bending moments, and were established in order to reach the qualifiquation levels equivalent to the current VEGA PLA.

Finally, a rupture test in the APA structure was carried out to know the real limits and the failure mode of this structure.

The planned sequence of tests has been successfully performed, and a correlation between the test prediction and test results has been done, showing a good accuracy with respect to the analysis performed:

- Based on the displacement transducers measures, the stiffness prediction was accurate with respect to the actual one. The maximum deviation between predictions and results is lower than 20%.
- The strength test cases at ultimate load level j=1,25 were introduced in the APA, in order to reproduce maximum flight fluxes of VEGA 937/1194 PLA. The APA was able to withstand those loads without failure.
- The load level reached before the rupture was j=1.9, quite higher than the ultimate load and very close to the prediction at j=1.85. The rupture mode was produced by a local instability of the stiffeners and circumferential frames in the most loaded part of the structure.

## 6. CONCLUSIONS

This programme has accomplished several objectives:

- Different topologies of the lattice geometry have been studied. Specifically, different types of nodes are evaluated from both points of view manufacturing and mechanical performances.
- Several DVPs and technology demonstrators are produced and tested. The repetitiveness of the results shows a robust manufacturing process, validated regardless of the set-up and AFP machine programme.
- It has been developed and matured a technique that allows producing any type of lattice geometry without over-costs, comparing to conventional isogrid geometries.
- The manufacturing of lattice structures in one shot by AFP, by using a ECE internal process is consolidated, with a process that allows repeatability and robustness in terms of production and sound quality.
- The CFRP rings in the I/F areas allow a high level of integration and automatization, with savings in mass and assembly activities.
- Different design and analysis tools for lattice structures are used and validated by means of tests. The good correlation of the APA structure consolidates the proposed design and analysis philosophy.
- The technology readiness level (TRL) achieved is 6. The full-scale technology demonstrator has proved the critical functions of the structure in a relevant environment, following the same specification of the VEGA 937/1194 PLA flight parts.

## Acknowledgements

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