# Executive Summary Report

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# CHANGE LOG

| Issue | Rev | Date | Affected | Changes |
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| 1 | 0 | 29-Oct-2021 | All | First issue |
| 1 | 1 | 22-Nov-2021 | All | Client confidential removed from title page and footers |

# DISTRIBUTION LIST

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| ESA | Arnoud Keereman | |

# Table of Contents

# 1 Introduction

## 1.1 Scope and approach

This executive summary provides a non-technical summary of the contract goals and the status of these goals at the end of the contract execution. It will provide a summary of the work that was intended to be done, status overviews for design, procurement and testing as well as a concluding statement.

The scope for this contract is to prepare for the manufacturing of two lattice structure cylinders that can be used as interstages for a small space transportation rocket. The business case for this development is based on the interstage being used by a specific non-disclosed End-User.

As part of the preparation phase, a set of activities was started (and some finished) which included, but was not limited to, the design of the lattice structure cylinder, the procurement of the tools required for manufacturing as well as the CFRP materials needed, and the production and testing of material coupons.

For this work ATG worked together with Airborne Aerospace (AA) as the main manufacturing partner/subcontractor. AA's scope included some of the design and procurement work as well.

## 1.2 Applicable Documents

| Item reference | Title | Date | Issue | Comment |
|---|---|---|---|---|
| [AD1] 4000134690/21/NL/GLC/idb | ESA Contract | 15-Jun-2021 | 1 | |

## 1.3 Reference Documents

| Item reference | Title | Date | Issue | Comment |
|---|---|---|---|---|
| [RD1] GSTP1-ATG-TNO-0002 | Final Report | 29-Oct-2021 | 1 | |
| [RD2] ATG-NL-CX-OF-20-0409 | Preliminary phase full proposal | 04-Mar-2021 | 2 | ESA reference: RFQ/3-17054/21/NL/GLC/idb |
| [RD3] GSTP1-ATG-MOM-0001 | Negotiation on RFQ3-1705421-NL-GLC-idb | 04-May-2021 | 1 | |

# 2 Outputs and success criteria

The goal of this contract [AD1] was to prepare the building blocks for the manufacturing of several lattice structure interstages. More detail on the exact work that was done can be found in the work package descriptions of the full proposal for this phase [RD2] and in the Final Report for this contract [RD1].

For easy reference, a summary of the work package outputs is given below together with the success criteria that were agreed for concluding this contract.

The preparation work for this contract can be split in three main topics: design, procurement, and testing. The outputs of these different work packages are summarised as follows:

Design:

- Detailed design CAD and FE models
- Design status overview for the Preliminary phase (D01)
- Consolidated margin and safety factor policy
- Creation of the needed inputs for the Follow-on project Phase

Procurement:

- Detailed design CAD models for the mandrel and expansion tooling
- Mandrels incl. jigs.
- Cast silicone sheets and blocks
- CFRP material for use in the Preliminary phase and part of the Follow-on project phase

Testing:

- Cure cycle profile for the grid-stiffened structures
- Results of the CFRP material characterization tests

Next to these outputs being required for the successful completion of the work, the success criteria of this contract were defined as (see [RD3]) the availability and acceptance of:

- The mandrel
- Materials
- Trial panels and
- Test coupon results

In the Final Report [RD1] more details are provided on the final status of these three packages. This summary is focussed on the main items in these packages.

Please note that the manufacturing of these lattice structures is not part of this contract and is the subject of a different tender process.

# 3 Design status overview

The final cylinder design meets all design requirements which are outlined in detail in the Final Report [RD1], and summarised here as:

- Inner diameter of 2153 mm
- Height of 2995 mm
- Combined loading of axial load, bending moment and shear load (see Table 1)
- Sufficient strength margin for cut-outs and holes as per the End User requirements
- Able to withstand temperatures of more than 100 deg C due to aerodynamic loading in flight

***Table 1 - Mechanical flight loads (first stage interstage).***

| Load | Magnitude |
|---|---|
| Overall axial load FZ | -269 kN |
| Overall bending moment MX | 367 kNm |
| Shear load FY | -52 kN |

Note that the outer appearance of the cylinder (see Figure 1) does not change (much) as the lattice design parameters are varied internally within the structure. The design activity largely relates to determining the best parameters of features “on the inside” of the cylinder such as the height of the ribs, the angle of the ribs, the spacing of the hoop ribs and the number of plies in the skin.

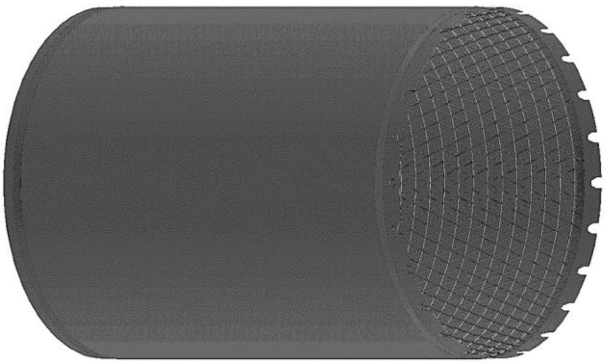

***Figure 1 - Cylinder CAD***

In order to validate the design, Finite Element Analyses were performed to assess the structural performance of the cylinder under the provided loading. There are two main parameters that determine this performance, the Failure Index (FI) and the first buckling EigenValue (EV). Details on these analyses can be found in the Final Report [RD1], concluding that the Failure Index has a margin of safety of 0.29 and the first buckling EigenValue has a margin of safety of 0.35. In both cases these margins are positive, hence the design is able to withstand the provided loading with sufficient margin.

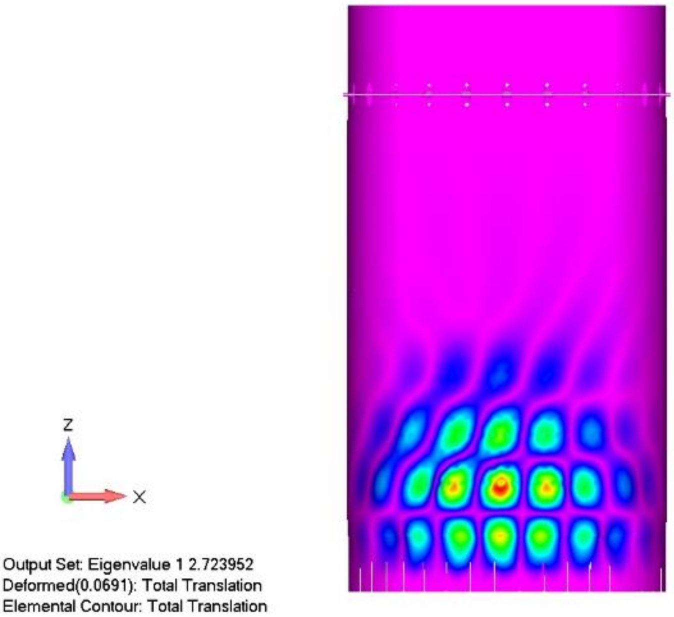


***Figure 2 - FE Analysis results showing global cylinder failure***

The final design weighs approximately 87.5kg and uses 5 skin plies across the full cylinder length. Depending on the progress in a follow-up phase, this could possibly be reduced by a further 10-15%, mostly by reducing the number of skin plies. This would however result in much lower margins for the Failure Index and the first buckling EigenValue.

In conclusion, the following outputs for the design work were all completed:

- Detailed design CAD and FE models (included in Technical Data Package)
- Design status overview for the Preliminary phase (D01) (included in the Final Report [RD1])
- Consolidated margin and safety factor policy (included in the Final Report [RD1])
- Creation of the needed inputs for the Follow-on project Phase (included in the Final Report [RD1])

In addition, the design provides the parameters required for manufacturing the lattice grid from which the test coupons were made, which in itself is another step towards the successful completion of this contract.

# 4 Procurement status overview

At the end of this contract the procurement status is that the mandrel, the supporting jigs, expansion tooling and the CFRP materials have been procured successfully.

The mandrel was specified by ATG and then designed and manufactured by our supplier. With specific tolerances mostly on the outer diameter of the mandrel (related to the inner diameter of the lattice cylinder) as well as the deflection of the shaft of the cylinder under thermal loading and gravity.

***Figure 3 - Mandrel without shaft***

The mandrel was manufactured to specification and transported to the Airborne premises where the cylinder manufacturing is intended to be executed.

Meanwhile, Airborne have designed and procured the jigs on which the mandrel is to be placed. The structural analyses of the jigs were performed by ATG (see Figure 4), showing the jigs were sufficiently strong for the heavy mandrel (around 6000 kg).

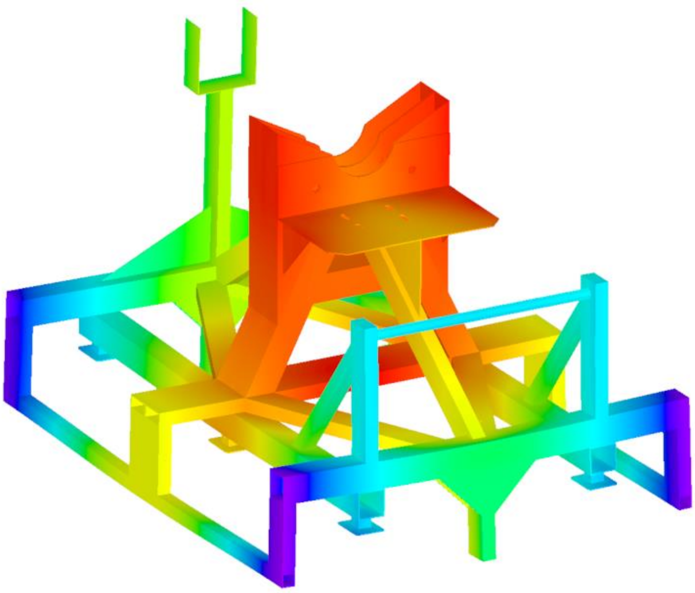

***Figure 4 - Finite Element Analysis of the jig supporting the mandrel***

Next to the mandrel and its supporting jigs, ATG have also procured additional smaller tooling such as the edge dams and the caul plates as can be seen in Figure 5.

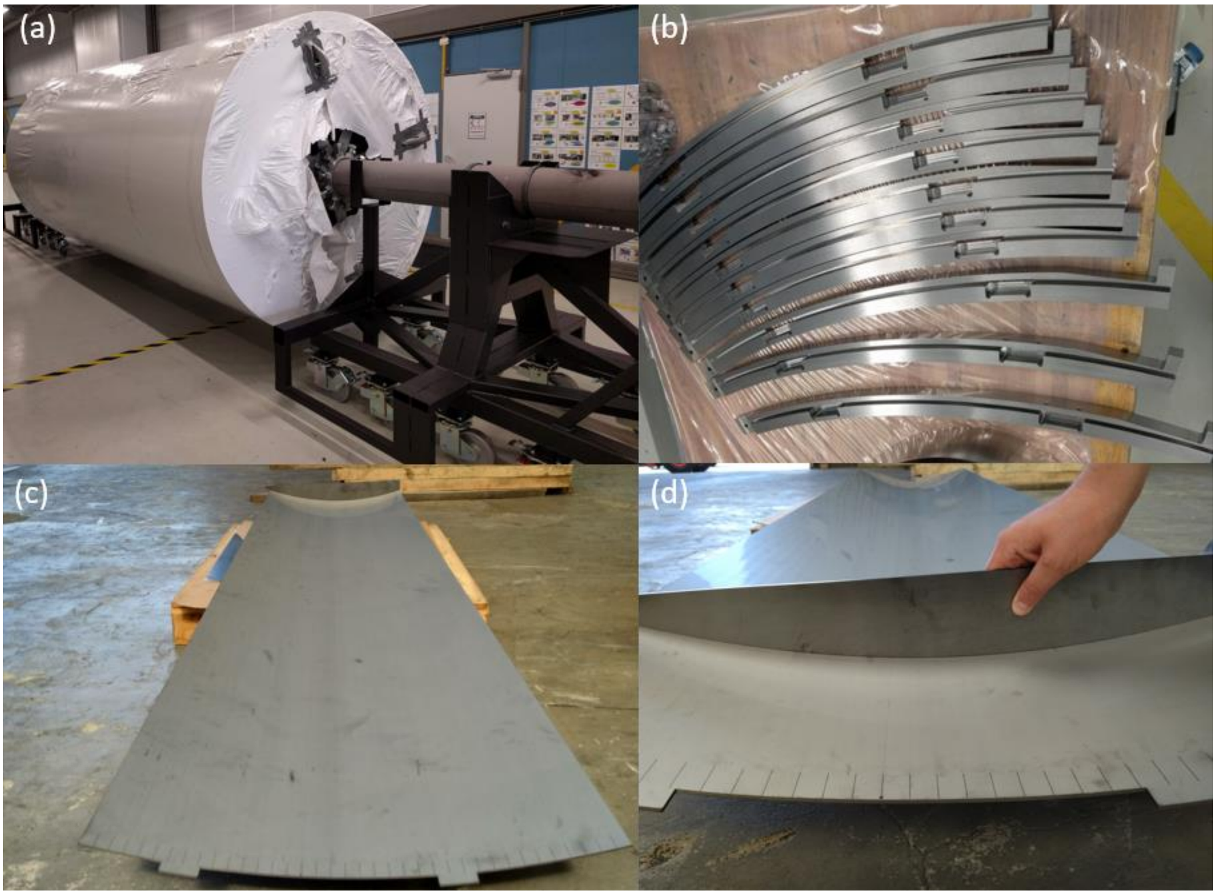


***Figure 5 - Images showing (a) the mandrel and its support jigs, (b) edge dams, and (c) a caul plate, as well as (d) a dimensional check with a laser cut template.***

Apart from the steel tooling, ATG have also procured the silicone materials required for producing the expansion tooling and have started preparations for manufacturing. The moulds for casting plates (from which the expansion tooling is waterjet cut) were ordered (see figure 6a) and manufacturing of the silicone plates was completed. In addition, 3D printing of moulds for specially shaped expansion tools was completed (see figure 6b) along with the production of all irregular shaped blocks.

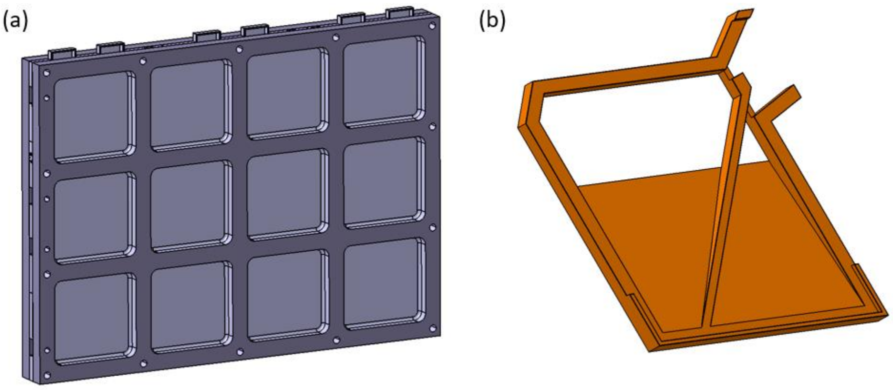


**Figure 6 - 3D models of (a) the flat plate production tooling and (b) the individual 3D printed moulds used to create silicone cell blocks for the lattice grid design.**

In total over 130 silicone plates were produced which are planned to be waterjet cut into approximately 4000 cell blocks in the follow-on project. This together with the 500 specially shaped blocks manufactured with the 3D printed tooling will be used to complete the manufacturing of the cylinders in the follow-up phase.

The final procurement item of this phase was the carbon fibre pre-pregs needed for manufacturing the material characterisation test samples and the eventual cylinders. The material of choice was Toray TC350-1/T700, manufactured by Toray in the UK.

Overcoming significant challenges with customs due to Brexit and controlled materials export limitations, Airborne have, on behalf of ATG, managed to procure and ship the materials required. In short, all the desired CFRP materials intended to be procured at the end of this contract are procured and onsite at AA premises.

In conclusion, the following outputs for the procurement work were all completed:

- Detailed design CAD models for the mandrel and expansion tooling
- Mandrels incl. jigs (at AA premises)
- Cast silicone sheets and blocks
- CFRP material for use in the Preliminary phase and part of the Follow-on project phase (at AA premises)

Thus, at the end of this phase all tooling and materials required for starting the follow-up phase are procured and ready as intended. All materials required for the testing phase of this contract are in house and ready for use.

# 5 Testing status overview

At the end of this contract, the requirements on testing were that small scale material property characterisation tests were completed and results were made available.

For making the coupons, panels were made using the same cure cycles as were to be used for curing the final cylinders. In order for these samples to be manufactured in the same way as the cylinders, the correct cure cycle profile was required. To obtain this profile, a heat survey with the mandrel tooling was executed to verify the expected heat up rates during actual manufacturing. With the output of this heat survey, the final cure cycle profile was established, and the panels were manufactured using the same cure cycle. Since they mass of the mandrel will influence the final cure cycle rates during manufacturing, and thus the material properties of the CFRP under investigation, it was decided to produce the panels while the mandrel was in the autoclave with the panels. From these panels, samples were cut into various shapes as dictated by the relevant test standard.

With said coupons material characterisation testing was performed (see Table 2). These tests were used to define critical material properties and A-basis allowable strain values as inputs for the design analysis. Tests were performed at room temperature, i.e. 21°C, and at -70°C to give added insight into property changes between these temperature ranges. For full details on the testing performed please refer to the Final Report [RD1].

***Table 2 - Coupon testing overview***

| Test Type | Method | Layup | Dimensions (mm) | Samples Tested | Test Temp (°C) |
|---|---|---|---|---|---|
| UD Compression Strength/Modulus | ASTM D6641 | $[0]_{11}$ | 140 x 12.7 x 3.08 | 7 | 21 |
| UD Compression Strength/Modulus | ASTM D6641 | $[0]_{11}$ | 140 x 12.7 x 3.08 | 7 | -70 |
| In-Plane Shear | EN 6031 | $[45/-45]_{2s}$ | 230 x 25 x 2.24 | 7 | 21 |
| In-Plane Shear | EN 6031 | $[45/-45]_{2s}$ | 230 x 25 x 2.24 | 7 | -70 |
| Interlaminar Shear Strength | EN 2563 | $[0]_{11}$ | 30 x 15 x 3.08 | 7 | 21 |
| Interlaminar Shear Strength | EN 2563 | $[0]_{11}$ | 30 x 15 x 3.08 | 7 | -70 |
| QI Compression Strength/Modulus | ASTM D6641 | $[90/0/45/-45]_{2s}$ | 140 x 12.7 x 4.48 | 7 | 21 |
| QI Compression Strength/Modulus | ASTM D6641 | $[90/0/45/-45]_{2s}$ | 140 x 12.7 x 4.48 | 7 | -70 |
| QI Tension | ASTM D3039 | $[90/0/45/-45]_{2s}$ | 250 x 25 x 4.48 | 7 | 21 |
| QI Tension | ASTM D3039 | $[90/0/45/-45]_{2s}$ | 250 x 25 x 4.48 | 7 | -70 |
| Fibre Volume Fraction | EN 2564 | $[90/0/45/-45]_{2s}$ | 20 x 10 x 4.48 | 3 | 21 |
| Glass Transition | EN 6032 | $[90/0/45/-45]_{2s}$ | 35 x 10 x 4.48 | 3 | 21 |

The results from the coupon tests have successfully provided the required data for further refinement of the design and FE analyses. This brings more confidence to the current design as well as the possibility of further optimisation in the follow on phase.

In conclusion, the following outputs for the testing work were all completed:

- Cure cycle profile for the grid-stiffened structures
- Results of the CFRP material characterization tests

With this, the final work package was completed, thereby completing the work for the full contract.

# 6 Conclusion

In conclusion, the outputs for the work packages in this contract have been successfully produced and all the success criteria for this contract have been met.

The design for the cylinder was completed successfully and analyses show that the cylinder is predicted to withstand the provided loads.

The design and procurement of the long lead time tooling, such as the mandrel with its support jigs, the edge dams and caul plates, as well as the expansion tooling and the prepreg materials, were completed successfully. The cure cycle profile required for manufacturing representative testing coupons was established successfully, followed by successful manufacture of the coupons. The testing was also completed successfully providing the required parameters for the design and manufacture of the cylinders in the next phase.