DEVELOPMENT OF MASS AND COST EFFICIENT GRID-STIFFENED AND LATTICE STRUCTURES FOR SPACE APPLICATIONS

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Leonid Pavlov [1], Ivar te Kloeze [1], Bart J. R. Smeets [1], Sahak Menzo (Samo) Simonian [1]

[1] ATG Europe BV, Huygensstraat 34, 2201DK Noordwijk, The Netherlands; +31715795554, leonid.pavlov@atg-europe.com

ABSTRACT

Composite grid-stiffened (also known as lattice) structures have long been of interest as a replacement for honeycomb sandwich, aluminium isogrid and skin-stiffener-frame structures for aerospace applications. Such interest is caused by the multiple advantages of this structural architecture amongst which the cost per unit weight is the most attractive one.

The apparent challenges related to the lattice and grid-stiffened technologies is often the reason to disregard these technologies for various structural applications, specifically for launcher and spacecraft structures. Extensive studies of existing products and one-to-one comparisons are necessary in order to offer solid proof of lattice structures' applicability for specific products.

ATG Europe has developed a cost-efficient manufacturing methodology for fibre placed grid-stiffened and lattice structures that allows manufacturing high quality, complex integrated grid-stiffened composite products in the form of a one-shot process. For performing detailed preliminary design investigations an efficient semi-automated optimization approach has been developed and applied in a number of feasibility studies featuring products with a grid architecture.

This work describes the development of grid-stiffened structures for launcher and spacecraft applications in progress at ATG Europe, of which the manufacturing methodology and optimization approach are integral parts. The development logic, considering the specifics of the architecture, is presented along with the particular executed testing campaigns required for technology maturation. These testing campaigns increase the fidelity of the optimization results. These results ultimately provide the answers regarding the mass and cost efficiency of the grid architecture applied particularly to the interstage structure (ISS) of the Ariane 6 launcher (PPH configuration) and the central cylinder of the EDRS-C satellite. The development logic, executed test campaigns, optimization studies, integration of particular aspects of the technology and main lessons learned are discussed. Mass optimization results and cost-related indications are presented.

1. INTRODUCTION

Composite lattice structures are normally fabricated using a continuous fibre composite material. These structures are defined by a lattice pattern (grid) of intersecting stiffeners often called ribs. Where the ribs intersect nodes are formed. In the case that this grid is supporting a shell structure (skin) – the architecture is typically referred to as a grid-stiffened (GS) structure. Further popular reference terms are isogrids or anisogrids depending on the configuration. In most cases ribs run in two to four directions forming a regular pattern (Fig. 1). In rare cases, a second shell structure (skin) is present at the top of the stiffener pattern, opposite the first skin. Sometimes the cell pattern is made irregular by adding further ribs in specific locations.

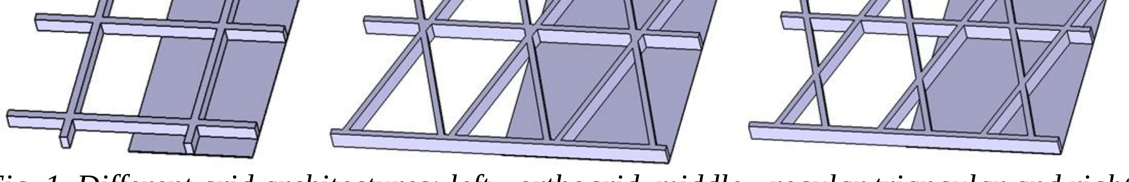

Fig. 1. Different grid architectures: left - orthogrid, middle - regular triangular and right - anisogrid grids. Lattice types are shown on the left of each figure and GS types on the right.

Grid-stiffened structures provide a unique tailor-able directional stiffness and strength due to the use of multi-directional grids and unidirectional composite fibre orientations within the ribs that form the grid. This offers a significant potential increase in structural efficiency in terms of material usage and mass. Manufacturing techniques associated with these structures also offer a more integrated approach, with fewer parts leading to large cost savings. Further benefits of Lattice or Grid-Stiffened structures are: inherent damage tolerance due to multiple load paths, efficient attachment possibilities at the stiff and strong nodes, ease of integration of e.g. wiring harness and piping in an open lattice structure, damage tolerance, etc. Due to all these benefits, Grid-Stiffened structures have long been of interest as a replacement for honeycomb sandwich, aluminium isogrid constructions and skin-stiffened structures for aerospace applications. On the other hand, the complexities associated with design, manufacturing, quality assurance and the relatively low volume of knowledge about this architecture have historically acted as hurdles for industry to adopt, mature and implement these structures in large scales or volumes.

During the past 2 decades, remarkable progress has been made in the manufacturing of these structures at several locations around the United States, Russia, Japan and Europe. Programs at CRISMB, The Boeing Company, the US Air Force Research Lab, JAXA and others have pushed the state of the art in grid-stiffened structures, finally leading to processes and methods of interest to large-scale production. As a result of their development, composite grid structures have found their way for instance into the Proton-M launcher interstages, payload adapters and satellites. These structures are most commonly produced using a filament winding manufacturing process, with a rather low (in the order of 40%) fibre fraction by volume due to the intersection and overlap of filaments at nodal locations. This limitation has significant implications on the weight and stiffness of the obtained designs, making the possible weight savings lower than the potential savings offered by the GS structures manufactured using e.g. fibre placement.

ATG Europe is involved in development of technologies and products using composite materials. One of the development directions is in the field of composite grid-stiffened structures. Here, ATG Europe has created a high-quality cost-efficient production process for lattice and GS structures. The process allows for the integration of all structural features required for highly functional and large scale space structures in a true one-shot production process. Additionally, a highly flexible, accurate and holistic design and optimization approach for GS structures has been developed, implemented and validated through extensive testing. This paper further elaborates on the main achievements of ATG Europe on the topic of design, analysis, manufacturing and testing of GS and lattice structures.

2. DESIGN CASES

ATG Europe is working towards implementation of the grid-stiffened and lattice composite architectures in a number of products across different industries. This paper presents a sub-selection of studies executed by ATG Europe during 2014 and 2015 and focuses on two large space engineering products: a grid-stiffened Ariane 6 interstage 2/3 (PPH configuration) and a lattice central cylinder version for the EDRS-C satellite (Fig. 2). The feasibility studies for these two products have been executed in-house as an effort to advance the technology by proving its benefits on a case-by-case basis and solving the largest perceived issues (listed further) associated to the application of GS and lattice structures to these products. The distinctive features of these two applications are different from one another, but together they result in a complex and comprehensive set of challenges to be solved in order to prove the state of GS structures technology and the advantages of its application.

The main features of the A6 PPH Interstage 2/3 are that it requires an outer shell for environment protection and it is formed by a combination of conical and cylindrical sections which provide a challenging load distribution and manufacturing implementation. It also requires rather large cut-outs and one of the load introduction zones needs to be metallic (for separation system integration purposes). The main advantages sought from applying the GS architecture to this product are a reduction in mass and cost (due to efficient production) as compared to conventional architectures.

The distinctive features of the EDRS-C satellite central cylinder are that it features a set of ~380 attachment points through which loads are introduced. It further has stringent stiffness requirements. The main advantages of applying the lattice architecture to this product are mass savings as well as cost and lead time decrease due to a true one-shot manufacturing process that can be applied for its production in case all the attachment provisions are integrated in a single layup step. No previously existing optimisation approach was capable to handle such geometry and loading scenarios as the ones for A6 and EDRS-C structures. Hence a quick and relatively accurate preliminary design is close to impossible to obtain using existing optimisation approaches.

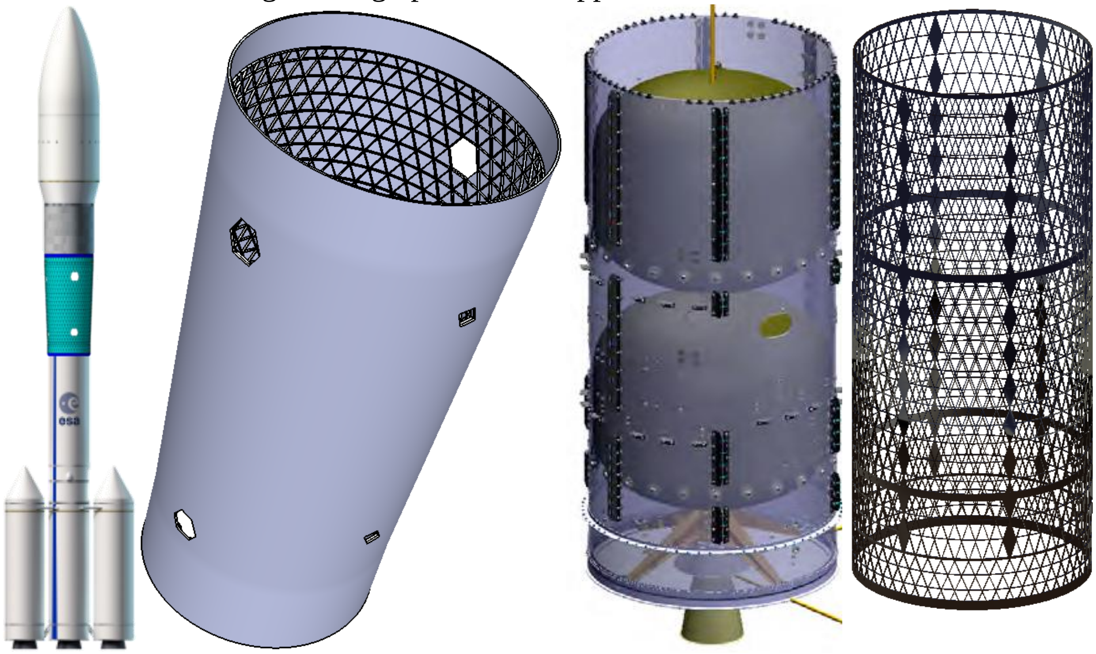

Fig. 2. Discussed design cases: Left - Ariane 6 PPH Interstage 2/3,
Right - EDRS-C central cylinder structure (semi-transparent - existing, lattice - proposed).

The list of products where the GS technology shows great promise in terms of cost, lead time, functionality and mechanical performance is however much broader than the two presented applications. The apparent challenges related to the lattice and grid-stiffened technologies is often the reason to disregard these technologies for various structural applications. The former lack of realistic case studies and hence the unavailability of reliable results related to the real gains achievable by using lattice and GS structures also stands in the way of their further industrialization. In order to advance and market the technology it is important to demonstrate the feasibility of certain technological aspects that are often regarded as critical in product realization. It is also paramount to prove the feasibility of these structures on real case studies (hence minimizing development risks) in order to convince the industry to commit to using such architectures. This is mainly due to the fact that for every single space product there can be no single answer regarding stiffness to weight or strength to weight ratios of certain architectures to define architecture's suitability for a certain product. The devil is in the details and the suitability strongly depends on the product geometry, its complexity, load cases and very often non-structural requirements.

3. DEVELOPMENT LOGIC

Grid-stiffened structures are defined by a complex structural architecture with significant coupling of failure modes, and hence it is non-trivial to design, optimize, manufacture and qualify them. Classical proving of viability and suitability of a structural architecture then often entails a prohibitively expensive full-blown development campaign.

Alternatively, the Pareto principle (80/20 rule) was used by ATG Europe in order to solve a significant part of the perceived issues at a fraction of the cost of a full development campaign. It is then essential to thoroughly understand the challenges and to answer the main questions about the suitability of the architecture by testing certain parts of it that are perceived as most challenging and risky. This should be done by providing working structural concepts that serve as means of transforming the theoretical architecture into a working structural solution. Upon proving the architecture's viability and suitability for certain structural components a full development campaign can be initiated, but already at a significantly minimized risk of failure. This approach enabled ATG as an SME, to solve the main perceived structural issues associated with grid-stiffened structures by using internal funding means. The developments conducted by ATG focused on generating an efficient design and optimization framework supported by manufacturing process development and testing campaigns. These manufacturing and testing campaigns provided answers to the essential questions regarding architecture's viability. In particular, for both lattice and grid-stiffened structures the main tackled challenges were:

- Provision of load introduction and end zone concepts for attachment to neighbouring structures, with metallic and composite interfaces
- Provision of attachment concepts for internally and externally mounted equipment
- Introduction of reinforced cut-outs and their impact on the load-carrying ability of the structure
- Correlation of an accurate analysis approach to capture the far-field behaviour and that of the localized interface zones.
- Provision of a high quality, repeatable and predictable manufacturing process.

Fig. 3 provides a graphical indication of the route followed to efficiently tackle the most stringent issues associated with the architecture at a significantly reduced cost compared to a full-blown development campaign. A reduced number of material sample tests was performed to obtain realistic analysis allowables at an affordable cost. Further, the obtained allowables were used to conduct element tests vital for higher order analysis methods correlation. Using the element test data, testing of important structural details and concepts was made possible and further affinity with the behaviour of GS structures was gained. This fed into the global optimization campaigns for various structures using the GS and lattice architecture. Ultimately, all the developments in terms of both analysis and structural concepts were implemented into a demonstrator structure to showcase the achieved level of the technology.

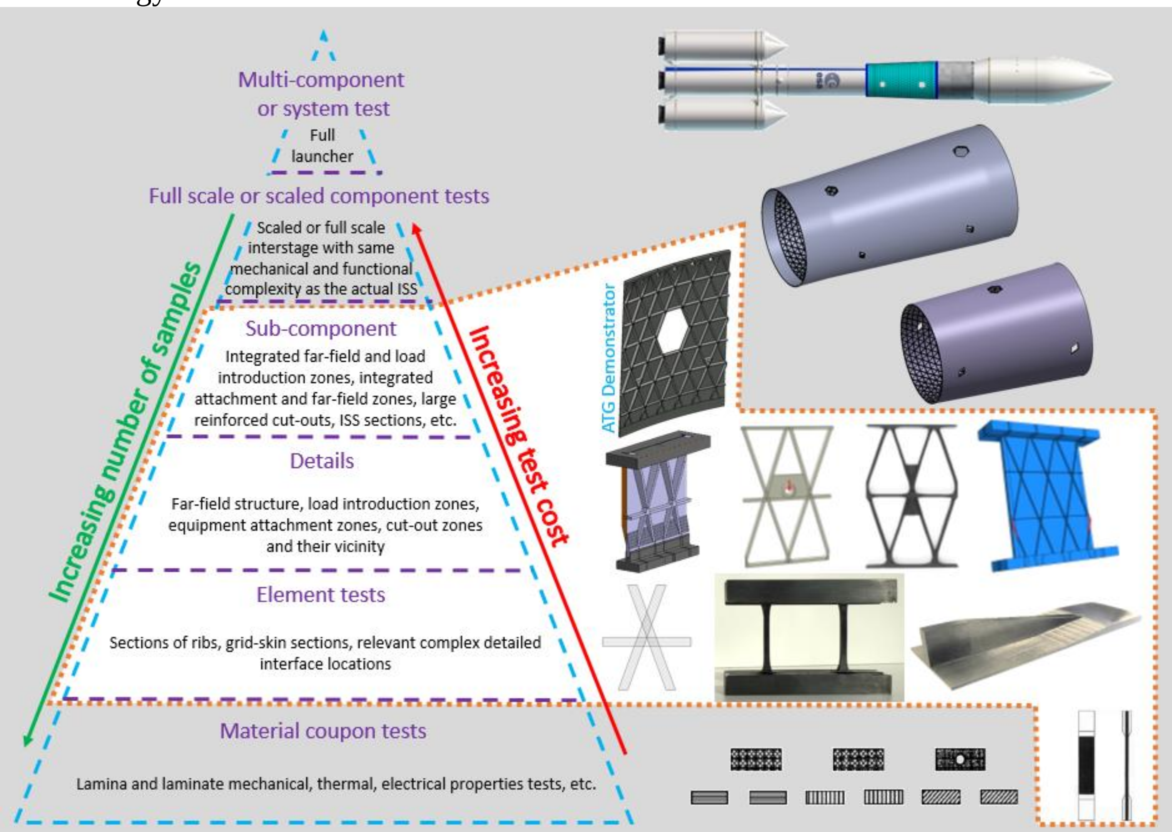

Fig. 3. An example building block testing approach for grid-stiffened structures development. The parts in white indicate the developments tackled by ATG in its internal development campaigns.

4. ANALYSIS APPROACHES AND APPLICABILITY

Apart from the various challenges listed in Sections 1 and 2 associated with the application of GS structures, the structural optimality plays an important role in paving the way towards a broad application of the lattice architecture in real-life structures in order to make them truly competitive. Since the start of GS structures developments numerous analysis/optimisation approaches have been proposed for both "quick and dirty" and accurate analysis of these structural architectures for various purposes and types of applications [1-7]. These range from closed-form solutions based on type/magnitude of loading to energy minimisation approaches offering accurate solutions depending on the extent to which various structural aspect are modelled.

A comprehensive overview of analysis methods for GS structures available at the end of the 20-th century is provided in the works of Huybrechts et al. [8]. Since that time this topic has received significant attention and a large number of theories and approaches have been refined. Particularly, the smeared stiffness approaches [3] have received a significant amount of attention in the recent years. Additionally, a number of alternative approaches have resulted in analysis methods capable of handling different failure modes of GS structures [4, 9].

A common trait of all of the existing methods is that none of them allows combining the seven main features necessary for setting up a generalized optimisation method supported by accurate analysis of real-life grid-stiffened structures.

The seven features that are sought are the following:

1. Accuracy and representativeness of the obtained analysis results
2. Possibility of handling a variety of structural geometries (universality)
3. Easy and reliable integration or availability in commercial computation software
4. Ease of method set up and customization for changes of structural parameters (flexibility)
5. Inclusion of local failure modes and detailed structural features
6. Computational efficiency of the method (both in set up and analysis time)
7. Ability to handle extensive sets of global and local load cases

It is a common characteristic of currently available analytical design/optimisation methods for GS structures that these remain applicable to a certain configuration or group of structural configurations (cylinder, cone, plate, etc.). These methods have rather limiting applicability boundaries, hence not being directly transferable to significantly different structural configurations, i.e. features 2, 4 and 7 are not sufficiently developed.

In the recent past, performing a realistic full FE based optimisation of a certain GS structure was not feasible due to the limitations of the pre-processing software and coordination with CAD geometry, particularly related to difficulties in modification of the number of grids or their orientation [20]. However the relatively recent advances in modern CAD/FEM software allow overcoming these issues and building an accurate, efficient and close to universally applicable method for multi-disciplinary optimisation of a wide variety of structures. The capabilities of current software also allow for integrating multi-scale modelling as part of the overall optimisation, in such a way that the critical zones of a structure can be modelled in more detail (e.g. high fidelity solid element meshes) while the overall behaviour (e.g. load distribution) is analysed at a larger scale with a more simplified approach (e.g. high/medium fidelity shell mesh), the entire sequence from design generation to design post-processing being fully automate-able.

In summary, none of the to-date proposed analysis/optimisation approaches for GS structures provide a good balance between accuracy, universal applicability, computational efficiency and ease of setting up the analysis for a realistic structural configuration, but new enabling general computational advances are available.

An optimisation approach developed at ATG Europe provides the flexibility necessary to overcome such an imbalance. The optimisation approach builds on accurate modelling of the structural geometry through full parametrization using commercially available Computer Aided Design (CAD) software. Coupled with a scripting based full parametrization of finite element (FE) models, that use the generated CAD geometry, this allows an automated loop of design generation, analysis and design post-processing. Such an approach offers a great deal of flexibility since the model generation and the corresponding FE solution steps can be executed and modified, if necessary, in an automated way. An engineer must define the scripts for the generation of the CAD and FE models prior to the initiation of an optimisation; hence the approach is considered "semi-automated". This allows for elements of human intelligence to be implemented in the optimisation process by designing the scripts such that these account for certain smart design rules. In essence, the proposed approach is a smart combination of engineering tools, where the formal optimisation routine/algorithm is no longer the delimiting core of the method, but an efficient design-enhancement enabler.

The proposed method for GS analysis/optimisation is visualised in (Fig. 4). In its current implementation, a genetic algorithm is used, drawing the fitness function from FEM evaluation. The FE models used here allow for a more accurate representation of the structure than any of the assessed analytical models, especially when they have been verified/correlated through efficient limited manufactured sample tests. This is especially beneficial for cases where a complex structure or a complex loading scenario are present which would otherwise be very time consuming if not impossible to implement. In turn this leads to a reduced solution time, reduced mass of the solution, improved prediction of local behaviour and hence unique optimisation opportunities. An example of approach application is schematically shown in Fig. 5.

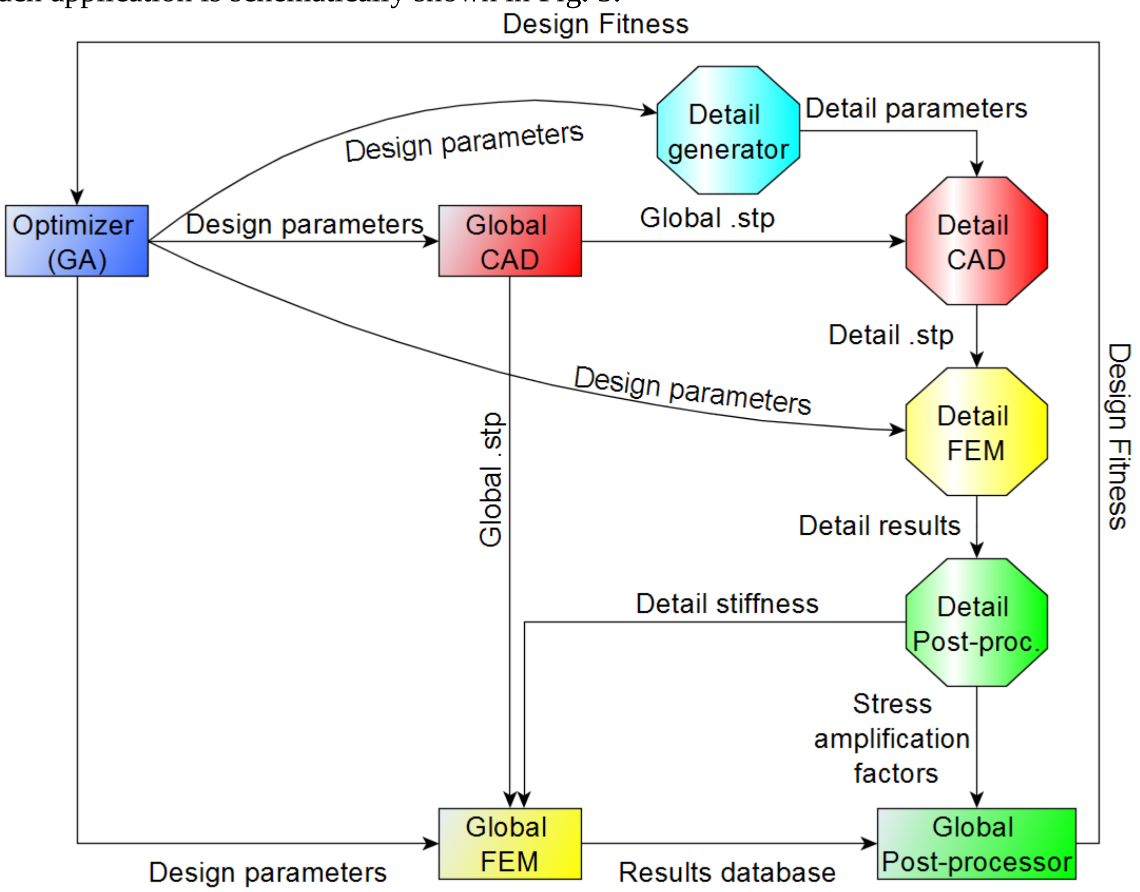

Fig. 4. Developed optimisation approach flowchart.

The developed optimisation approach offers a good balance between computational speed and accuracy. This balance is achieved by defining the approach according to the seven listed features that are sought from a universal optimisation method. The developed optimisation approach was applied to a number of structural applications in order to prove GS or lattice architecture suitability and advantages. The outcomes of these studies are provided in Section 8. For more information about the approach and its application the reader is invited to consult [10] and [11].

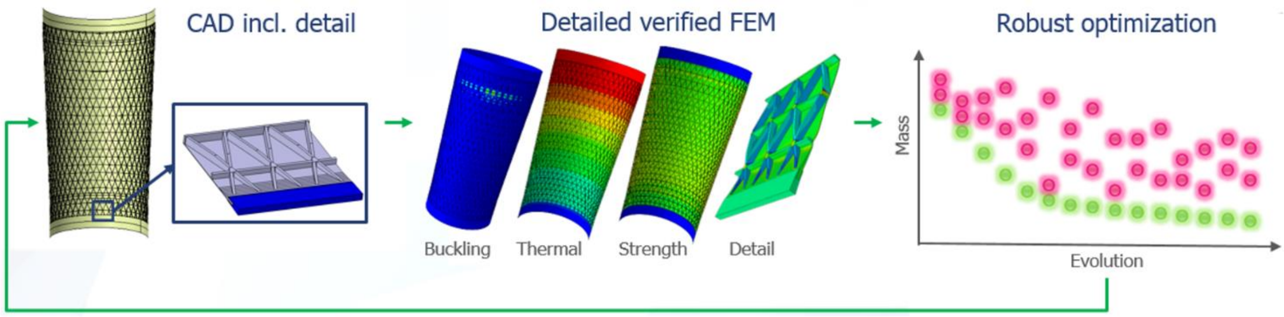

Fig. 5. Example of optimisation approach application.

5. MANUFACTURING TECHNOLOGY AND COST ASPECTS

The GS structures manufacturing technology was developed by ATG Europe according to the following main concepts and requirements (predominantly for reasons of low cost, high quality and simplicity):

- The process must be suitable for full automation, especially for large scale components. This must be achieved using existing automatic composite layup equipment.
- All structural features must be integrated during the layup phase – one-shot cure process, in order to minimise production lead time and cost.
- The tooling must be re-usable
- Predictable and repeatable end dimensions and micro-structural quality must be guaranteed
- The process must be suitable for both lattice and grid-stiffened structures
- Last-minute minor local geometry changes must be accommodate-able
- The process must result in minimal scrap rate of the material
- Minimum post-machining / finishing should be required

The developed manufacturing process features continuous-tow pre-preg fibre placement as the production method. The use of pre-preg materials with 58-63% fibre volume fraction maximizes the obtained stiffness, weight and cost advantages. These advantages are obtained with respect to more wide spread manufacturing methods such as filament winding (~40% volume fractions) or fibre placement with cutting the tows at nodal intersections which avoids nodal material build-up, but weakens the structure.

The process consists in the placement of the free-standing grid onto a mandrel surface using un-interrupted pre-preg tows. Because the fibres at the node are continuous and not interrupted (unlike in many other fibre placement methods for GS composite structures) additional structural efficiency gains are obtained and manufacturing time and complexity is reduced. Further, expansion tooling is used to provide compaction of the material during cure. Through proper tooling design and calculation the nodal material build-up is eliminated upon cure resulting in controlled (uniform) rib height. During the layup of the grid, all local features are laid up and integrated into the structure (e.g. load introduction, attachment zones and cut-out reinforcements). Composite plies between the unidirectional grid and the local load introduction/attachment features are interwoven for optimal load transfer. An outer skin can be laid up on top of the grid to form an outer structural shell (an inner shell is possible as well, the shell can also be non-structural – for environment preservation only).

The smart tooling design allows for obtaining a continuous surface of the grids, attachment and load introduction zones after their integration during layup. The composite layup paths are defined such that a robot can easily repeat the process with no process modifications required. Robotic process limitations are fully taken into account in the definition of the layup: tow widths, placement head reach, start-stop distances, relative positions of the mandrel and the tow/tape placement head, etc.

The developed manufacturing is thus an example of a true one-shot production process since it features one layup and one curing cycle during which all necessary local features are integrated into the structure. This creates unique advantages for highly functional, complex and large scale aerospace structures. The developed manufacturing technology and structural concepts are part of a pending patent application.

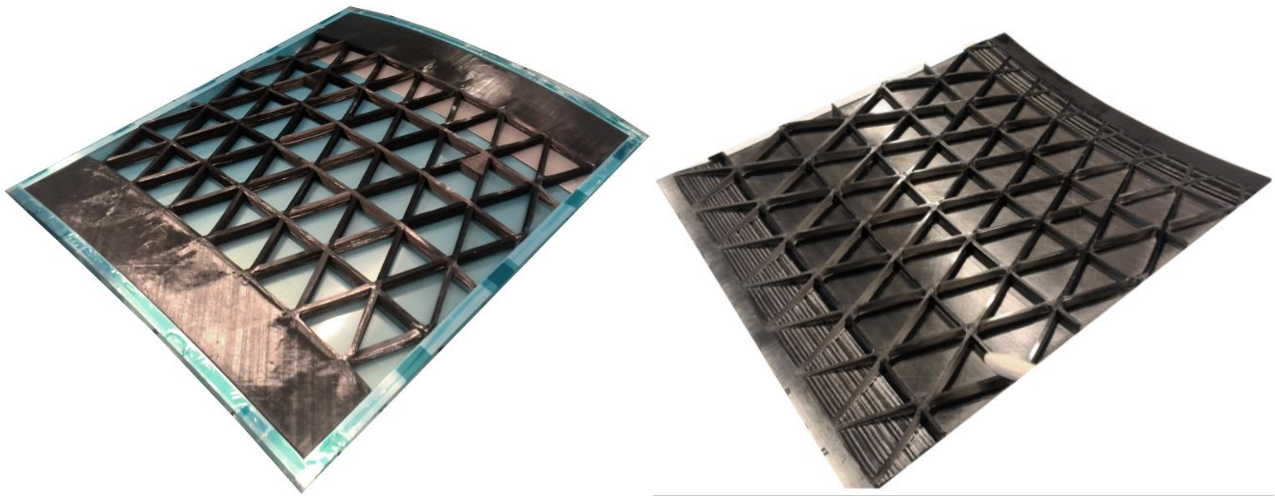

Fig. 6. Highlights of the developed manufacturing process: Left - uncured laid-up grid structure before the placement of the outer skin (observe the fully integrated load introduction and attachment zones); Right – resulting GS structure following the one-shot cure immediately after de-moulding.

6. TESTING AND CORRELATION

In order to demonstrate the performance of the developed GS structures, to validate the developed analysis approaches and to increase the maturity of the technology a number of test campaigns have been performed by ATG Europe. A selection of three of these testing and correlation campaigns are described in this work. For all three test campaigns the Hexcel 8552/IM7 pre-preg material system was used with the cure cycle recommended by the material manufacturer.

6.1 Far-field structural performance

Based on the optimisation results of the Ariane 6 interstage structure [11], "far-field" GS structure test samples were manufactured. Far-field refers to an undisturbed grid section, without any local details. This can lead to overlooking or underestimating the local effects, but provides sufficient means to study the global structural behaviour. In order to preserve similar stiffness and load distribution behaviour to that of the interstage the grid layout was maintained by using the same helical rib angle. The cells were then scaled down by a factor of 4 by scaling the height and width of each cell down by a factor of 2. This was needed to lower the material usage and to obtain a test-able and representative sample size. The scaling also allowed observing a variety of failure modes.

In order to maximize the information that could be extracted from the tests three different sets of panels were produced. The first set was designed with the thinnest skin to induce significantly earlier local buckling, with global buckling only following at a much larger load. The second panel was designed with a thicker skin to result in local buckling occurring first but close to global buckling. The third and final set were designed with a skin thick enough to ensure immediate global buckling, not proceeded by local buckling. The full set of tested panels is shown in Fig. 7 (left). All panels were tested under uniform compression. In order to achieve the variation in failure sequence, which the panels were designed for, supporting aluminium beams were implemented to prevent the side half cells from always buckling pre-maturely, see Fig. 7 (right). The test samples were instrumented with strain gauges and a speckle pattern in order to monitor strains globally using digital image correlation (DIC). The test results were predicted with dedicated FEM models. To account for the presence of the beams and the offset due to skin thickness while maintaining the use of shells, the aluminium beams were modelled as solids and tied to the panel, as shown in Fig. 9. The tie constraint mimics the glue which is considered to be stiff enough to be implemented as a rigid constraint, given its shear stiffness of over 200 MPa. Although known to be lacking, as a first simplistic prediction, linear analyses were performed.

In the test campaign conducted on these flat GS composite panels, findings confirmed linear FEA analyses to be inaccurate, especially considering the out of plane behaviour of the structures. During detailing and correlation activities it was found that thermal strains generated by the difference in thermal expansion between the grids and the skin during after-cure cooldown are pre-stressing the panels. Modelling these after-cure effects and the induced deformations associated with them were key to recreating the observed out-of-plane behaviour. The existence of initial curvature and stresses make any linear buckling or static loading analyses unrepresentative of the actual structure. Hence an "ideal" sequence was developed where the structure is first thermally pre-loaded in a non-linear static analysis, after which a non-linear buckling analysis and Riks arc-length method step are used to determine the stability characteristics and material failure in the post-buckling regime Fig. 8. This approach was found to accurately capture the test panel behaviour, but at a higher computational cost.

Fig. 7. Panels produced for testing of the "far-field" GS structures, incl. reinforcing side beams.

The thermal modelling was found to be critical when modelling the flat panels, due to the out-of-plane deformation significantly affecting the geometrical stiffness properties of the models. For this reason thermal pre-loading is seen as crucial, in general, when modelling grid-stiffened composite test panels.

The test campaigns conducted on "far-field" grid-stiffened structures allowed for a successful model correlation for global and local stiffness as well as buckling behaviour. These results were then used to improve the global optimisation approach.

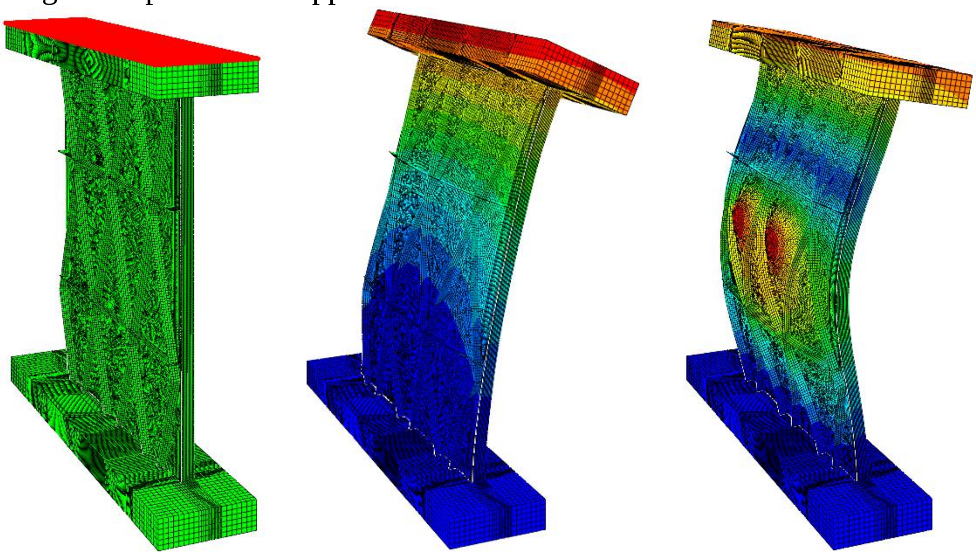

Fig. 8. Developed "ideal" analysis sequence for GS structures: Left - initial step of the simulation, Center - thermal loading simulating cure induced deformations pre-stresses the structure and provides imperfections that result in an accurate buckling estimation, Right – Riks analysis step capturing non-linear post-buckling behavior.

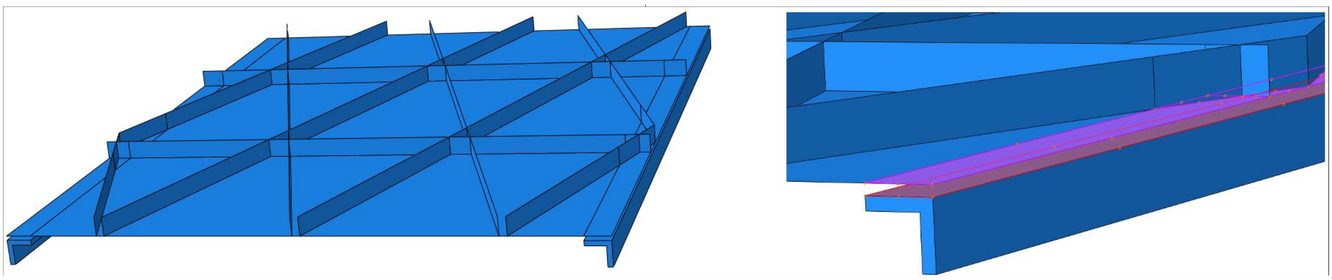

Fig. 9. Schematic indication of the reinforcement beams attached to the GS panels in order to prevent early local buckling at the sides of the samples.

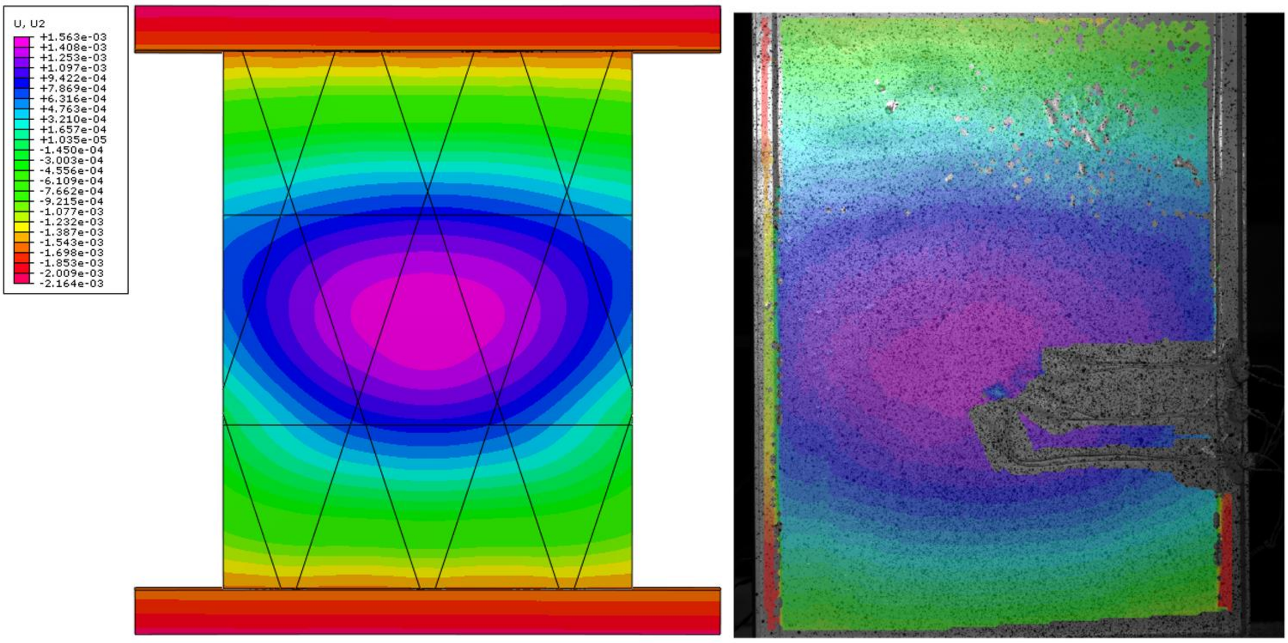

Fig. 10. Analysis model (left) and DIC results (right) with similar out-of-plane deformation patterns.

Additionally, significant information was gained regarding various failure modes and strength aspects of flat GS panels (accurate strength prediction was not the goal of this testing campaign).

6.2 Load introduction zones (End zones)

In order to prove the universality of the developed manufacturing approach a complex interface zone was selected for testing of the load introduction zones for GS structures. The requirements for this end zone are that it provides a metallic interface to the neighbouring structure (e.g. for interstage separation purposes). The developed end zone (Fig. 11 right) concept features grids tapering down towards a gradually building up thick laminate that can then be integrated into a metallic interface by means of bonding or bolting. This design is fully manufacture-able with automated methods.
A fully parametric high-fidelity solid element FE model (Fig. 11 left) has been setup according to the approach outlined in Section 4 to investigate a number of local effects that the end zone has on the far-field structure and vice-versa. Because of full model parametrisation the following influences (and many others) could be studied in an automated way:

- Influence of the grid helical angle and cross-section on stresses and stress concentrations
- Relationship between length of the solid laminate zone and stress distribution
- Influence of thickness and length of the adhesive zone on stress transfer between composite-metal
- Requirements for the laminate build-up and grid tapering regions for optimum load transfer

To confirm the findings of this research two distinct load introduction zone designs were tested in uniform compression (Fig. 12 left), the FE models being subsequently correlated with the test results.

The test samples were instrumented with strain gauges and DIC. Excellent agreement has been obtained on stiffness and buckling (Fig. 12 right) as well as predicting first ply failure and its location.

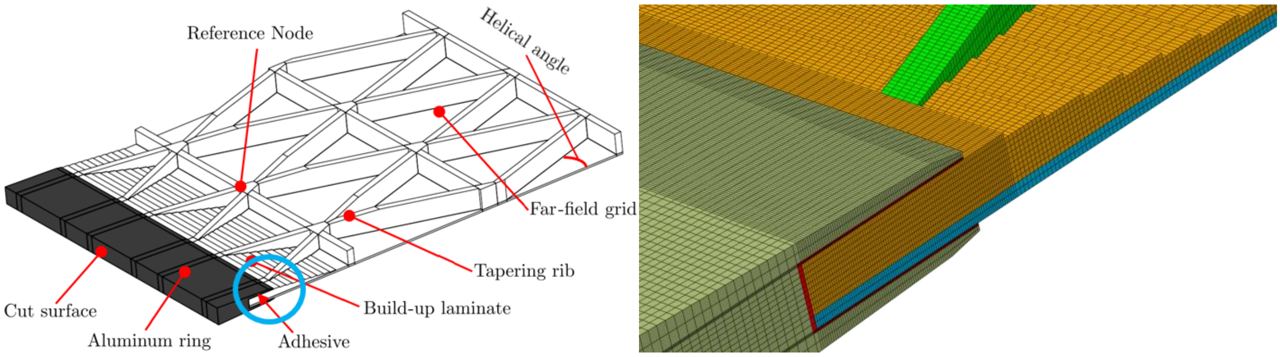

Fig. 11. Left – layout of the load introduction zone, Right – detail of the developed parametric solid element FE model.

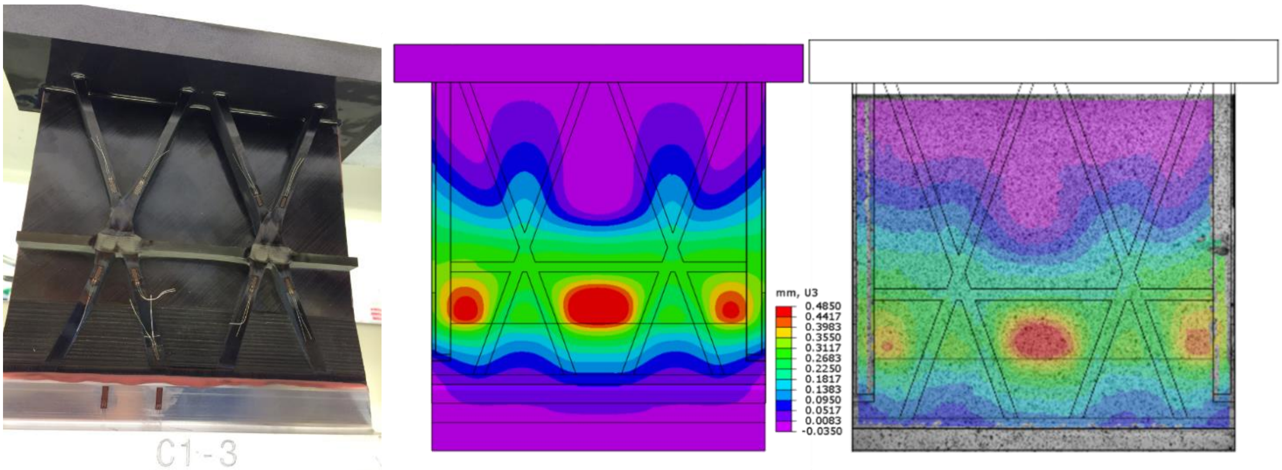

Fig. 12. Left – Example of manufactured test sample, Centre and Right - analysis model and DIC results with similar out-of-plane deformation patterns and matching overall values.

6.3 Attachment zones

One of the main design drivers for the investigated satellite central cylinder structure is the ability to introduce loads through local attachment points at ~380 locations. Some of these loads are very significant and come from a combination of inertial loads from heavy propellant tanks and CTE difference induced deformations due to propellant storage at cryogenic temperatures. ATG Europe has performed a thorough concept investigation into an efficient universal attachment point concept: A separate paper covers the details of this work [12]. Upon manufacturing trials, trade-off and concept selection a parametric solid element FE model of the attachment zone has been set-up in order to identify the main design trends and guidelines for such a zone. The outcomes of investigation have been again verified by testing of two different representative sample types in combined compression and bending (Fig. 13) right. The loads were applied as a downward force with an offset at the bolt location (Fig. 13 left). Samples were instrumented with strain gauges and DIC and a correlation of the test data followed. All samples proved an excellent design performance showing failure above the conservative predictions generated using a combination of analytical tools and FE results. Additionally, both the strain distribution and stress concentrations could be accurately predicted indicating a high level of maturity of the developed FE models (Fig. 14).

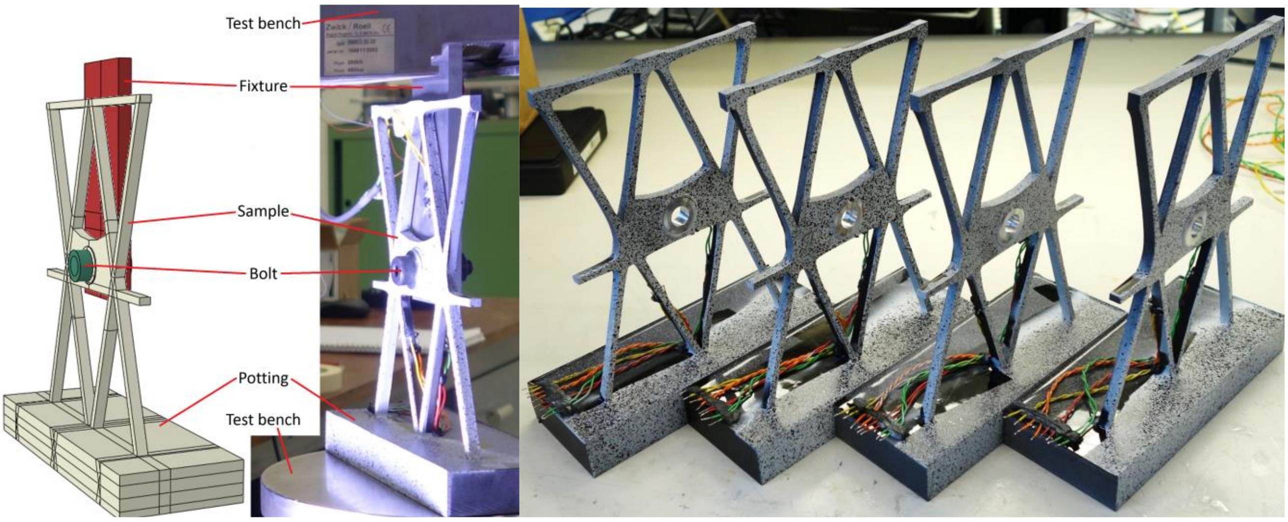

Fig. 13. Left – layout of the test fixture and sample, Right – Part of the test samples batch.

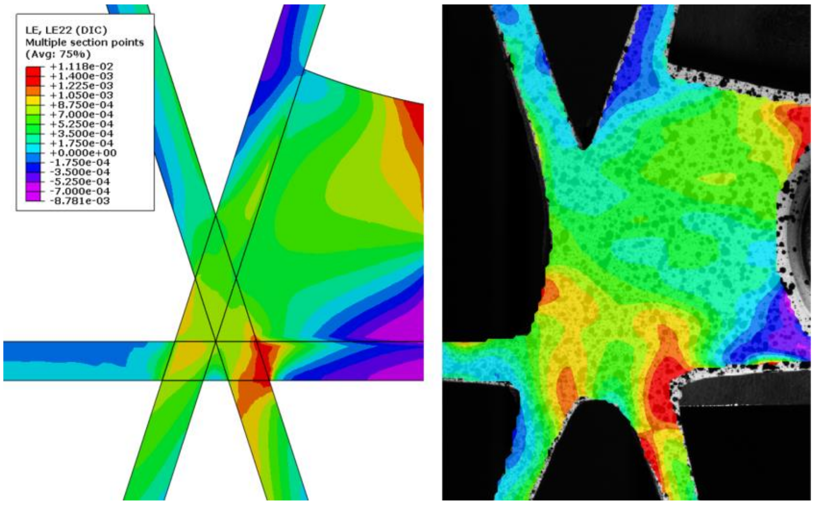

Fig. 14. Simulation model (left) and DIC results (right) show excellent correlation of the (in this case) strain patterns, strain in vertical direction shown.

7. TECHNOLOGY DEMONSTRATOR

The Demonstrator panel (Fig. 15) produced by ATG Europe in 2015 serves the purpose of showcasing the advances in grid-stiffened structures made by ATG. These advances are bridging the gap between the theoretical concept behind the architecture and the practical requirements and needs of real structures. The design of the demonstrator has been based on the Ariane 6 (PPH) Interstage 2/3 structure and the attachment concepts developed for the EDRS-C lattice central cylinder version, as well as insights from various other space and non-space developments. Its performance has been verified by FEM calculations using (Section 8.1), featuring the load introduction zones, cut-out and cut-out reinforcement (for most dimensions a scaling of 1:2 was used); the demonstrator is representing part of the structure circumference.

Two distinct type of load introduction zones have been implemented: one that has a flat edge and can be integrated with other metallic or composite interfaces through bonding or bolting and one that can be bolted directly to the other stages of the launcher (Fig. 16 left, centre).

Equipment attachment zones of two types have been introduced: metallic insert protruding through the structure, and a blind metallic insert embedded from one side only (Fig. 16 right).

The findings and the structural concepts described in Section 6 (grid architecture, load introduction, attachment zones) have been analysed and implemented according to the structural test validation campaigns executed by ATG.

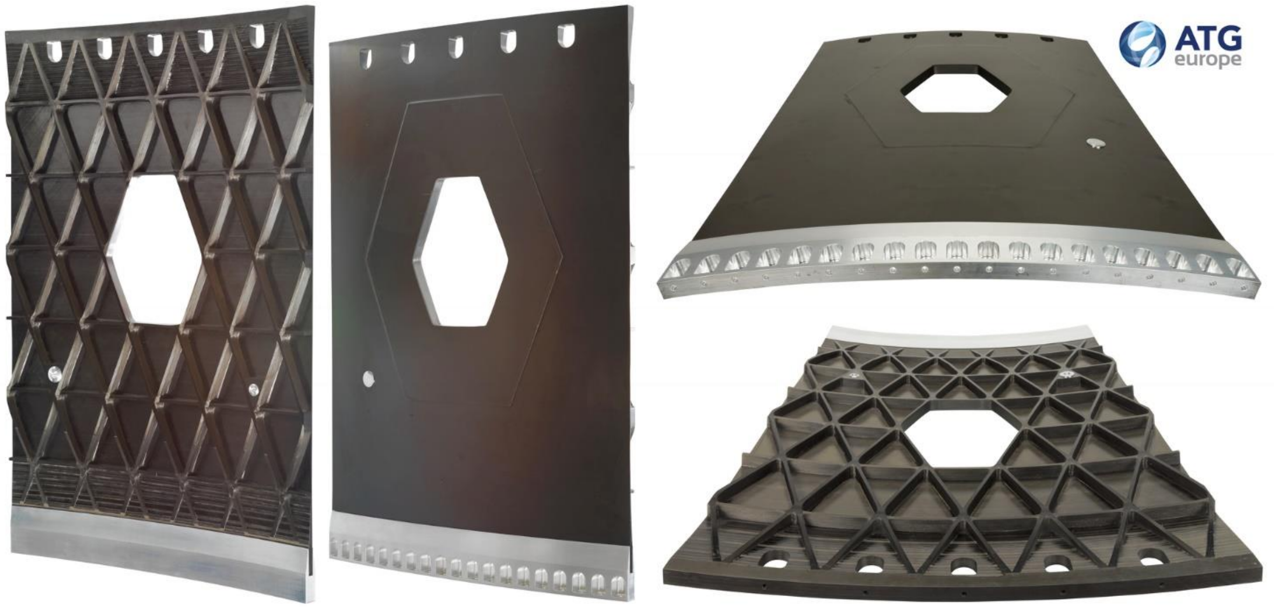

Fig. 15. Layout of the demonstrator panel.

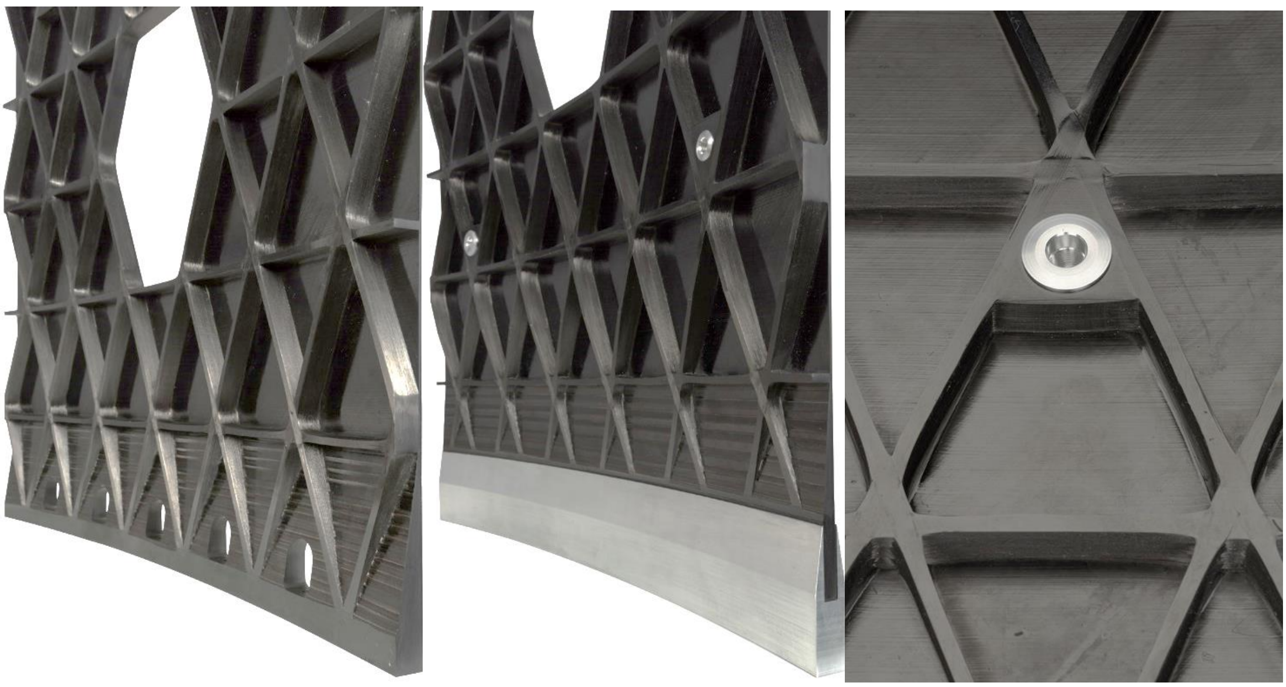

Fig. 16. Notable features of the demonstrator panel: Left – composite load introduction zone, Centre – metallic load introduction zone, Right – attachment point.

8. CASE STUDIES

8.1 Ariane 6 Interstage 2/3

In the case of the case study of the Ariane 6 interstage, no existing structure was available to compare with. A mass budget of 1380 kg was provided for a structure of 7.6 m length and a base and top diameters of 3.5m and 4.0m respectively [13]. Using the approach outlined in Section 4 and the developments described in Section 6, the interstage structure was optimised. As an outcome of this optimisation the optimal GS interstage design was found to weigh 1033kg which is **25% lower** than the provided mass budget [11]. The costs of the structure are expected to be lower than those of potential competing architectures firstly because a lower amount of material used (lower mass) – assuming that the mass budget was derived based on knowledge of current architectures and secondly because of the one-shot manufacturing process. Consequently the lead times to deliver the interstage are expected to be lower as well.

8.2 EDRS-C Central cylinder

The EDRS-C lattice central cylinder could actually be compared to its existing counterpart (unlike the A6 PPH interstage – a hypothetical structure). The current version of the cylinder is a CFRP/AL honeycomb sandwich. Using the findings and method developed by ATG a thorough optimisation and estimation was carried out. As an outcome the benefits of the application of the lattice architecture have been estimated. Particularly, this lattice architecture offers the following benefits:

- 27% lower mass
- 30% lower manufacturing cost
- 20% shorter lead time (important aspect due to structure's criticality for satellite integration)
- Superior integration means and design flexibility due to an open architecture (lattice).

Following a thorough cost estimation, the following cost item breakdown was derived for the further development of the technology (up to industrial scale production of central cylinders) and the one-off production of a lattice satellite central cylinder of dimensions comparable to EDRS-C (Table 1).

Table 1. Development and one-off cost breakdown for a lattice central cylinder for EDRS-C.

Development		**One-off production**	
Activity	**Cost share (%)**	**Activity**	**Cost share (%)**
Management & overhead	16%	Management, overhead, buffer	14%
Manufacturing	26%	Tooling manufacturing	6%
Design/analysis	10.5%	Mandrel	25%
Testing	17%	Material + Layup	10%
NDI	10%	Processing overhead	3%
Quality assurance	7.5%	Machining + attachments	15%
Miscellaneous	13%	NDI + testing	6%
		Finishing	2%
		Design/analysis	19%

Additional gains have been demonstrated by ATG Europe in case of GS architecture application to other space structures applications, such as: small launcher interstages and payload adapters, as well as highly loaded planar products. These advantages include simultaneous cost, mass and lead time savings.

9. CONCLUSIONS

Grid-stiffened structures are a versatile architecture with a lot of promise that requires a design-material-process thinking for harnessing its full potential. Only by a concomitant and integrated development of all three of these aspects it is possible to fully use the benefits of the architecture.
ATG Europe applied this logic to conduct its internal development campaigns for GS structures. This was done in order to prove the potential of the architecture without having to undergo a full-blown development campaign. The internal developments of ATG are mainly defined by the following highlights:

- An accurate, efficient and universally applicable parametric optimisation approach has been developed and confirmed by means of testing
- Design concepts and integrated structural solutions have been developed and verified
- An automate-able, tune-able, repeatable and reliable manufacturing process for manufacturing high quality GS structures has been developed
- The overall state of the technology has been advanced significantly at a relatively low technology development cost.

During the internal developments conducted it has been concluded that existing GS structures optimisation methods fail to provide a reasonable preliminary design of a structure when applied to actual structures or using realistic load cases and requirements.

The conducted developments have proven by means of rigorous detailed investigations that the architecture is applicable to a large variety of space structures. The benefits of architecture application are quantifiable and considerable, reaching up to 27% mass reduction, up to 30% manufacturing cost reduction and a decrease in lead times of up to 20%.

Due to the importance of the design-material-process trinity in the development of GS structures, it is paramount to perform detailed case studies based on actual structural examples with real requirements. This is the only way to properly quantify the benefits offered by the architecture. The depth of such case studies must be considerable in order not to miss certain critical details that might either increase or decrease the suitability of the architecture.

The findings from the reported developments and case studies confirm that the potential efficiency offered by the GS architecture is actually achievable and that uniquely efficient and versatile structures can be produced using the architecture. Using a pragmatic approach, ATG Europe has significantly advanced the industry readiness of GS structures. Now a more consolidated effort and a higher energy development push is required in order to advance this technology towards industrial applications in Europe.

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11. REFERENCES

[1] Chen H. J. and Tsai S. W., *Analysis and Optimum Design of Composite Grid Structures*, Journal of Composite Materials 30 (4) (1996) 503-534.

[2] Ambur D. R. and Jaunky N., *Optimal design of grid-stiffened panels and shells with variable curvature*, Composite Structures 52 (2001) 173-180.

[3] Vasiliev V. and Razin A., *Anisogrid composite lattice structures for spacecraft and aircraft applications*, Composite Structures 76 (1-2) (2006) 182-189.

[4] Wodesenbet E., et al., *Optimization for buckling loads of grid stiffened composite panels*, Composite Structures 60 (2) (2003) 159-169.

[5] Weber M. J. and Middendorf P., *Semi-analytical skin buckling of curved orthotropic grid-sti ened shells*, Composite Structures 108 (2014) 616-624.

[6] Gendron G. and Gurdal Z., *Optimal design of geodesically stiffened composite cylindrical shells*, Composites Engineering 3 (12) (1992) 1131-1147.

[7] Wang D. and Abdalla M., *Buckling analysis of grid-stiffened composite shells*, in: 11-th World Congress on Computational Mechanics, no. WCCM XI, 2014, pp. 4173-4190.

[8] Huybrechts S. M. et al., *Grid stiffened structures: a survey of fabrication, analysis and design methods*, Proceedings of the 12th ICCM.

[9] Zhang Z. et al., *A Stiffened Plate Element Model for Advanced Grid Stiffened Composite Plates/Shells*, Journal of Composite Materials 45 (2) (2011) 187-202.

[10] Pavlov L. et al., *Optimization of a Composite Lattice Satellite Central Cylinder Structure Using an Efficient Semi-automated Approach*, AIAA 2016-1497, DOI: 10.2514/6.2016-1497.

[11] Maes V. K. et al., *An efficient semi-automated optimisation approach for (grid-stiffened) composite structures: Application to Ariane 6 Interstage*, Composite Structures, 2016.

[12] Smeets B. J. R. et al., *Development and testing of equipment attachment zones for lattice and grid-stiffened composite structures,* Presented at ECSSMET 2016, Toulouse, France.

[13] Ariane 6 Project Team, *Ariane 6 Project: Request for Proposal – Statement of Work: Aero Structures*, European Space Agency; 2013.