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DEVELOPMENT AND TESTING OF EQUIPMENT ATTACHMENT ZONES FOR LATTICE AND GRID-STIFFENED COMPOSITE STRUCTURES
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ABSTRACT

Grid-stiffened and lattice structures often exhibit lower mass and manufacturing costs compared to conventional composite and metallic structural architectures.

For an adequate application of the grid or lattice architecture a thorough investigation and development of realistic design features is required. An example of such features are the equipment attachment and concentrated load introduction zones. Examples of such zones are propellant tank and shear web attachment to a lattice satellite central cylinder and electric battery mounting in a grid-stiffened launcher interstage, etc. In order not to hinder the efficiency of the unidirectional fibre orientation grid load-carrying concept, attachment provisions/zones need to be developed in a structurally efficient and cost effective way.

A large variety of possible attachment concepts can be generated that each have their specific advantages and are suitable for particular needs of the structure. The challenge is to create a unique concept that fits all possible requirements for an attachment zone for grid-stiffened and lattice structures used in various applications. Such a unique concept can significantly reduce the qualification efforts thus reducing costs and development time.

A universal attachment concept for lattice and grid-stiffened structures has been developed where an attachment patch of an arbitrary shape and dimensions is integrated with the load carrying grids and a skin (if applicable) through a one-shot manufacturing process. The concept allows for a full tailoring of the load-carrying ability of the attachment zone and serves as an efficient means of load transfer from the equipment attachment into the grids. Equipment can be mounted either directly in/onto the composite by means of mechanical fastening or adhesive bonding, or alternatively, with the use of metallic inserts for interface improvements.

To verify the efficiency of the developed attachment concept, a parametrized finite element model has been validated by means of mechanical testing of a number of generated configurations. Mechanical tests have been performed on samples featuring variations of the attachment concept in order to verify their load-carrying ability, influence on global structural stiffness and the efficiency of the integration with the grid structure.

These test campaigns along with the validated parametric FEA model facilitated the generation of guidelines for the design of attachments for grid-stiffened and lattice structures. The outcomes of the work further allow assessing the mass, cost, manufacturing process and quality implications of the developed concept. The flexibility and robustness of the design process allow for quick redesigns to accommodate load and geometry changes and permit rapid trade studies. Details about the integrated patch concept design, test results and evaluation of its performance are presented.

1. INTRODUCTION

Grid-stiffened (GS) and lattice structures offer a number of unique advantages over other structural architectures that can in some cases drastically improve the achievable structural efficiency of a certain product. These advantages mostly relate to the unidirectional nature of the grids in a lattice and the one-step manufacturing process that allows for the integration of all the structural features in a single process, saving cost and time. The more complex the structure is, the bigger the advantages offered by such a one-shot manufacturing process. The main ideas behind the implementation of the concept as well as its advantages and disadvantages can be found in numerous publications [for example 1-9].

The perceived low maturity of the architecture and the reluctance to apply it extensively to real structures comes mainly from its complexity and the fact that it has little in common with the widely used sandwich and skin-stiffener-frame composite architectures. The complex interaction of failure modes, the lack of widely accepted structural solutions for interfacing with other structures, and issues with processing are mainly responsible for the fact that lattice and GS structures have not yet taken their deserved place among other structural architectures. ATG Europe is working in a consolidated effort to advance the state of the fibre-placed GS/lattice technology towards applications on modern space structures. The main focus of this development work is introduced in [3]. Part of this effort focuses in developing universal, reliable and efficient structural concepts for interfaces between a lattice component and neighbouring or complimentary structures. Among these, forming a special sub-category, are attachment structures and concentrated load introduction points. These are used to introduce point forces into the structure or secure and support equipment during the mission; during a launch such zones can experience considerable forces.

If such an attachment zone can be integrated into the overall structure without the need for subsequent joining steps or additional reinforcements a very efficient structural concept would be created.

An example of such a structure with a large number of localized equipment mounting points and concentrated load introductions is a satellite central cylinder. The role of the central cylinder in a spacecraft is to ensure the integrity of the spacecraft by supporting all equipment and transferring the launch and in-orbit acceleration from the launch vehicle or on-board engine onto the rest of the spacecraft. This work further describes the development of a universal, cost- and weight-efficient attachment concept for lattice and grid-stiffened structures on the example of a satellite central tube, which was selected due to the extensive amount of attachment points that are present.

2. EDRS-C SATELLITE CENTRAL CYLINDER

For central cylinder applications, the advantages offered by lattice structures can be qualitatively characterised as follows (elaborated in more detail in [1, 3]):

- Reduced structure mass – due to the efficiency of the architecture and diverse possibilities for optimisation.
- Significantly reduced manufacturing cost – due to the use of a lower amount of material, lower count of manufacturing steps, the possibility of modularity where a representative unit repeats and a one-step cure followed by machining operations.
- Reduced lead time – due to the one shot manufacturing process and a lower count of manufacturing steps.
- Superior accessibility and flexibility – due to an open nature of the structure ensuring easy access to all internally and externally mounted equipment for assembly/disassembly and inspection.

The selected lattice central cylinder structure is a candidate for replacing current state-of-the-art central cylinders produced using ultra-high modulus CFRP/Aluminium honeycomb sandwich. For the purpose of a one-to-one comparison with an existing structure, the EDRS-C satellite central cylinder was selected (baseline). The availability of structural requirements and performance information regarding the baseline structure allowed for a subsequent objective comparison of the performance of the sandwich and lattice cylinder versions.

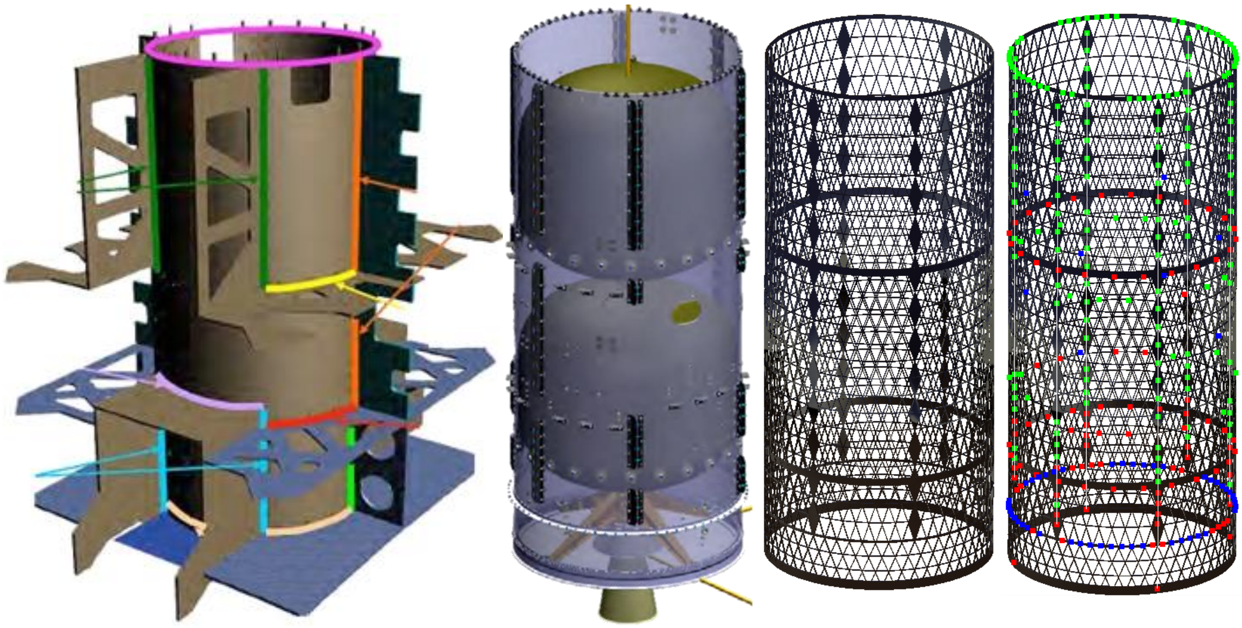

Fig. 1. From left to right – Existing EDRS-C central cylinder, integrated; Semi-transparent representation of central cylinder to show the propellant tanks; Proposed lattice central cylinder; Lattice cylinder with a highlight of attachment points.

The distinctive design feature of satellite central cylinders is that they need to accommodate a large number of attachment points while at the same time featuring a high stiffness, flexible integration possibilities and a low mass. The EDRS-C central cylinder has a length of 2.8 m and a diameter of 1.2 m, featuring 378 attachment points – Fig. 1. The colours used in the rightmost lattice cylinder in Fig. 1 correspond to highly loaded points – red (see [1]), moderately loaded points – blue, and lightly loaded points – green.

Since a large amount of attachment points require localised reinforcements, the optimisation problem of a lattice central cylinder is a coupled one. On the one hand, the best grid topology needs to be used in order to carry the launch loads efficiently, and on the other, the topology needs to be compatible with and ensure the adequate performance of the attachment locations. Decoupling these two aspects of the optimisation is a rather difficult task, but performing an optimisation considering the particularities of such a cross-coupling is an even more tedious process. In order to solve this problem and to devise a robust lattice central cylinder optimisation approach, ATG has investigated a number of attachment concepts from the point of view of their universality, load transfer and ease of integration into a/any grid topology. As a result, a universal attachment concept was developed that allowed for a partial de-coupling of the two aspects of the optimisation problem thanks to the concept's universality. For more information regarding the global structural optimisation of the EDRS-C lattice central cylinder, [1]. The present work focuses further on the development and testing of the developed attachment concept.

3. ATTACHMENT STRUCTURES DEVELOPMENT

3.1 Overall development approach

The development of the attachment concept was performed according to the building block testing philosophy (Fig. 2). Tests of increasing complexity were performed in order to validate the computational models and to increase the level of design maturity and confidence in the selected concept.

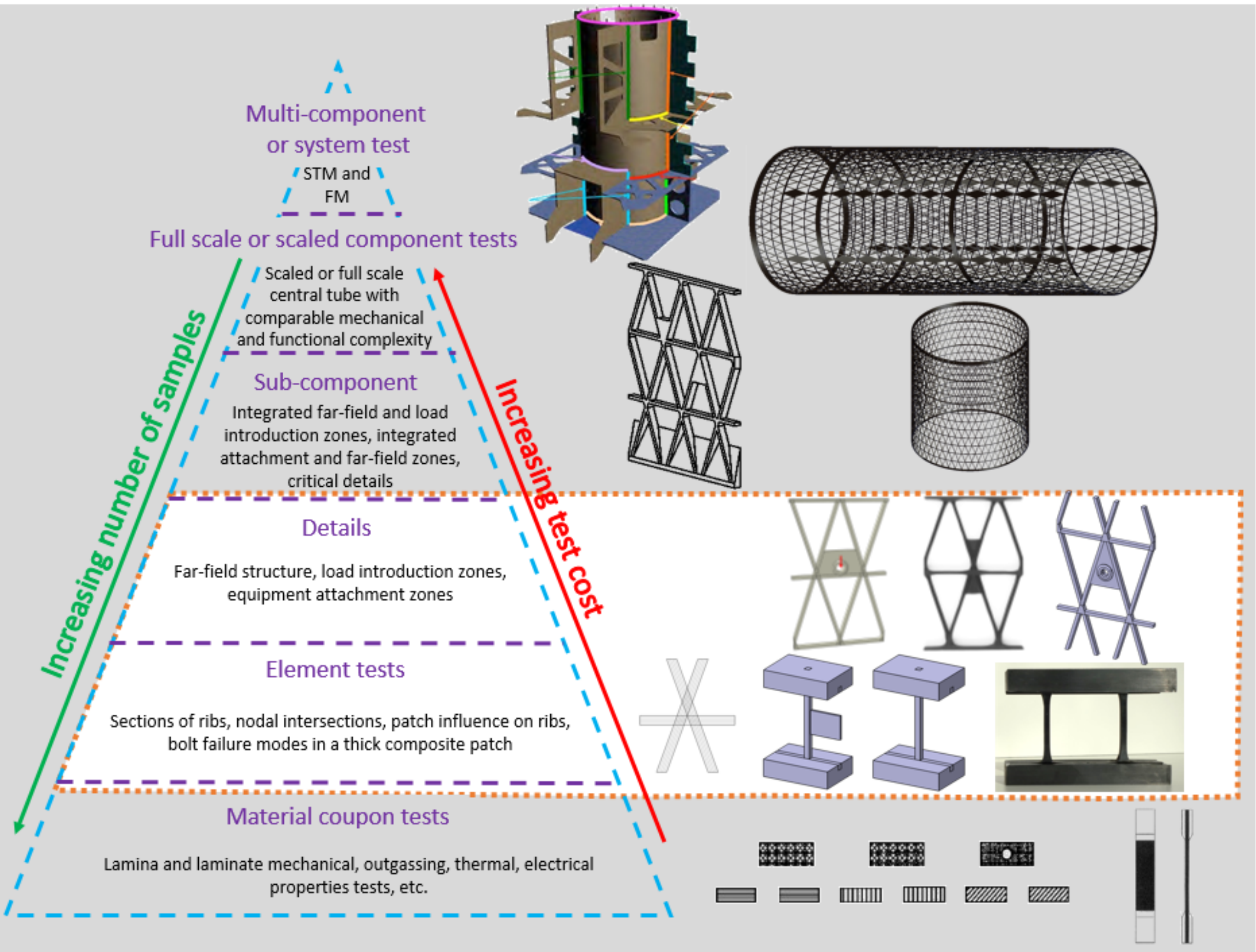

Fig. 2. An example building block testing approach for lattice central tube development. The parts in white indicate the developments performed for the reported attachment concept.

Material manufacturer provided information and corresponding knockdowns were used to complete the missing information due to the lack of an extensive material qualification campaign. The Pareto principle was applied to these developments (80% of results in 20% of cost/time), helping to solve a significant part of the structural and development complexities at a reduced value of the cost of a full development campaign. The most important aspects of the attachment development campaign are described in more detail.

3.2 Typical attachment loads

To make sure that the developed solution is applicable to typical space structures, the typical loads in the EDRS-C cylinder were first investigated. As was shown in section 2, the EDRS-C cylinder used as a reference has 378 in-panel attachments, for each of which a total of 40 quasi-static load cases are defined. This resulted in a total of 15120 attachment load sets, each with combined in-plane, out-of-plane and moment loads. Analysing all these load cases separately was not an option, but investigation of the load spectrum identified that the in-plane loads are typically an order of magnitude higher than the out-of-plane loads. This is due to the plane of the structure being in the vertical direction and accelerations during launch of the satellite are mostly oriented in this direction, thus resulting in high in-plane loads. Additionally, these in-plane loads are accompanied by a moderate bending moment, as if the in-plane load is offset from the neutral plane of the structure. For the initial development of the attachment concept an in-plane load offset from the neutral plane is therefore considered, keeping in mind that other loads can occur as well. The highest occurring magnitude of such a load is 10.5 kN in-plane, as was also used in [1].

3.3 Concept selection

In order to identify the best solution for the attachment points, possible concepts were identified and a trade-off was performed. To improve the structure and reliability of the selection procedure, the concepts were subdivided into 8 groups, each holding 3 to 6 concepts. All concepts were still evaluated separately. The concepts ranged from bonding or clamping directly to the existing grid, to several methods of altering the structure locally to accommodate an attachment. There were multiple constraints that limited the amount of possible concepts. Most constraints were due to the required compatibility with automated fibre placement (AFP), which is the automated manufacturing method foreseen for the lattice SCT. Other constraints were imposed by the required locational flexibility and the large variety in loads.

The concepts were evaluated on 12 criteria, in a quantitative way where possible, and qualitative elsewhere. After evaluation of all the concepts, a sensitivity study was performed on the trade-off results to further increase the confidence that the best solution was chosen. The following criteria (not in order of importance) were considered the most important and were driving the selection:

- Far-field load continuity, the ability of loads on the base structure to transfer across the attachment.
- Obtainable strength of the attachment point.
- Mass efficiency.
- Manufacturability.
- Cost.

From all concepts, the one of a laminate patch was selected. The comparison of concepts showed that this particular choice combines relative ease of manufacture, unlimited scalability and adjustability to match different grid patterns, low weight through tailored layup, a smooth transition to adjacent structure and relatively low local stress concentrations. The laminate patch concept essentially consists of a small area of laminate that is added in between the ribs of the base structure. It is co-cured with the base structure, and plies from the patch extend into the ribs to form a single structural part. The shape and thickness of the patch are variable, dependent on the design. The laminate is then used for a bolted attachment. If necessary or desired, metal inserts can be used for the attachment point, to increase strength, surface quality, and wear resistance. Key elements of the concept are shown in Fig. 3.

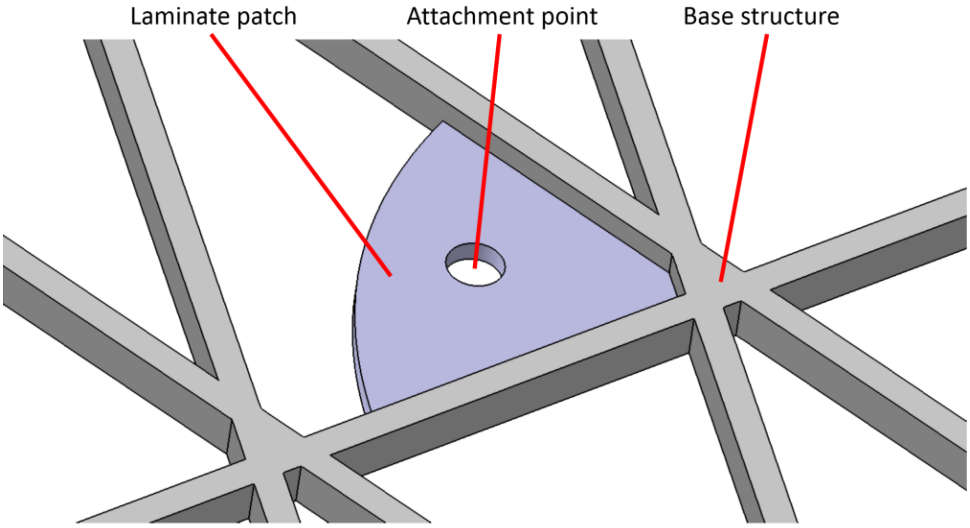

Fig. 3. An example laminate patch in a triangular grid.

To illustrate the layout of the laminate-rib interface a microscope image showing the cross-section of such an interface is shown in Fig. 4. A laminate consisting of multiple plies of different orientations can be seen on the right, where the plies of differing orientations are identifiable by a slightly different shade of grey. Some of these plies extend into the rib in the leftmost part of the image. In the rib no individual plies can be seen, since all the plies that make up the rib are oriented in the same direction. The upper extending plies slightly curve into the rib, this is caused by the lateral compaction that is applied to the ribs during the curing process, causing the rib plies to shift slightly.

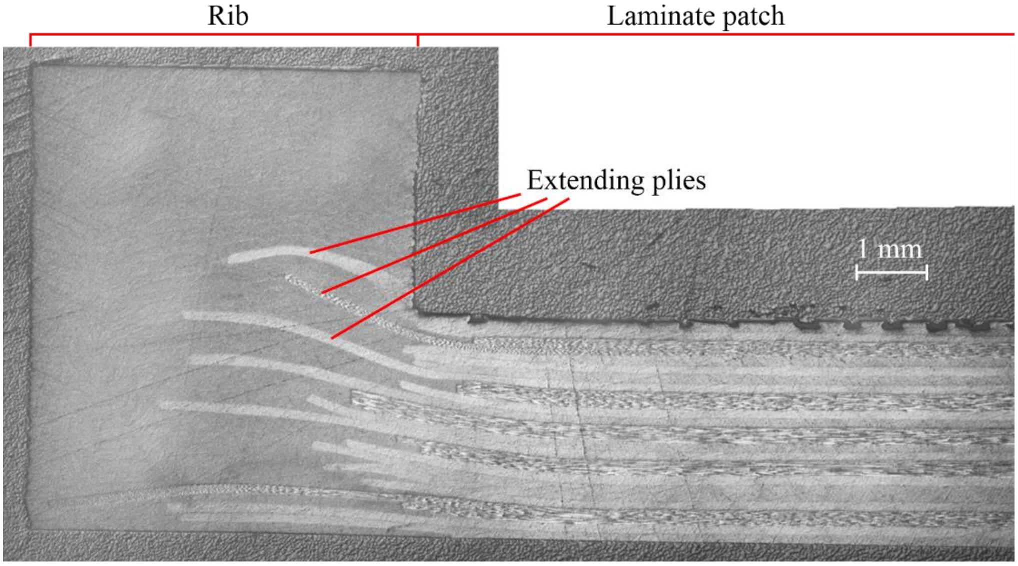

Fig. 4. Microscope image of a rib-laminate interface.

Main advantages of the use of an additional laminate are the flexibility, allowing an attachment to be made anywhere in the grid, and regardless of the presence of a skin. The large interface area between the plies of the patch and the plies in the ribs provides a high-strength interface, with the load transfer distributed through the height of the rib. This outstanding load distribution also allows a relatively efficient use of the laminate itself, leading to a low overall mass.

Considering that the laminate is co-cured with the base structure, several modifications have to be made to the selected manufacturing process. The plies that form the laminate are placed during the same layup phase that creates the base structure, with multiple plies extending into the rib to form a large interface area. Since the layup method used for the base structure is automated, it is desired that the layup method for the laminate is automated as well. A method using either fibre placement or pick-and-place of pre-cut plies is foreseen. Even if those methods prove to be impossible, the base structure can still be made using automated methods, but manually placing the laminate plies.

In order to accommodate the laminate, the tooling in the cell with the attachment is altered, but all other tooling is left unchanged. This is advantageous because it reduces the amount of additional tooling needed in order to include an attachment point.

4. ATTACHMENT MODELLING

In the attachment point several different failure modes are identified:

- Bolt failure.
- Bearing failure of the laminate.
- Shear-out.
- Pull-through.
- Insert or bushing failure, if included
- Failure in the structure surrounding the attachment.

The first five failure modes are treated using analytical methods, simplified if necessary. The complex geometry of the structure calls for FE methods to be used to calculate the stresses, strains, and failure in the structure surrounding the attachment. In the FE model a simplified method is used to introduce the bolt loads, where the applied loads are distributed over the areas where they would be introduced by a bolt. This is done for all load components separately to increase the accuracy. The simplified method was compared to a load introduction method using a bolt modeled with solid elements and contact, this showed that the simplified method gives accurate results. Additionally, to simulate a far-field load an overall displacement of the model boundaries can be applied. The convergence of the mesh was studied, and a converged mesh was used for further analyses.

The described analysis methods are implemented in a script, which automatically generates and solves all the required models, as well as performing the analytical calculations to find the corresponding failure indices (FI). A flowchart highlighting the tasks performed and controlled by this script is shown in Fig. 5.

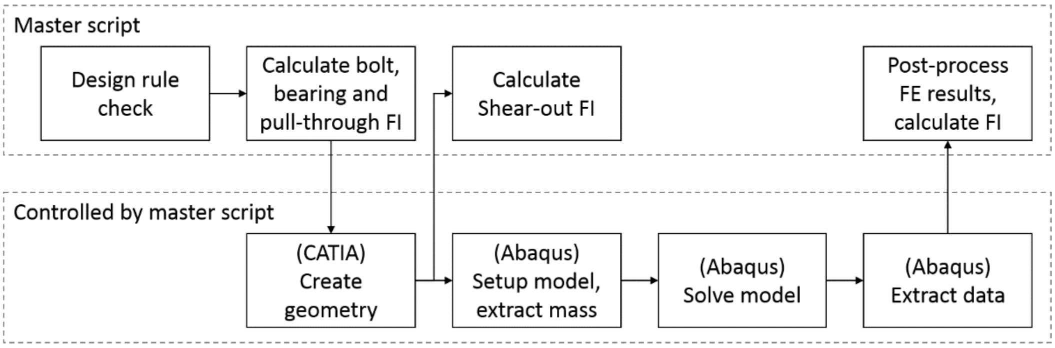

Fig. 5. Flowchart of the scripted implementation.

To facilitate this scripted implementation, the entire attachment design and the local surrounding structure are parametrised. The used parametrisation of the model not only allows the shape, size and location of the patch to be varied, it also allows the method to be applied to different variations of the base structure, increasing the flexibility and applicability to differently sized structures. To illustrate this, several designs are shown in Fig. 6. With the input parameters describing the entire design, generation of the geometry and FE model by the script takes around 30 seconds.

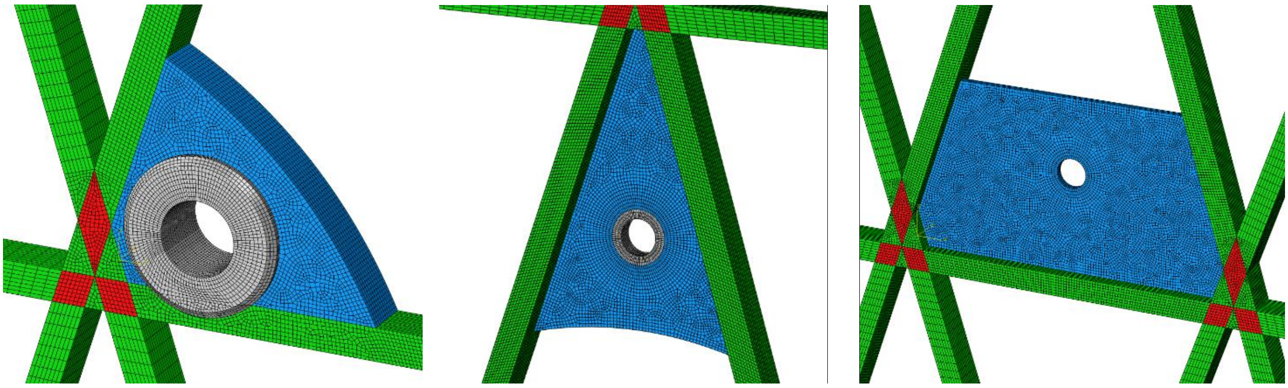

Fig. 6. Details of FE models of several attachment points, showing the mesh and the different zones in the model – ribs (green), nodes (red), laminate patch (blue), and if present an insert (grey). The shown models are generated using the scripted analysis approach, based only on input parameters, no manual adjustments were made.

Using the scripted method, the time required for the entire analysis of the attachment is reduced to 5 to 10 minutes when ran on a standalone workstation. The majority of this time is spent on solving the FE model. The only user input that is required are the parameters describing the design. This allows a rapid design of an attachment point, and would allow integration into an optimisation algorithm.

5. TESTING

To show the suitability of the attachment not only must an attachment show sufficient strength, it may also not have a negative impact on the strength of the surrounding structure. Therefore two types of samples were tested, one type to test the attachment point strength, and the other to test the influence of a patch on the strength of a rib.

5.1 Attachment point test samples

To test the attachment points, samples were loaded by introducing load into a bolt using a custom test fixture. The FE model and test setup are shown in Fig. 7, highlighting some key components of the setup. When the test bench loads the setup in compression, the load is introduced into the bolt by the steel fixture that extends past the test sample. The potting on the lower end of the sample stabilised the sample on the compression plate, preventing rotation and translation.

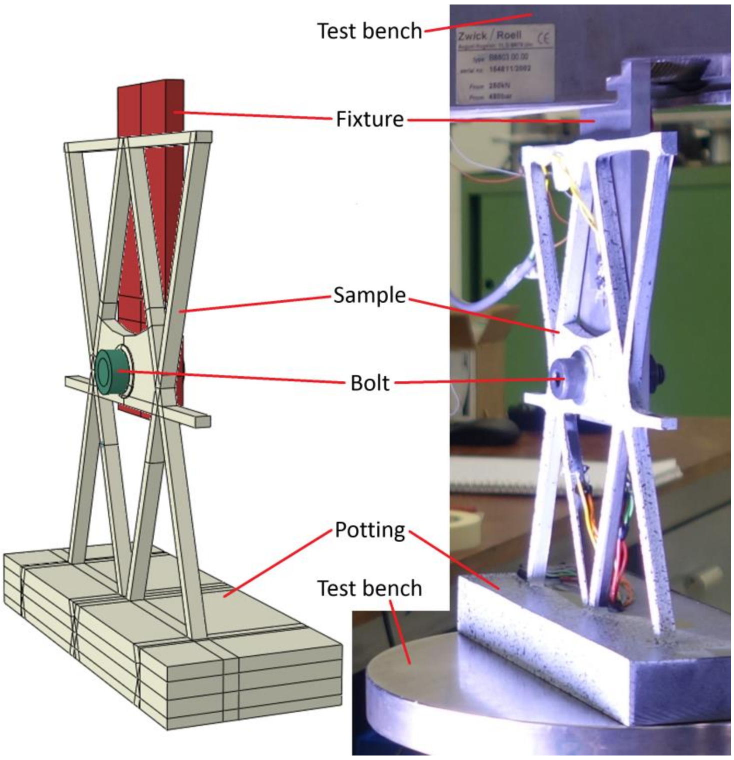

Fig. 7. Test setup for the attachment point samples, indicating several elements in the setup. Left – as in the FE model. Right – actual test setup.

The use of load and displacement sensors, strain gages, and a digital image correlation (DIC) system generated a large dataset which was used for correlation to the model data. Some details of this correlation are shown in section 5.1.

The high-strength attachment samples, of which one is shown in Fig. 7, achieved a strength of over 21 kN in-plane. Samples with a medium-strength design supported an in-plane load of 15.5 kN before bearing damage occurred in the laminate. In both cases the strength of the attachment exceeded predictions of the design by 20-90%, which can be attributed to conservatism in the used analysis methods. The achieved strength is sufficient for all attachment points in the EDRS-C satellite cylinder. With the added mass of the laminate and insert(s) typically around half the mass of the bolt, the tested designs are already mass-efficient. The efficiency of the design approach allows additional iterations to further reduce the weight while still meeting all the requirements.

5.2 Rib test samples

The rib test samples are of a simpler design and are directly loaded in compression, without the need for a custom test fixture. To determine the influence of the laminate patch, two versions of these samples are tested, one version with a patch, and one without. Examples of both these sample types are shown in Fig. 8.

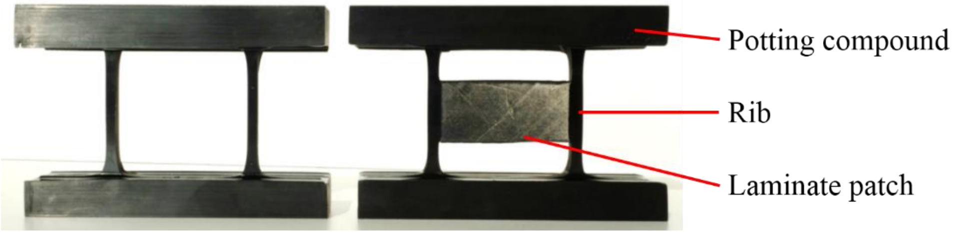

Fig. 8. Rib test samples without (left) and with a laminate patch (right).

Three samples of both types are tested, and the results averaged. As can be seen in Fig. 9 the differences in strength are very small, indicating the presence of a patch does not have a high influence on the rib strength. Additionally, the influence of the patch on the sample stiffness was also very low, showing only a 2% increase.

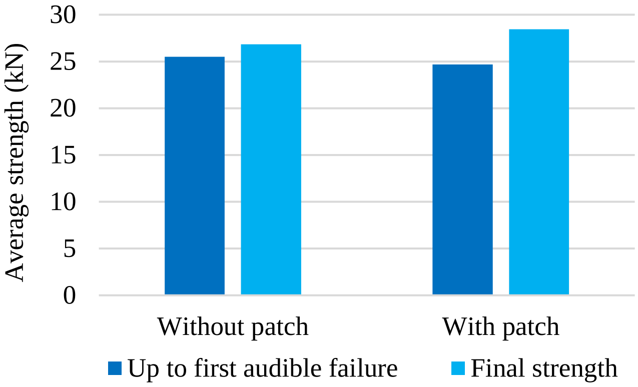

Fig. 9. Average strength of the rib test samples.

5.1 FE model correlation

The datasets obtained from testing the attachment samples were compared to the FE model results to see if the model is able to predict the behaviour of the structure accurately. Only a fraction of the datasets that are generated are shown, in the interest of brevity.

Of foremost interest are the strains in the structure surrounding the attachment, since it is in these areas that the FE model is used to predict failure. Because the DIC system gives the strains in the horizontal and vertical directions and not in the material direction, the FE results are first transformed to the same coordinate system. A comparison of the strains can then be made. One of such comparisons is shown in the left of Fig. 10, showing the strains in the laminate and ribs just outside of the attachment point. The strain in the vertical direction is shown, in the same direction in which the load is applied. Good to excellent correlation between FE predictions and DIC measurements is observed.

Additionally the overall displacements can be compared, this is shown in the right of *Fig. 10*. Looking at the displacements, again in the loaded direction, an excellent correlation between the model and test data can be seen, where it must be noted that the scale for the measured data is corrected to account for the initial offset, but the range is kept the same.

The excellent correlation of the results shows the accuracy of the FE modelling method, and its suitability for modelling the structure containing the attachment.

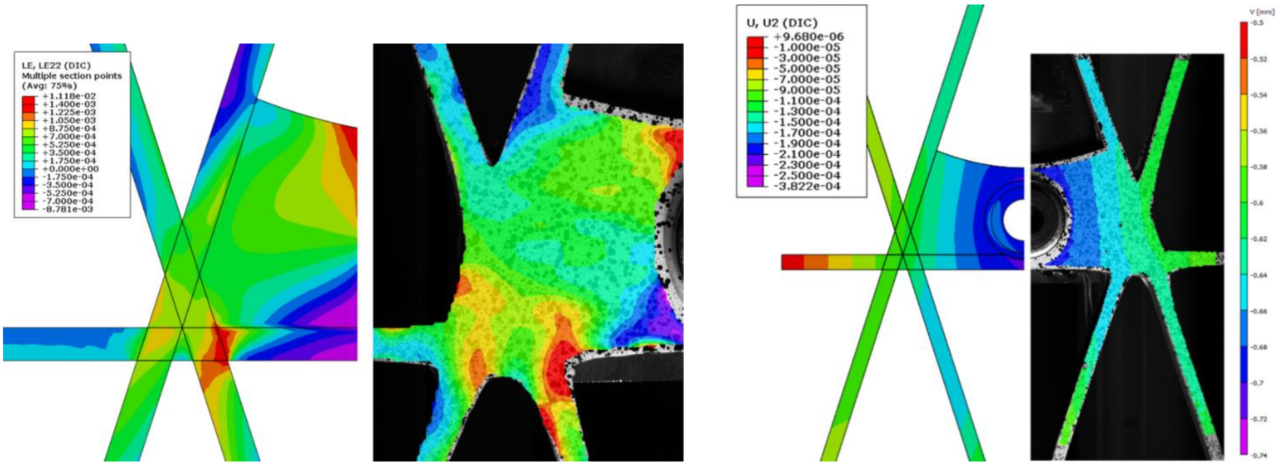

Fig. 10. Comparison of FE model results and DIC measurements. From left to right – Strain in the vertical direction, FE model results; and DIC measurements; displacement in the vertical direction, FE model results; and DIC measurements, corrected for the initial offset.

6. ATTACHMENT STRUCTURES INTEGRATION

6.1 Demonstrator

The developed attachment concept for lattice structures is applicable to both lattice and grid-stiffened structures (lattice structures with an outer or inner shell). To demonstrate the concept's applicability and integration possibilities into larger scale structures produced using one-shot cure, two attachment zones were implemented in the demonstrator structure fabricated by ATG Europe [3]. Two different attachment zones were integrated, one with a blind and one with a through bolt hole (Fig. 11).

Fig. 11. Attachment zones with bonded inserts implemented into the demonstrator structure: Left – through bolt with a larger insert. Right – smaller insert for a blind hole.

The performance of the concept applied to grid-stiffened structures (in addition to lattice structures implementation covered in this work) has been verified through modelling and inspection. The application of the two attachment zones to the curved demonstrator structure has resulted in structural joints of high quality and dimensional precision.

6.2 Impact on weight and production cost

Considering the goal of the attachment concept development (to ultimately provide real structural solutions) it is important to estimate the impact of the concept on the weight of the overall structure. Using the optimal blank shell configuration reported in [1], the mass of the equipped lattice central cylinder structure can be calculated for a comparison with the mass of the existing reference sandwich tube. Such a calculation requires an estimation of the masses of reinforcement patches, metallic inserts, adhesives, nuts, clamps, piping supports, etc.

For calculation of the ancillary masses of the EDRS-C central cylinder, the reinforcement patches were grouped into four categories based on the magnitude of loads these need to carry and transfer: propellant tank, medium to high load, medium and low load patches. The conservative design approach presented in Section 4 allows to perform an adequate patch sizing for each load group. An overview of the number of estimated required patches for each load grouping is given in Table 1. The provided estimates are of a conservative kind in order to provide the heaviest possible baseline of a lattice cylinder for a conservative comparison with the sandwich version. In reality, the mass of the attachment patches and the blank shell of the lattice tube can be significantly reduced using the findings reported in the previous sections of this work.

The combined conservative mass estimate of all ancillaries corresponding to the lattice central cylinder configuration is 6.08 kg, of which the attachment zones make only a fraction. Combining it with the blank shell mass of 21.36 kg [1] the mass of equipped cylinder becomes 27.44 kg. This mass of the central cylinder is 27% lower than the mass of the equipped baseline sandwich central cylinder (37.7kg), confirming the structural benefits of a lattice central cylinder over the state-of-the-art sandwich cylinders.

Table 1. Reinforcement patches per load group and corresponding bolt diameters.

Type	Number of occurrences	Bolt diameter (mm)
Propellant tank	48	11
Medium to high load	71	8
Medium load	145	6
Low load	114	4

7. CONCLUSIONS

A new concept has been developed for in-panel attachments or local load introductions into lattice and grid-stiffened structures. This concept makes use of a locally added laminate, which is co-cured with the structure and allows mechanical fastening methods to be used. This concept was down-selected from a pool of concepts, keeping typical requirements in mind that would apply if the attachment were used in a space application. Manufacturing of such attachments in multiple samples and structures has shown that the method is applicable to both lattice and grid-stiffened structures.

The design process of the concept is fully automated and parametrized allowing (a) rapid incorporation in an existing design (b) high level of adjustability to be usable in almost any grid configurations, (c) trade studies to examine the effect of changes in various geometry or material parameters and (d) optimization.

Mechanical testing of several attachment samples showed that the attachment method is not only capable of supporting the design loads, but even exceeds the expected strength. This, when combined with other tests that have shown that the laminate has no substantial effect on the rib strength and stiffness, proves the feasibility of the concept as an attachment method.

Additionally, other studies have shown that the presented attachment concept, when used in the design of the EDRS-C satellite central cylinder, results in an overall potential mass saving of at least 27% compared to the reference honeycomb sandwich design.

8. ACKNOWLEDGEMENTS

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