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NLR-TP-2016-201 | April 2017

Comparison of integrated rib stiffened and L-blade stiffened composite panels manufactured using simple tooling methods

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EXECUTIVE SUMMARY

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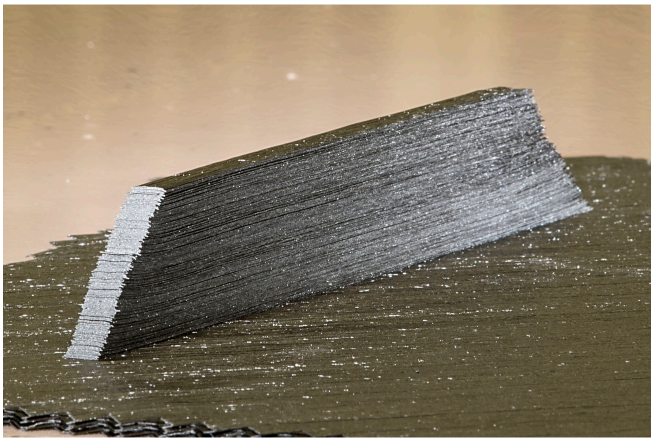
Comparison of integrated rib stiffened and L-blade stiffened composite panels manufactured using simple tooling methods



Problem area

Manufacture of stiffening elements in composite structures usually requires different steps and associated tooling. Often, the composite skin and stiffening elements are manufactured separately and either subsequently co-cured in one single cycle, co-bonded or secondary bonded after cure. Complex tooling is necessary during laminating of the components as well as additional tooling during cure. Methods that reduce the amount of tooling necessary were investigated.
Two alternative methods to manufacture stiffened panels using simplified tooling are presented.

Description of work

One method investigated uses fibre placement to manufacture integrated stiffening ribs by creating a stack of tape by automatically fibre placing various layers of a single thermoset 6.35 mm wide tape. Another method investigated metal pins only to position cured L-blade stiffeners on an uncured skin.

REPORT NUMBER
NLR-TP-2016-201

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REPORT CLASSIFICATION
UNCLASSIFIED

DATE
April 2017

KNOWLEDGE AREA(S)
Structures Technology

DESCRIPTOR(S)
Automated Fibre Placement
rib stiffening
orthogrid
composites
blade stiffening

Stiffened post-buckling compression panels using both manufacturing methods were designed and analysed to have the same dimensions and performance (buckling load factor/weight) to enable a fair comparison between the two methods. The L-blade stiffened panel, which is of a more conventional configuration, was used as a reference panel to compare performance to the rib stiffening method and as test case for the metal pin positioning.

The panels were subsequently manufactured and tested in compression.

Results and conclusions

Ribs with a height of over 30 mm could be fibre placed without any additional tooling to stabilize and support the stack during placement. The stack was placed without any support on an uncured skin. Integrated ribs on a panel were manufactured successfully in this way.

Metal pins manufactured by stamping or additive manufacturing protruding from cured L-blade stiffeners were inserted into an uncured panel skin laminate. Positioning the stiffeners was done using simple tooling. Once the stiffeners were positioned, they were locked in place by the pins. The entire assembly was vacuum bagged and successfully co-cured without any additional tooling.

Test results showed that the rib stiffening method has the potential for better performance compared to the more traditional blade stiffened panels with, at least, 8% lower weight.

Rib stiffening offers an alternative method to manufacture stiffening elements in an automated way. The use of metal pins simplifies the manufacturing process of the L-stiffened panels, no influence on strength was observed during testing.

GENERAL NOTE

This report is based on a presentation held at the SAMPE Technical Conference, Long Beach, USA, May 23-26, 2016.

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This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

CUSTOMER	**European Commission**
CONTRACT NUMBER	**Grant Agreement n°314003**
OWNER	**NLR + partner(s)**
DIVISION NLR	**Aerospace Vehicles**
DISTRIBUTION	**Unlimited**
CLASSIFICATION OF TITLE	**UNCLASSIFIED**

APPROVED BY :

AUTHOR	**REVIEWER**	**MANAGING DEPARTMENT**
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DATE 2 1 0 4 1 7	DATE 2 4 0 4 1 7	DATE 2 5 0 1 1 7

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COMPARISON OF INTEGRATED RIB STIFFENED AND L-BLADE STIFFENED COMPOSITE PANELS MANUFACTURED USING SIMPLE TOOLING METHODS

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ABSTRACT

Manufacture of stiffening elements in composite structures usually requires different steps and often complex tooling. Methods that can reduce the amount of tooling during laminating and cure necessary were investigated.

One method uses automated fibre placement to manufacture integrated stiffening ribs with a height of over 30 mm by stacking various layers of a single thermoset 6.35 mm wide tape on an uncured skin.

Another method utilises metal pins protruding from cured L-blade stiffeners to position and locking the stiffeners into place on an uncured skin. The entire assembly can be vacuum bagged and co-cured without any additional tooling.

Stiffened post-buckling compression panels using both concepts were designed to have the same dimensions and performance (buckling load) to enable a fair comparison of both manufacturing methods.

The panels were subsequently manufactured and tested in compression. Test results showed that the rib stiffening method has the potential for better performance in buckling compared to the more traditional blade stiffened panels with, at least, 8% lower weight.

Rib stiffening offers an alternative method to manufacture stiffening elements in an automated way. The use of metal pins simplifies the manufacturing process of the L-stiffened panels, no influence on strength was observed during testing.

1 INTRODUCTION

Manufacture of stiffening elements in composite structures usually requires different process steps and associated tooling. Often, the composite skin and stiffening elements are manufactured separately and either subsequently co-cured in one single cycle, co-bonded or secondary bonded after cure. Complex tooling is often necessary during laminating of the components as well as additional tooling during cure. In the European project LOw COst Manufacturing and Assembly of Composite and Hybrid Structures (LOCOMACHS) [1], two methods to reduce the amount of tooling necessary for manufacture were investigated. In this paper they are referred to as the rib stiffening method and the pin positioning method. Panels using these methods were designed, manufactured and tested.

The material used for all experiments and panels was Hexcel AS4/8552 slit tape, 6.35 mm (¼ inch) wide. A standard cure cycle recommended by the manufacturer was used with a dwell at 110°C and cure at 180°C.

1.1 Rib stiffening method

Rib stiffening concepts, also known as grid or isogrid, have been investigated since the 1970's, particularly in space structures [2]. The use of rib stiffening is very interesting from a mechanical performance point of view as it enables the manufacture of lighter and more robust structures by offering multiple load paths. It is also interesting from an assembly point of view as it offers the possibility of function integration. Rib stiffening techniques can be used to fully carry the structural load or to reinforce the skin with freedom of variation of e.g. rib angles and rib height. Therefore this technique can also be used for local reinforcement to actually put the fibres where the loads are [3].

When manufactured from composite material, these grid structures usually contain rib stiffeners. In Figure 1, a space application for the Minotaur payload fairing with grid-type reinforcement manufactured using rib stiffeners is shown.

Figure 1: Grid stiffened panel from the Minotaur payload fairing [6]

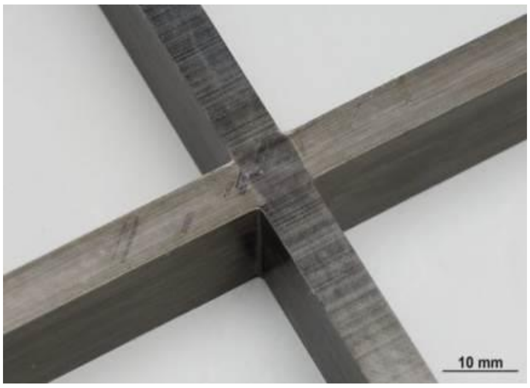

Figure 2: Rib stiffening crossing section sample manufactured at NLR [4]

In previous research at the Netherlands Aerospace Centre (NLR) [4], rib stiffening was used to improve the buckling performance of fuselage crown panels in the low loaded areas in the forward section of an aircraft fuselage, see Figure 2.

With the rib stiffening technique, co-curing of the skin and the rib sections is feasible, but the interface is often critical because of high residual stress caused by differences in thermal expansion and curing shrinkage.

The interface between the rib and skin is probably also sensitive to impact damage. The traditional design using a stressed skin concept for fuselage panels may therefore not be feasible if damage tolerance is taken into account. To accommodate damage tolerance requirements the structure may become too heavy or it may even be possible that it is not feasible to meet the damage tolerance requirements at all. An alternative design fuselage panel design could be considered where the structural load is carried by an (iso)grid structure and the skin is no longer stressed. In this way, the damage tolerance requirements for the skin will be different. It will still need to carry e.g. a pressurisation load, but longer need to transfer shear. A fuselage concept similar to the Vickers Wellington aircraft could be considered. In this aircraft, the loads are carried by the frame and the skin only serves to preserve the aerodynamic shape.

The rib stiffening method discussed in this paper uses Automated Fibre Placement (AFP) to manufacture integrated stiffening ribs. AFP is used to automatically place various layers of a single thermoset tape on top of each other. In this way a stack of tape is created that can serve as a stiffener. This entire lay-up is subsequently cured using relatively simple tooling blocks.

1.2 Pin positioning method

The pin positioning method uses only metal pins to position cured parts with protruding metal pins on an uncured skin. Metal pins manufactured by stamping, additive manufacturing or another method can be incorporated in a cured component in such a way that they protrude from the cured surface. The protruding pins from the cured subcomponent are inserted into an uncured laminate and the assembly is subsequently cured. Positioning the component can be done using simple tooling, e.g. using spacer blocks or a template. Once the components are positioned, they are locked in place by the pins. The entire assembly can then be vacuum bagged and co-bonded without any additional tooling.

In this way, positioning of e.g. spars or stiffeners on a skin during assembly/manufacturing could be simplified by using less additional parts or tooling while at the same time improving the accuracy of the positioning and the overall end result.

2 EXPERIMENTS AND RESULTS

2.1 Rib stiffening concept

To investigate the curing and thermal effects, a simulation approach was developed and used to investigate the residual stress on the interface of the skin and ribs. Variations in rib design have been investigated using simulations and manufacturing trials. This was done before manufacturing of the actual panel demonstrators.

2.1.1 Thermal and cure analysis

As already mentioned, high residual stresses in the interface between rib and skin can occur in rib stiffened structures when co-curing rib and skin. The ribs are made using unidirectional (UD) material laid-up in one single direction and the skin is often of a semi-isotropic nature. When considering chemical shrinkage and thermal expansion, the length reduction in fibre direction is fibre dominated and typically less than 0.1%, while shrinkage perpendicular to the fibre direction is matrix dominated and might be in the order of 3% or larger [5]. Due to the large shrinkage of the resin in transverse direction of the rib, tension stress develops in the rib and compression stress develops in the skin, see Figure 3. This difference in linear expansion between the rib and the skin needs to be accommodated for in the interface, and can lead to high residual stresses or even damage.

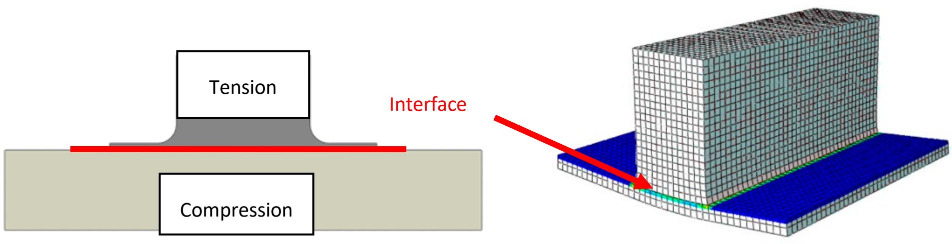

Figure 3: Stress directions after cool down of the co-cured skin and rib part.

Previous research at NLR identified issues with respect to the quality of the laminate in the cross section (rib crossing) and of the skin to rib interface. The rib stiffening in some situations actually separated from the skin after curing and cooling down due to thermal stresses. Distortion of the entire rib-skin grid structure was also observed due to anti-symmetry in the laminate.

Reduced strength of the rib to skin interface can reduce panel strength and damage tolerance significantly. Better understanding of the mechanism described above is necessary, so some analyses were carried out to gain more insight.

Using a fracture mechanics model employing cohesive elements [7], the thermal and curing effects were investigated. The skin and rib were modelled as separate parts and an interface behaviour using the cohesive elements was applied. Variations were applied in the height of the rib and skin-laminate definition to investigate the effect on the residual stress on the interface and possible crack growth.

The following variations were investigated:

- rib base type
- rib height
- skin thickness

Conclusions from these investigative simulations were that, as expected, there is considerable tension in the direction perpendicular to the fibres which can result in cracked ribs in longitudinal direction.

Several effects were identified from the simulations when co-curing ribs on the skin:

- Bending of skin:
  Due to the different coefficient of thermal expansion (CTE) and resin shrinkage for the orthotropic rib and the often quasi-isotropic properties in the skin, there is a bending effect. Also the a-symmetrical material distribution will contribute to the bending. This bending is undesirable as it will cause deviations from the designed structure, particularly in compression loading this might cause early buckling.
- Interface damage between rib/skin:
  Due to the different CTE and resin shrinkage in the different directions, the interlaminar stress might increase up to failure of the interface. From the simulations it is observed that damage will initiate from the sides of the ribs.
- Residual strength of the interface:

  Although the co-curing of the rib might give satisfactory results, still the residual strength might be influenced by internal stress and small damages.

2.1.2 Manufacturing trials

Manufacturing trials were carried out to study the effect of internal stresses due to thermal and chemical shrinkage on rib stiffeners. The effect of rib height was also investigated.

Three panels with different skin thickness with quasi isotropic lay-up and different rib types were manufactured to study these variations. See Table 1 below for an overview of the parameters.

Table 1: Overview of rib trials with different setups, variation in rib type, shape and rib height.

Rib nr.	*Skin thickness [mm]*	*Lay-up skin*	*Rib type*	*Rib height [mm]*
1	2.0	$[+45/0/-45/90]_{2s}$	Trapezoid	5.0
2	2.0	$[+45/0/-45/90]_{2s}$	Standard	2.0
3	2.0	$[+45/0/-45/90]_{2s}$	Standard	5.0
4	2.0	$[+45/0/-45/90]_{2s}$	Standard	10.0
5	3.0	$[+45/0/-45/90]_{3s}$	Standard	5.0
6	3.0	$[+45/0/-45/90]_{3s}$	Standard	10.0
7	4.0	$[+45/0/-45/90]_{4s}$	Standard	5.0
8	4.0	$[+45/0/-45/90]_{4s}$	Standard	10.0

Rib number 1 was a trapezoid, which had a wide base of two tows placed side-by side (12.7 mm) and a height of 5 mm, see Figure 5. The remaining ribs numbers 2 to 8 were standard rectangular cross section, 6.35 mm wide. For this rib type, the height was varied to investigate the effect on the interface quality between skin and rib.

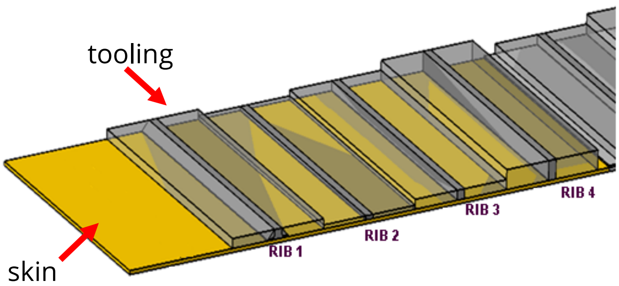

Figure 4: Including ribs numbered 1 to 4

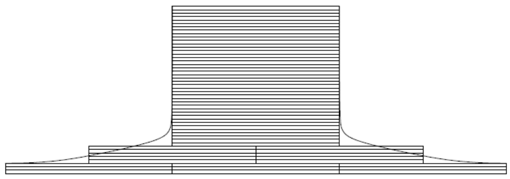

Figure 5: Trapezoid rib shape with layer build up

2.1.2.1 *Sample manufacture*

Ribs were manufactured by fibre placing various layers of 6.35 mm wide thermoset tape on top of each other on a skin. During this, tooling was used to support the ribs. This tooling consisted of 2 mm thick aluminium plates that were stacked depending on the rib height. See Figure 6 for samples before cure. Aluminium tooling blocks were used for cure, see Figure 4 and Figure 7.

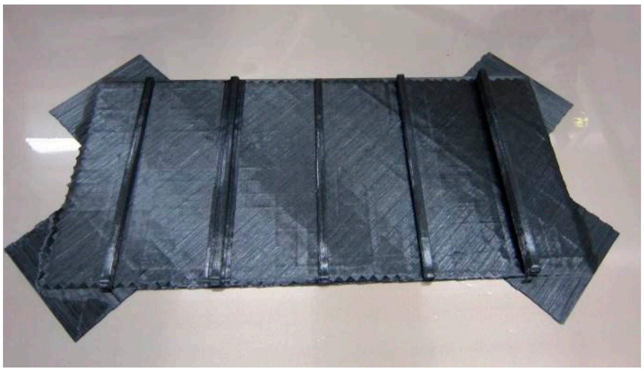

Figure 6: Fibre placed test panel before cure

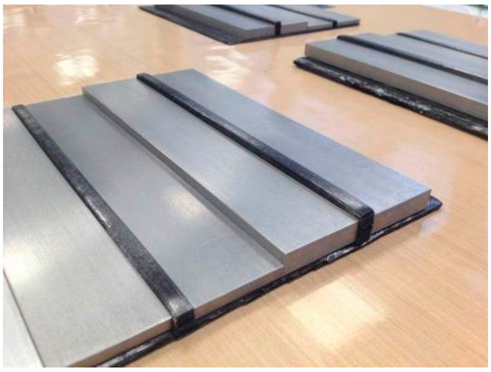

Figure 7: Cure tooling for the manufacturing trials

2.1.2.2 Results

The results of the trial manufacturing of the rib stiffened samples were satisfactory. After removal of the support blocks the ribs all appeared intact and no separation from the skin was observed.

Cross-sections of the panels were taken to assess laminate quality. The rectangular shaped ribs number 2 to 4 are shown Figure 8. The tooling was kept simple and to enable sufficient pressure was put on the ribs, the ribs were made somewhat oversized, leaving them protruding above the tooling, see Figure 7. This caused the overhang or “hat” on top of the ribs, see Figure 8.

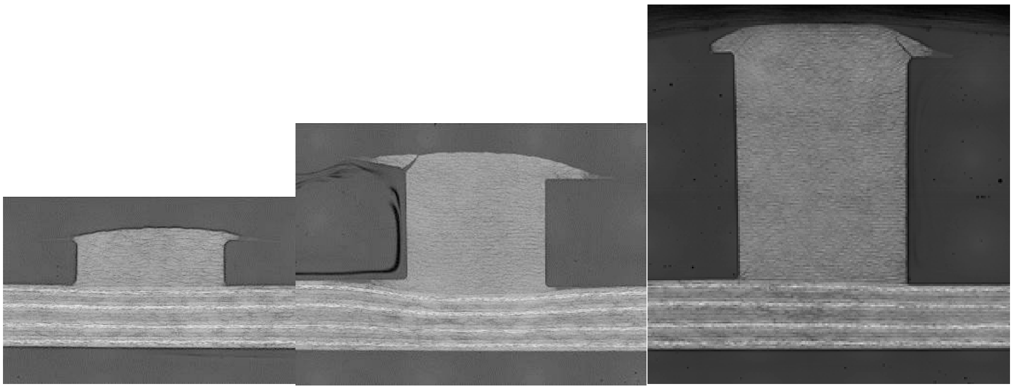

Figure 8: Cross-section of cross sections of ribs number 2 (left), 3 (middle) and 4 (right).

At the interface between skin and ribs, short cracks up to 1 mm cracks were observed. This is shown in Figure 9. Some local deformation of the skin near the ribs was observed, leading to fibre volume fraction variations and some distortion, see rib number 3 in Figure 8. No separation of ribs was observed in the manufacturing trials.

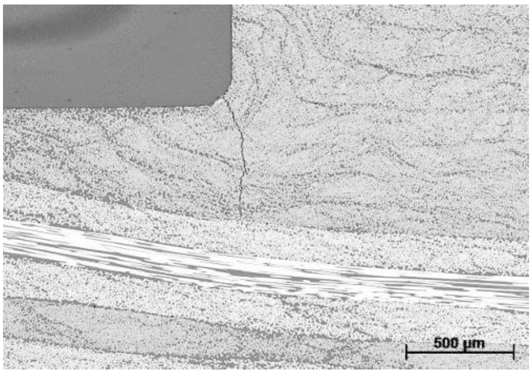

Figure 9: Crack near the corner of rib number 3.

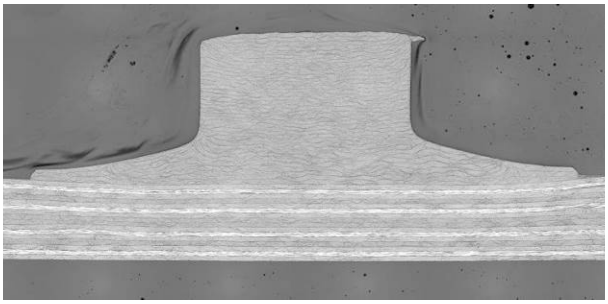

Figure 10: Trapezoid rib number 1 after cure

The trapezoid shaped rib number 1 showed a high quality laminate. No damage was found in the rib and at the interface, see Figure 10.

No cracking was observed in the trapezoid rib, in rectangular shaped ribs cracks near the interface were observed. It is therefore necessary to have a smooth transition between the rib and avoid sharp corners the skin to prevent cracking.

From the manufacturing trials of the rib variations it can be concluded that:

- The predicted damage size (crack lengths) from the Finite Element Method (FEM) simulations were not observed,
- Some matrix cracking at the interface was observed at sharp corners,
- No significant effect of rib height variation on damage patterns or distortion was observed,
- Local distortion of the skin near the ribs was observed,
- Ribs did not separate from the skin.

2.1.2.3 Maximum unsupported rib height trial

The manufacturing trials described in the previous section showed that the rib height could be increased without additional reduction of interface strength.

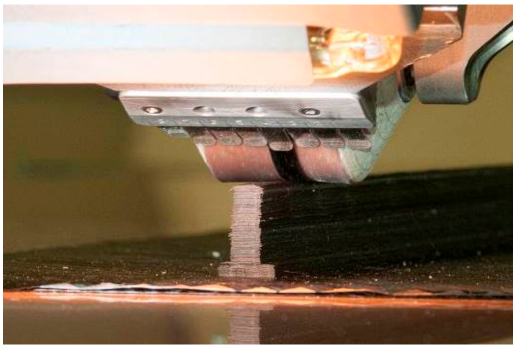

Figure 11: Rib manufacturing using fibre placement without support during fibre placing

Additional trials were carried out to determine the maximum "stable" rib height that can be manufactured using fibre placement without supports during placing. If ribs can be placed without additional support tooling, this significantly simplifies the manufacturing process. Trials manufacturing ribs with increasing height were carried out, see Figure 11. The first trials showed that the compaction force had a significant effect on the maximum achievable rib height.

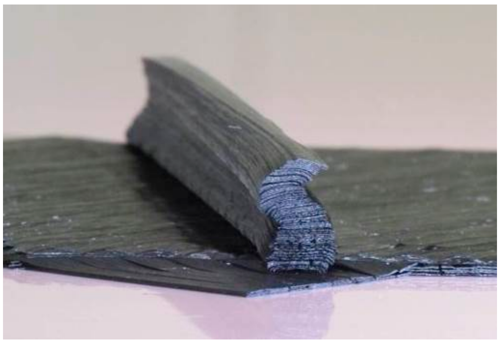

Figure 12: First rib height trial showing unstable behavior above 15 mm rib height.

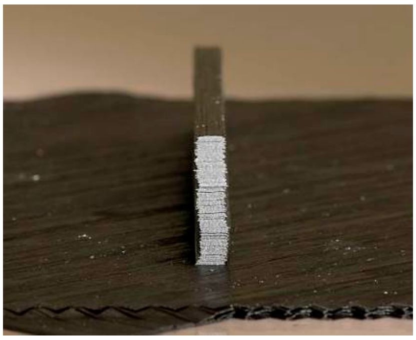

Figure 13: Final result of the rib height trial showing a good quality and stable rib

By decreasing the compaction force of the fibre placement roller during placing, it was possible to achieve rib heights of over 30 mm without much effort, see Figure 12 and Figure 13. These results gave sufficient confidence to manufacture a panel using the technique.

2.2 Pin positioning method

To evaluate the use of embedded pins as positioning aids during co-bonding, the actual embedding of the pins was investigated, as well as the manufacture of L-blade stiffened panels. These more traditional panels were also used to as comparison to the rib stiffened panel performance.

2.2.1 Embedding pins

Stainless steel mesh pins manufactured by stamping (see Figure 14), the Redundant High Efficiency Assembly (RHEA) meshes [8], were provided by Airbus Group Innovations Germany. Titanium mesh pins (see Figure 15) were manufactured at NLR by metal additive manufacturing (AM) using Selective Laser Melting (SLM). A grid of 4x4 pins was used, distance between pins was 4 mm, pin diameter is 0.3 mm, pin height is 1 mm. Diameter of connecting sections is 0.3 mm. Table 2 gives more details on the mesh configurations.

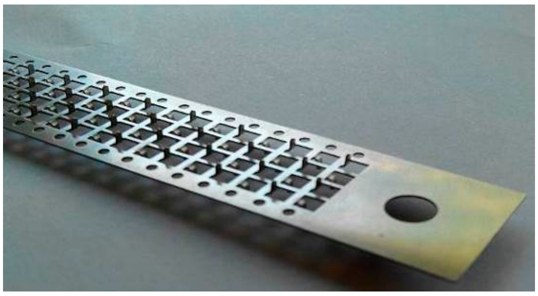

Figure 14: Stainless steel RHEA mesh

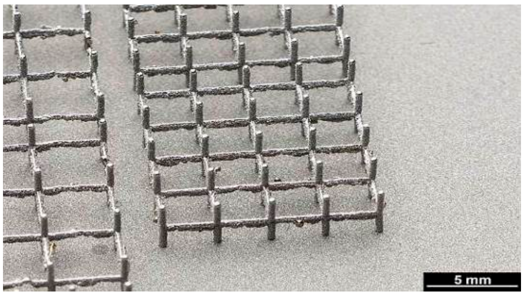

Figure 15: Titanium SLM mesh

Table 2: Mesh details

	RHEA Mesh	SLM mesh
Sheet width	20 mm	12 mm
Sheet thickness	0.4 mm	0.3 mm
Length of reinforcing area	183 mm	12 mm
Width of reinforcing area	13 mm	12 mm
Pin width	0.8 mm	0.3 mm
Pin height	2 mm	1 mm
Material	Stainless steel	TiAl6V4

To use the mesh pins as positioning aids, they must be embedded into a cured part. Trials were carried out to investigate a proper method to embed the meshes. Airbus Innovations had used rubber mats to press the meshes into the laminates during cure. This method was evaluated for the RHEA and SLM meshes.

Partial embedding of pins into a laminate appeared relatively straightforward. With the standard cure cycle used, a 50 Shore D rubber sheet gave adequate results, allowing the pin to protrude sufficiently from the laminate.

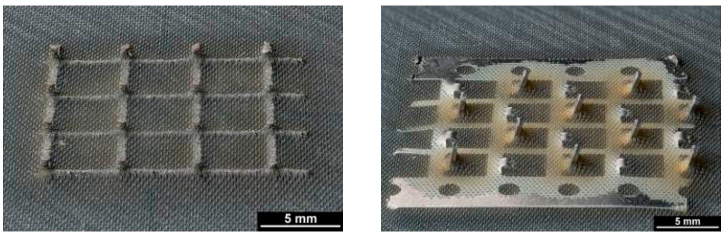

Figure 16: Detail of embedding using 50 Shore rubber sheet

2.3 Panels

2.3.1 Panel design

To evaluate the structural efficiency of the panels using the rib stiffening and pin positioning system as described, post-buckling stiffened compression panels were designed, manufactured and tested. The main goal was to demonstrate the technologies on a higher level with a relevant structure for aerospace applications.

The geometry of the stiffened panels is:

Length: 600mm, Width: 400mm
Four rib stiffeners, pitch 100 mm
Wide base (R=5 mm) for the co-cured rib stiffened panels
L-blade stiffeners for pin positioning panels
An illustration of the rib stiffened panel and blade stiffened panel is shown in Figure 17. The rib stiffeners have a wide base to enable a radius and thus reduce stress concentrations.

Skin thickness and rib height were varied during design to enable a design with local buckling response.

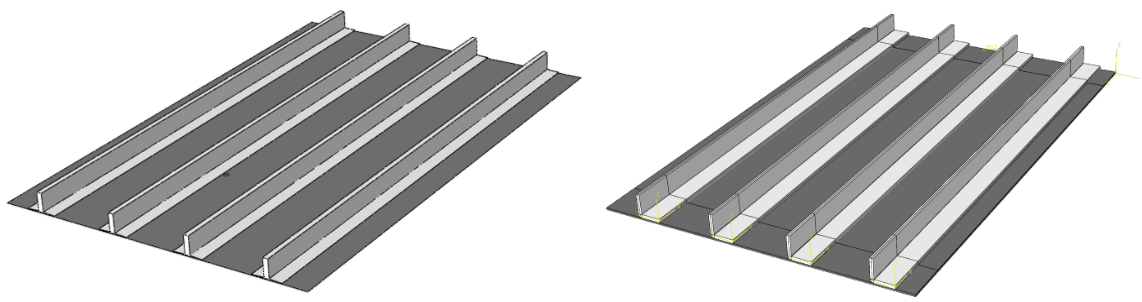

Figure 17: Illustration of the co-cured rib stiffened panel (left) and the co-bonded blade stiffened panel (right)

In the design process of the demonstrator panel the post-buckling performance is important to demonstrate. This post-buckling of the skin will stress the interface between the skin and the rib-stringer. A parametric model was created to investigate the variation of skin thickness and rib height on the performance. This was also compared to a blade stiffened panel. The choice for a relatively simple L-blade stiffener was due to budget constraints.

The panel performance was expressed in terms of linear buckling load and the weight of the panel. A balance had to be found between the skin thickness and rib height to enable good performance and local buckling. The final buckling pattern for the rib stiffened panel is shown in Figure 18.

The defined panels have the performance and dimensions figures as shown in Table 3. The performance (buckling load) is kept the same for good comparison of the weight advantage.

Table 3: Overview of calculated stiffened panel comparison

Panel type	*Grid height [mm]*	*Skin thickness [mm]*	*Buckling load factor [400N/mm]*	*Weight [kg]*	*Performance: (buckling load factor /weight)*	*Buckling mode*
Rib stiffened	23.5	2.08	2.0	1.427	1.40	local
Blade stiffened	25	2.08	2.0	1.552	1.29	local

The panel analysis results show that the rib stiffened panel in this case has an 8% lower weight compared to the blade stiffened panel at the same performance. Buckling occurs around 800N/mm which equates to 320 kN of load. The rib stiffened panel has a weight of 1.427 kg and the blade stiffened panel a weight of 1.552 kg.

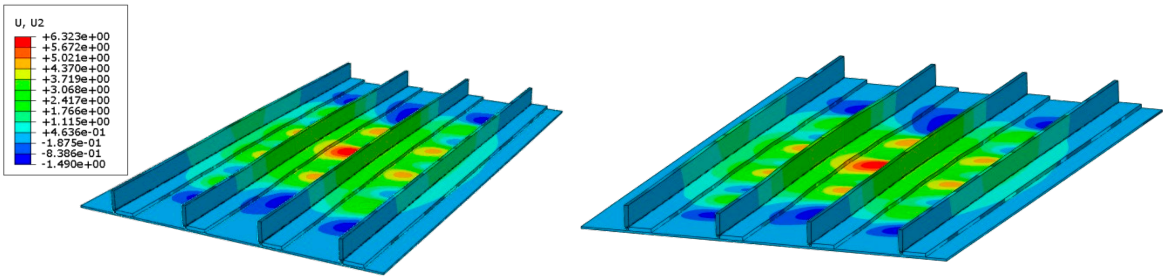

Figure 18: Rib stiffened panel buckling mode (left) and
blade stiffened panel with out of plane buckling displacements (right)

To estimate the deformation during curing of the co-cured rib stiffened panel, a thermal analysis was performed. This analysis included the material expansion coefficients and considers a cooling down from cure temperature (180 °C) to room temperature (20 °C). As previously observed in the rib samples, a bending in the skin occurs due to the rib material that creates an a-symmetric laminate locally. Analysis results of the cooling to room temperature are shown in Figure 19. A total offset from the undeformed panel of around 3 mm at the centre is expected.

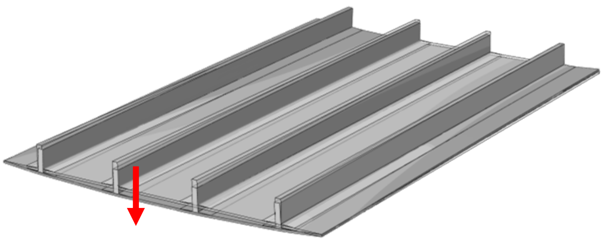

Figure 19: Bending of the rib stiffened panel due to cooling to room temperature after cure

2.3.2 Manufacture of a rib stiffened panel

The skin consisting of 12 layers $[45/90/-45/0/45/-45]_s$ with 2.08 mm thickness was fibre placed and the ribs were placed starting with a wide base by first placing 14 layers of two 6.35 mm tows side by side. After this, single tows were placed on top of the two tows to create the rib. In total 122 layers were placed for the ribs, see Figure 21.

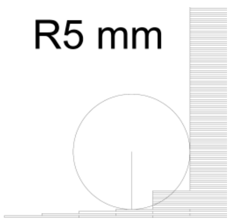

Figure 20: Schematic overview of radius used to "squeeze" tapes into place to form the rib foot

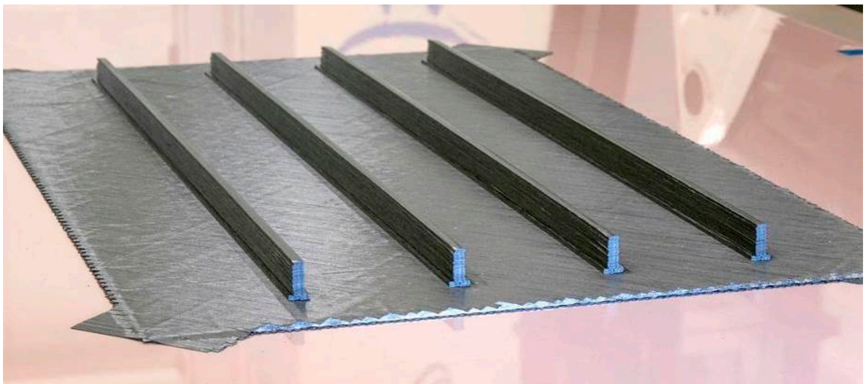

Figure 21: Fibre placed panel with skin and four ribs before autoclave cure

Aluminium tooling blocks were placed between and around the ribs. The tooling blocks had a radius of 5 mm at the foot of the rib and were used to squeeze the tapes into the desired shape, see Figure 20. Metal strips were placed on top of the ribs to apply pressure on the ribs, see Figure 22. The entire assembly was bagged and cured.

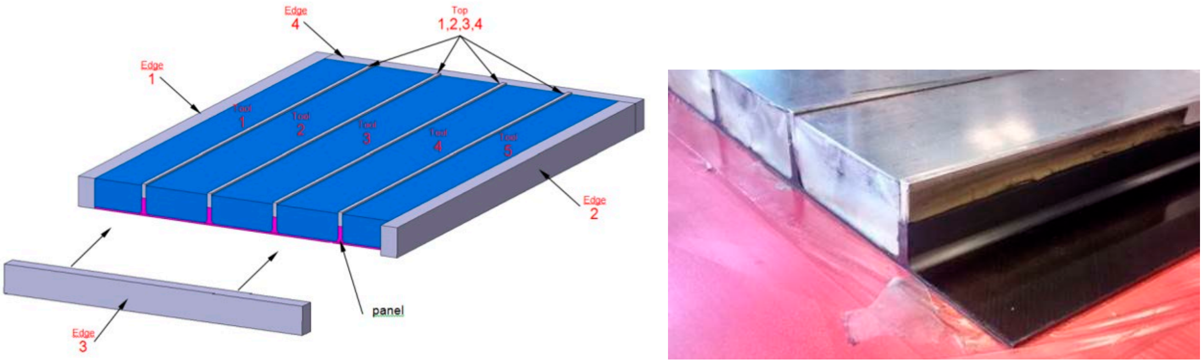

Figure 22: Tooling concept (left) and demoulding

After cure, it appeared that the rib stiffeners were slightly lower and somewhat wider than expected. Apparently, the tooling blocks were not held together tightly as separate tooling blocks were used around the panel during cure. A solid ring or at least triangular cross-section tooling blocks around the panel would probably have given more accurate results.

The final rib stiffened panel was C-scanned. Both skin and ribs, as well as the interface were of good quality, see also Figure 23.

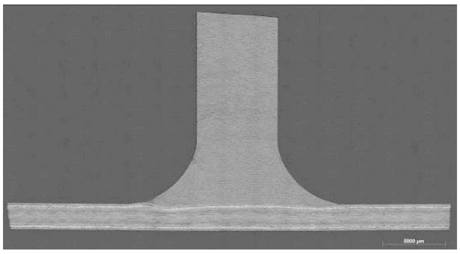

Figure 23: Cross/section of rib stiffener in panel.

Figure 24: bending due to transversal shrinkage of ribs. Maximum deviation measured 2.7 mm

Some bending of the panel is observed which is comparable to the analysis predictions, see Figure 19 and Figure 24. The maximum measured deformation is 2.7 mm. A slight lengthwise curvature is observed along the stiffeners due to the difference in stiffness between skin and rib stiffeners. The stiffeners bend towards the skin due to the difference in shrinkage between the quasi-isotropic skin and UD-stiffeners.

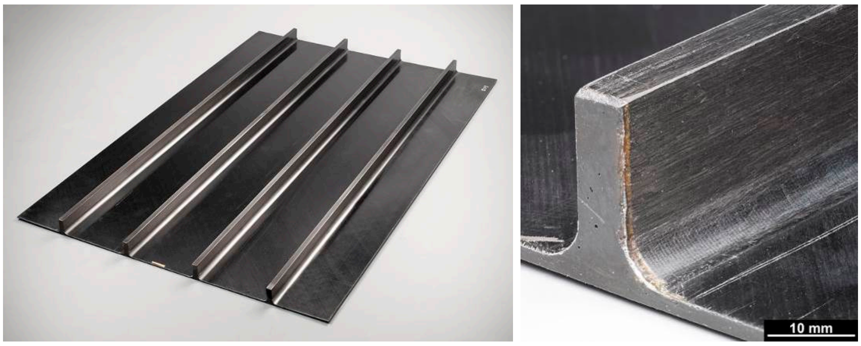

Figure 25: Final rib stiffened co-cured compression panel before machining

The panel was machined to net size and resin blocks were attached for compression testing.

2.3.3 Manufacture of blade stiffened panels

Panels were manufactured to evaluate the effectiveness of mesh pins during assembly. For this, L-stiffeners were manufactured in which mesh pins were embedded and cured, after which the stiffeners were co-bonded on an uncured skin using different methods. After co-bonding, the positioning of the stiffeners on the skin was measured and evaluated.

Stiffeners were co-bonded on an uncured skin using two methods. A reference method was used for the stiffeners without mesh. With this method, stiffeners were positioned and held into place at the outer ends by grips during cure. The other method was to use spacers to position stiffeners with embedded meshes on the skin. After positioning, the spacers were removed and a vacuum bag is made over the stiffeners without any additional support and the product is cured. Only the meshes were used to keep the stiffeners in place.

2.3.3.1 Manufacture of stiffeners

Lay/up of the stiffeners was $[45/-45/0/90]_{3s}$. Stiffeners were manufactured by fibre placing [45/-45/0/90] sub-laminates and stacking them in the proper sequence. The sub-laminates were subsequently folded over the edge of a square metal block as the mould. Four stiffeners were manufactured in one cure cycle in this way.

One set of stiffeners was manufactured without meshes, one set with RHEA meshes and one set with SLM meshes. The size of the meshes was approximately 18x18 mm which results in 4x4 pins per mesh.

One mesh was placed in the middle of the stiffener foot and the two other meshes were placed at 275 mm on either side of the first mesh on the same foot. Rubber, 50 shore, was placed over the meshes and the stiffeners were cured as described before.

After cure, it appeared that some of the SLM meshes had shifted during the process.

The stiffeners were machined to size. Due to a manufacturing mistake, the SLM meshes were placed on the wrong position on the foot of the laminate which led to 4 of the 16 pins being machined away at the foot, see Figure 26 right and Figure 27. Care must therefore be taken when incorporating pins into a laminate.

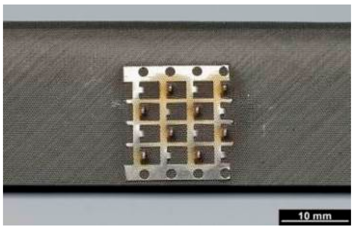
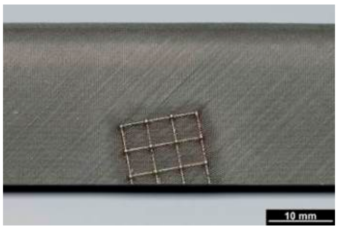

Figure 26: Embedded meshes in stiffeners.
Left RHEA mesh, right shifted SLM mesh

Figure 27: Cured with SLM meshes stiffeners after machining

Although a number of pins was machined away, it was decided to go ahead and use the stiffeners for panel manufacture, as it was expected that the remaining pins would still be sufficient for positioning.

2.3.3.2 Reference panel

An uncured fibre placed skin was used with a $[45/90/-45/0/45/-45]_s$ lay-up. Redux 322 adhesive was used between stiffeners and skin. The stiffeners were held in place by grips. The grip pressure was low, allowing the stiffeners to move in vertical direction during cure. The entire assembly was vacuum bagged and cured.

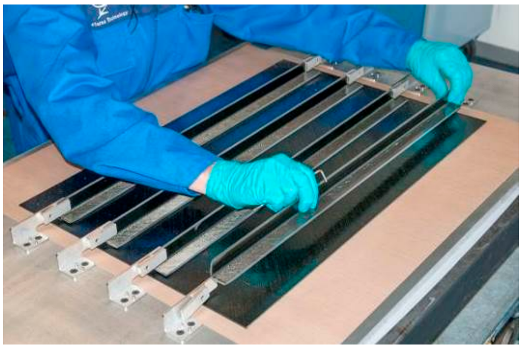

Figure 28: Positioning of stiffeners with grips

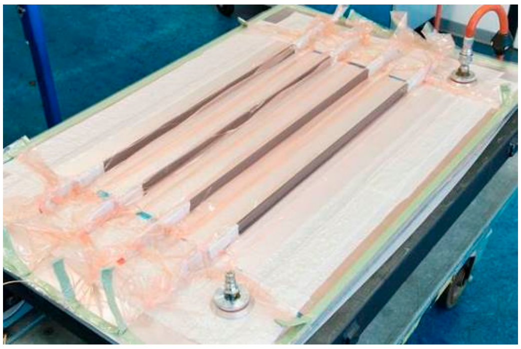

Figure 29: Finished vacuum bag with grips

Although great care was taken to make a vacuum bag without excessive bridging, a leak still occurred during cure due to bridging, resulting in a reduced quality skin laminate at one end of the panel.

2.3.3.3 Panels with meshes

The panels with meshes were manufactured in a different way. The stiffeners were positioned on the uncured skin using spacers. Figure 30 shows a detail and an overview of this method.

The skin laminate was heated locally before inserting the meshes to allow for penetration of the pins. For the RHEA mesh, it proved difficult to just press the pins onto the laminate by heating only, therefore blocks were placed on the stiffeners (without the Redux adhesive layer) and the pins were wedged into the laminate by gently wiggling the stiffener sideways. After the skin laminate was punched in this way, the stiffeners were removed, adhesive was applied and the stiffeners were positioned accurately again using spacers.

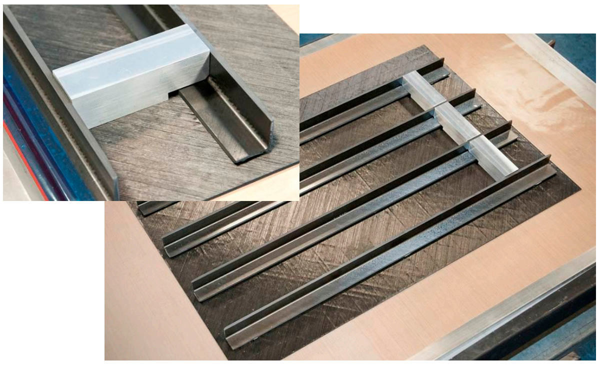

Figure 30: Spacers used to position L-blade stiffeners

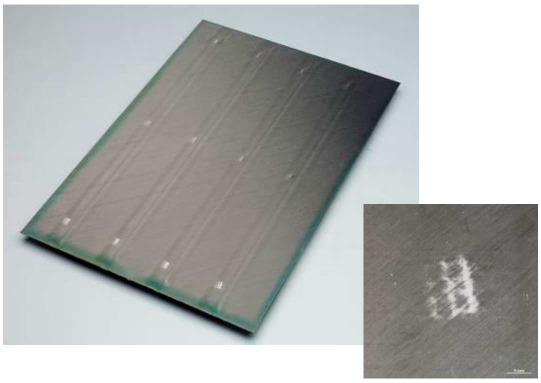

Figure 31: Cured SLM mesh panel.
Insert: dryier area at mesh location

Spacers were removed after positioning and the panels were bagged, cured, inspected and machined to size. Both mesh panels showed good skin quality and good bond quality except for one stiffener of the SLM mesh panel, see Figure 32 and Figure 33.

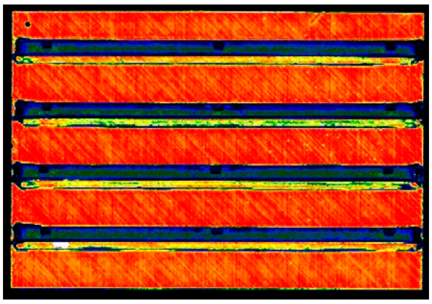

Figure 32: Attenuation C-scan of SLM panel skin

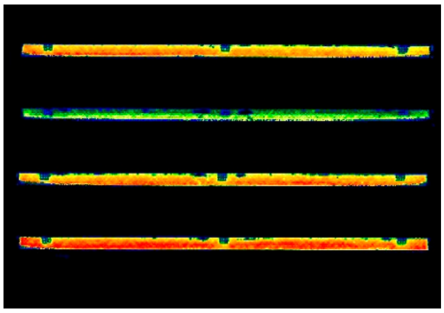

Figure 33: Attenuation C-scan of SLM panel stiffener-skin bond

One stiffener had rotated slightly on the SLM panel. This shows as a bond with more attenuation in the C-scan (2nd from top in Figure 33). Figure 34 shows the displacement, the rotation can be clearly seen.

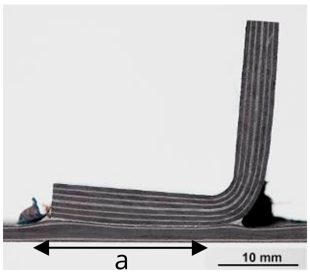

Figure 34: Rotated L-stiffener of panel with SLM meshes.

2.3.4 Mechanical test

The panels were tested in compression to evaluate and compare their performance to the predicted values. Digital image correlation (ARAMIS 3D) was used to visualise the deformation of the panels.

Both blade and rib stiffened panels with meshes and the rib stiffened panel were tested with anti-buckling guides. Due to a miscommunication, the reference blade stiffened panel was tested without anti-buckling guides.

Table 4 gives an overview of the test results. Figure 35 gives an example of digital image correlation measurements.

Table 4: Compression test results for panels

Panel	*Buckling load(kN)*		*Failure load (kN)*	*Weight (kg)*	
	Measured	*Calculated*	*Measured*	*Measured*	*Calculated*
Rib	378		-*	1.438	1.427
Reference blade	275 **	320	-	1.639	1.552
RHEA mesh	299		362	1.634	
SLM mesh	288		359	1.646	

* Not tested to failure ** Panel was tested first. No anti-buckling guide used, panel failed immediately after buckling

It was not possible to determine the exact failure mode due to the sudden failure of the panels.

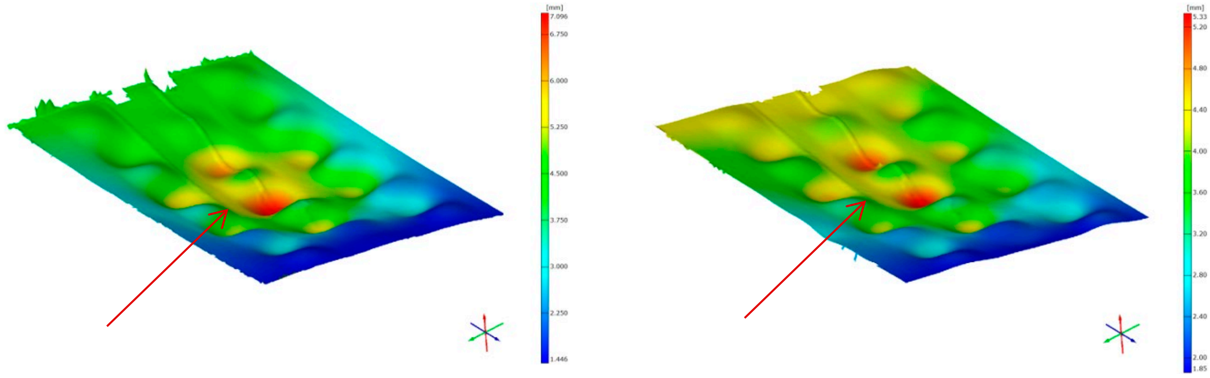

Figure 35: Displacement of panels during compression test measured using digital image correlation of RHEA mesh panel (left) and SLM mesh panel. View of outer skin side. The red arrow points at the mesh position.

3 DISCUSSION AND CONCLUSIONS

3.1 Panel manufacture

Ribs with a height of up to 30 mm can be manufactured using AFP without support during placement with relative ease. A high quality panel using this method was manufactured.

Relative simple tooling blocks can be used for curing rib stiffened panels. A radius between skin and rib can be easily incorporated. The use of separate tooling blocks that are positioned on the uncured laminate without any fixation allows for variation is dimensions. The tooling blocks must be restrained from moving during cure to achieve higher accuracy.

Due to shrinkage of the resin perpendicular to the fibre direction in the ribs, deformation of the panel was observed, as predicted in the analyses.

The use of pins to reduce the amount of tooling when a component must be manufactured using co-bonding can be attractive as only a vacuum bag is required. Tooling required can be relatively simple, only positioning aids need to be used to position the stiffeners and no tooling during cure is necessary as the pins lock the components in place. Attention still should be paid during vacuum bagging, as it is possible to displace parts during bagging, see the shifting of the SLM mesh in Figure 26. The rotation of the stiffener depicted in Figure 34 may have occurred during bagging.

An uncured (fibre placed) laminate is dense and it is not easily penetrated by thick pins. If mesh pins are employed, it is recommended to use the smallest pin diameters possible to allow for easier insertion into a laminate. Mesh pins with pin diameter of approximately 0.3 mm proved relatively easy to insert.

The gripping method used to position the stiffeners without pins has the advantage that it is relatively straightforward and there is no need to penetrate the laminate. However, bagging is more complex due to the tooling that has to be bagged together with the product leading to a higher risk of leaks.

The blade stiffened panels were approximately 5% heavier than calculated. After closer examination of the panels, it appeared that the height of the stiffeners was 2 mm larger than calculated. When accounting for this difference and the additional weight for the adhesive, the difference between calculated and measured weight is negligible for the blade stiffeners. Taking these differences into account, the relative weight comparison shows that rib stiffened panel is 8% lighter than the blade stiffened panel.

3.2 Compression tests

From the compression tests performed, the rib stiffened panel appears to perform 18% better than analytically predicted, the L-blade stiffened panels appear to perform 6.6 % (RHEA mesh) worse than analytically predicted.

Possible explanations for the differences observed in performance of the rib stiffened panel are the slight curvature of the panel after curing which was not included in the buckling analyses. Also the actual stiffener foot width was larger than assumed due to shifting of the tooling blocks during cure. This caused a smaller unsupported skin section and could explain the higher buckling loads as the free skin width is reduced, improving local buckling performance.

For the L-blade stiffened panel, the free skin width was actually larger than assumed for the calculations. Due to the radius of the stiffeners, a smaller area was available to bond the stiffeners to the skin. Length a in Figure 34 was actually 22 mm instead of the assumed 25 mm. If this difference is accounted for, the buckling load is approximately 296 kN, which is in the range of the values measured. It can be assumed that when the blade stiffened panel would have had the correct dimensions used in the analysis, it would have performed as predicted in the analysis. An L-blade stiffened panel with the correct dimensions would therefore be 8% higher in weight than a rib-stiffened panel and would perform as predicted.

The rib stiffened panel performed better than predicted and had a higher buckling load, probably due to geometric deviations from the assumed geometry. This indicates, however, that the rib stiffening method has the potential for a better performance compared to blade stiffened panels with, at least, 8% lower weight.

The reference blade stiffened panel fails at a load below that of the panels with meshes. Due to the absence of buckling guides during testing, no conclusion can be drawn from this other than that it is just slightly lower than the loads for the panels with meshes.

There is no direct indication that there is an influence of the meshes on the performance in compression of the panels. The difference in buckling load of the panels with meshes is 3.7%, the difference in failure load is even smaller at 0.8 %. The meshes at the outer edges will have little effect on the deformation of the panels as they are close to the clamped area. The meshes at the centre of the panel may have a larger influence. Further study must be conducted to evaluate the effect of mesh pins when they are located in highly stressed areas. However, no large deviation or discontinuity in the displacement was observed at a position near the mesh, see Figure 35.

3.3 Comparison of manufacturing methods

The rib stiffening method uses a relatively expensive AFP machine where positioning pins for the blade stiffening method could be manufactured in large volumes at relatively low cost using additive manufacturing or another suitable method. For both methods, a comparable amount of tooling is necessary: metal blocks are necessary to cure the rib stiffened panels, metal blocks are necessary to cure the blade stiffeners and grips for positioning the cured stiffeners. The vacuum bag for the cure of the rib stiffened panel is relatively simple and the risk of leakage is limited. The tooling configuration for the cure of blade stiffeners leads to more complex bagging, which increases the risk of leaks, rendering the method less reliable.

The rib stiffened panel performs better in buckling compression compared to the L-blade stiffened panels while at the same time being lighter. The rib stiffening method also requires only one autoclave cycle compared to two for the pin positioning method. The pin positioning method bagging method is more complex and likely less reliable compared to the rib stiffening method.

The rib stiffening method is therefore preferred over the pin positioning method from a mechanical performance and weight point of view, as well as from a manufacturing and reliability point of view. These claims should be substantiated by additional research focussing on e.g. cost, reliability, reproducibility and achievable production rate, as these subjects were not within the scope of the project.

4 ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°314003.

Airbus Innovations Group Germany is gratefully acknowledged for providing the RHEA meshes.

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